Greenhouse Gas and Energy Consumption Rates for On-road Vehicles:

Updates for MOVES2014

United States Environmental Protection Agency

Greenhouse Gas and Energy Consumption Rates for On-road Vehicles:

Updates for MOVES2014

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

NOTICE

This technical report does not necessarily represent final EPA decisions or positions. It is intended to present technical analysis of issues using data that are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments.

EPA United States Environmental Protection Agency

EPA-420-R-15-003
October 2015

Contents

1 Introduction

The goal of this report is to provide a reference to the energy and greenhouse gas values that are used in MOVES2014. This report presents the energy rates, nitrous oxide emission rates, and methane fractions stored in the MOVES2014 database in tables and graphs. Rather than a comprehensive documentation of the energy and emission rates, this reports provides documentation only of the updates made to the rates for MOVES2014. 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 five major sections:

1. Energy Rates Updates
2. Methane (CH_4) Emission Rates
3. Nitrous Oxide (N_2O) Emission Rates
4. Carbon Dioxide (CO_2) Emission Rates
5. Fuel Consumption Calculations

MOVES2014 incorporates the light-duty greenhouse gas (GHG) emission standards affecting model years 2017 and later cars and light trucks.[1] MOVES2014 also incorporates the heavy-duty GHG Phase 1 emissions standards for model years 2014 and later.[2] The energy rates for light-duty vehicles are based on work conducted in MOVES2004,[3] however, they have been significantly updated in subsequent versions of MOVES, including MOVES2009, MOVES2010, MOVES2010a,[4] and MOVES2014. The intent of this report is to document the changes in energy rates that were made between MOVES2010a and MOVES2014. We point the reader to the earlier reports that document the development of the energy rates prior to MOVES2010a.[3,4] In this report, we briefly discuss the impact of the HD GHG Phase 1 standards implemented in MOVES2014. However, the details of the energy rates for heavy-duty are documented in the MOVES2014 heavy-duty emissions rates report.[5]

The methane emission rates used in MOVES2014 are based on analysis done for MOVES2004. As for the energy rates, we do not provide a comprehensive derivation of the original methane rates. However, we document the updates made to convert these rates into the methane/THC fractions used in MOVES2014, and we display example ratios.

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

MOVES calculates carbon dioxide (CO_2) emissions 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.

Last, we 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 does calculate gallons for use in internal calculators. 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.

2 Energy Rate Updates

2.1 Light Duty Vehicles

In MOVES2014, the energy rates for motorcycles (MC) are unchanged from MOVES2010a, as well as energy rates from 2007 and earlier model year light-duty vehicles (LDV) and light-duty trucks (LDT). In MOVES2010a, the energy rates for MC, LDV and LDT were consolidated across weight classes and engine technologies, as discussed in the MOVES2010a energy updates report.[4] Earlier MOVES versions contained significantly more detail in the energy rates, which varied by engine technologies, engine size and more refined loaded weight classes. For MOVES2010a, the energy rates were simplified to be single energy rates for each regulatory class, fuel type and model year combination. This was done by removing advanced technology energy rates, and aggregating the MOVES2010 energy rates across engine size and vehicle weight classes according to the default population in the MOVES2010 sample vehicle population table. Because this approach uses highly detailed energy consumption data, coupled with information on engine size and vehicle weight for the vehicle fleet that varies for each model year, year-by-year variability was introduced into the aggregated energy rates used in MOVES2010a and now in MOVES2014, as shown in Figure 2-2,

We revisited the MY 2008-MY2016 rates that had been updated for MOVES2010a, and changed the ratio of reduction applied to the base rates between start and running. Many of the compliance technologies anticipated to be used in response to the light duty greenhouse gas regulation (transmission improvements, aerodynamic improvements, tires, etc) will not improve performance during vehicle start. Thus the MOVES2010a method, which applied the same rate of reduction to both running and starts, likely underestimated energy consumption from starts. For MOVES2014, the reduction applied to starts was revised to be half of that applied to running. Because energy consumption at start is a small fraction of the total, this increase has little impact on total CO2 emissions; however to keep the composite emissions the same, we also decreased fuel consumption for running emissions by about one percent.

EPA's Light Duty GHG MY 2017+ rule[1] phases in for passenger cars, light-duty trucks, and medium-duty passenger vehicles in MYs 2017 through 2025. After MY 2025, the standards continue indefinitely. The final standards are projected to result in an average industry fleet-wide level of 163 grams/mile of carbon dioxide (CO_2) in model year 2025, which is equivalent to 54.5 miles per gallon (MPG) if achieved exclusively through fuel economy improvements.

For MOVES 2014, we adjusted the projected CO_2 g/mile rates from the rulemaking regulatory classes (car/truck) to the regulatory classes in MOVES (regClassID 20/30), removed the air conditioning leakage improvements and left the air conditioning efficiency improvements in the rates themselves[a]. We also adjusted the emission rates for the on-road fuel economy gap of approximately 20% (multiplying the CO2 rates by 1.25x).

We calculated ratios needed to produce the emission rates projected in the LD GHG rulemaking, and then used these ratios to reduce the MY 2016 MOVES2010a base emission rates as shown in Table 2-1 The trend in the energy emissions rates can be observed in Figure 2-2 and Figure 2-4.

Table 2-1 – Overall reductions as compared to MY LDV and LDT energy rates 2016 rates

MY	Model year GroupID	LDV (RegClassID 20) CO2 g/mile	LDV 20 Ratio		LDT (RegClassID 30) CO2 g/mile	LDT ratio
2017	37	269	93%		348	97%
2018	38	258	89%		340	95%
2019	39	247	86%		332	93%
2020	40	236	82%		324	90%
2021	41	226	79%		304	85%
2022	42	217	75%		290	81%
2023	43	207	72%		276	77%
2024	44	198	69%		262	73%
2025	45	190	66%		250	70%
2026	46	190	66%		250	70%
2027	47	190	66%		250	70%
2028	48	190	66%		250	70%
2029	49	190	66%		250	70%
2030	50	190	66%		250	70%
2031-2050	9	190	66%		250	70%

In MOVES2014, we made a number of additional minor updates to MOVES database tables. These included updating the pollutantprocessmodelyear table to include references to new model year (MY) groups for MY 2020 and later. This table now includes MY groups for each model year from 2020 to 2030 and a new MY group for all MY 2031-2050 vehicles. We also updated the energy emission rates for ethanol (E-85) and electricity, such that they continue to have equivalent energy consumption as gasoline vehicles. Although the energy rates are the same for these alternative fuels, the carbon content is different, resulting in different CO_2 emission rates as discussed in Section 5.1.

[a] Instead of adjusting MOVES multiplicative air conditioning adjustments, we lowered the overall running energy emission rate to reflect the air conditioning improvements. The impact on emissions is equivalent.

2.1.1 Summary of Light-Duty Running Energy Rates

Figure 2-1 plots the MOVES2014 running energy rates by operating mode for motorcycles (MC), light-duty vehicles (LDV), and light-duty trucks (LDT) for model year 2012. For gasoline LDVs the relative trend between energy rates and operating modes is constant starting in 1999 model year going forward. For gasoline LDT, the relative trend between energy rates and operating modes is constant starting in MY 2001 going forward to MY 2050. However, as shown in Figure 2-2, the magnitude of LDV and LDT gasoline energy consumption rates decrease sharply beginning in MY 2012. As discussed earlier, E-85 vehicles and electric vehicles use the same energy rates as gasoline vehicles.

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 5-1) compared to gasoline fuel, such that the CO_2 emission rates are equivalent for 2012 MY+ gasoline and diesel vehicles. As shown in Figure 2-2, the magnitude of LDG and LDT diesel energy consumption rates decrease at the same rate as gasoline vehicles beginning in MY 2012.

The motorcycle running energy rates have the same relative shape between operating mode bins starting in MY 1999 through MY 2050 as shown in Figure 2-1. The energy rates were developed initially for MOVES2004[3] for three weight categories (<500 lbs, 500-700 lbs, and >700 lbs), and three engine size categories (<170 cc, 170-280 cc, and > 280 cc). When the energy rates were consolidated to a single energy rate for all motorcycles in MOVES2010a[4], this resulted in an average increase in energy motorcycle rates between MY 1991 and MY 2000 due an accompanying shift to larger motorcycles[6], which is shown in Figure 2-2. We assumed the same distributions of motorcycles starting in MY 2000 going forward to MY 2050 (2.9% <170cc, 4.3% 170-280cc, and 92.8%>280 cc, with 30% between 500-700 lbs, and 70% > 700 lbs). Thus there are constant motorcycle energy running rates starting in MY 2000 to MY 2050.

Figure 2-1. Running energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2012.

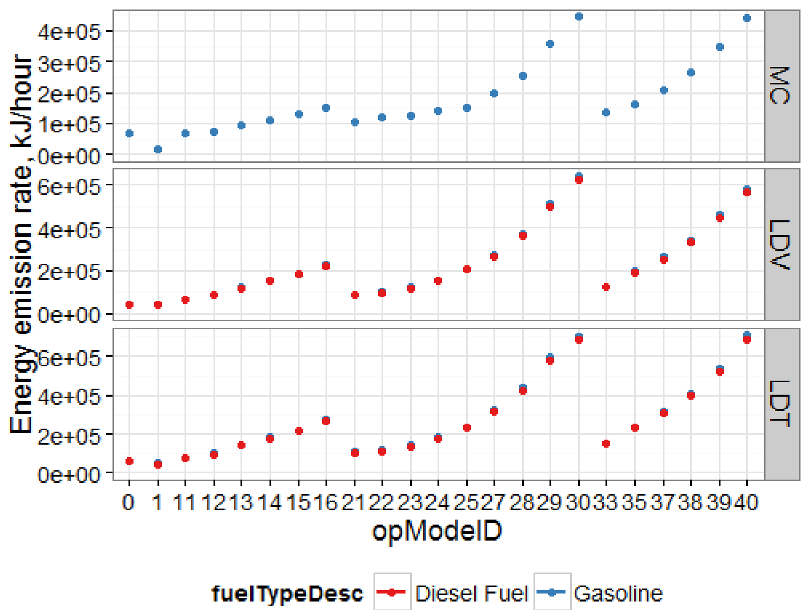
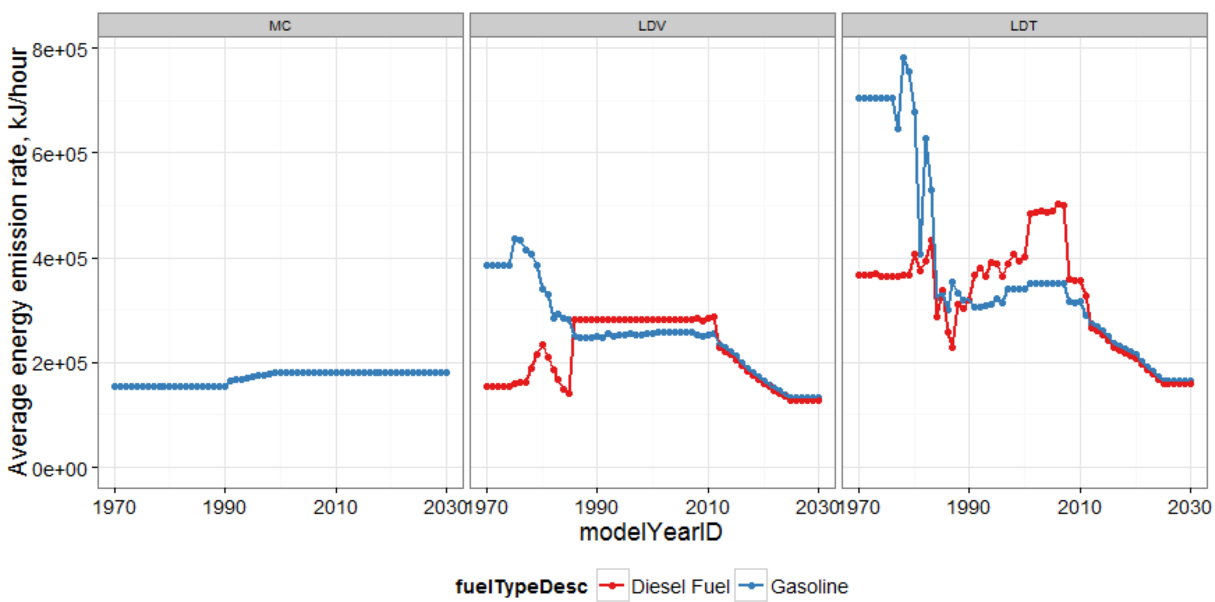


Figure 2-2. Average energy consumption rates for motorcycle, light-duty vehicles, and light-duty trucks across all running operating modes. 1960-1969 MY have the same energy consumption rates as MY 1970, and the MY 2031-2050 have the same energy rates as MY 2030



2.1.2 Summary of Light-Duty Start Energy Rates

Figure 2-3 displays the energy rates for starts by operating mode for MY 2012 motorcycles, light-duty vehicles, and light-duty trucks. As shown start energy increases for operating modes with longer soak times as defined in Table 2-2. These fractions are used for all model years and fuel types of light-duty vehicles. Additionally, the start energy rates are adjusted in MOVES for increased fuel consumption required to start a vehicle at cold ambient temperatures. The temperature effects are documented in the 2004 Energy Report.[3]

Figure 2-3. Start energy rates by operating mode (opModeID) for motorcycles (MC), light-duty vehicles (LDV) and light-duty trucks (LDT) for model year 2012.

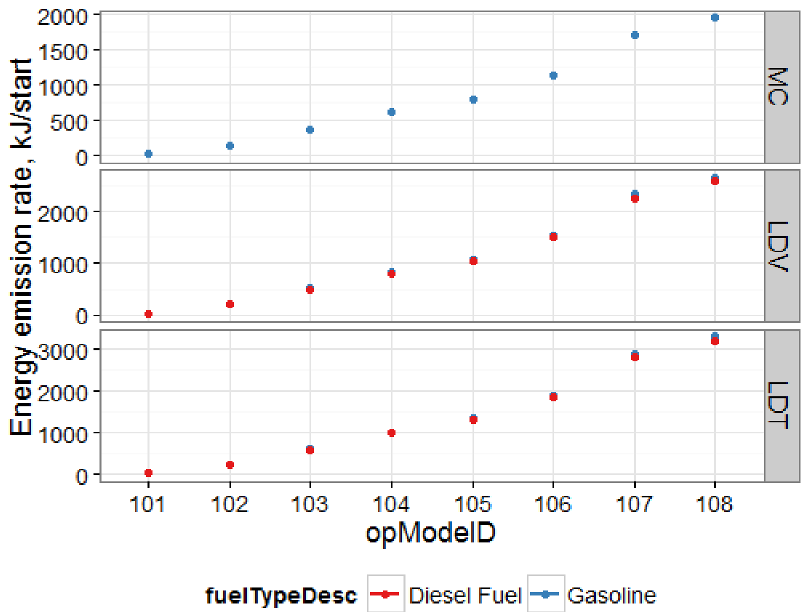
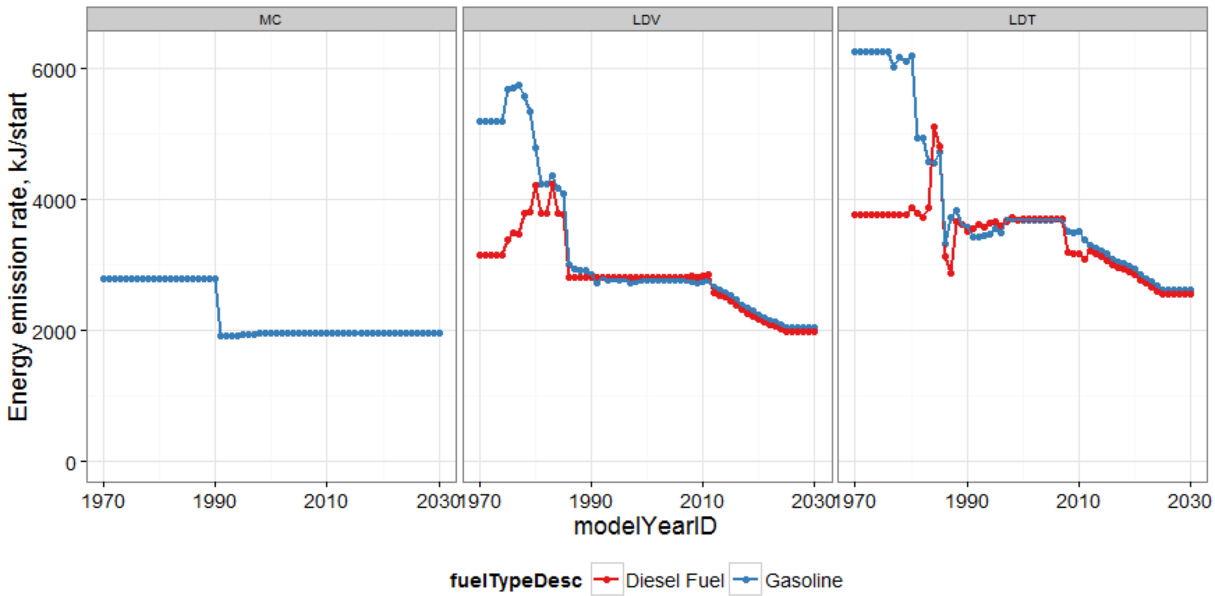


Table 2-2. Fraction of energy consumed at start of varying soak lengths compared to the energy consumed at a full cold start (operating mode 108).

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 2-4 depicts the energy start rates for a cold start (opMode108) across model years for light-duty vehicles. Motorcycles have a sharp decrease in energy starts in 1991 because MOVES assumes ‘controlled’ energy starts starting with MY 1991 as documented in the MOVES2004 energy report[3]. 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 2-4. Cold start energy rates (opMode 108) for motorcycle, light-duty vehicles, and light-duty trucks



2.2 Heavy-Duty Vehicles

The HD GHG Phase 1 standards[2] began with the 2014 model year and increase in stringency through 2018. The standards continue indefinitely after 2018. The program divides the diverse truck sector into 3 distinct categories:

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

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

In MOVES2014, the HD GHG Phase 1 rule is implemented through three key elements. These include (a) Revised running emission rates for total energy, (b) New aerodynamic coefficients and weights, (c) Auxiliary Power Units (APUs) largely replace extended idle in long haul trucks and are added as a new process. The revised running emissions rates for total energy and auxiliary energy and criteria emission rates are documented in the MOVES2014 heavy-duty

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

emissions rates report.[5] The revised aerodynamic coefficients for MY 2014 and later heavy-duty trucks are documented in the MOVES2014 Population and Activity Report.[7]

In addition to the energy updates made in response to the HD GHG Phase 1 rule, we updated the CNG transit bus energy rates based on data from CNG-transit bus driving cycle measurements as documented in the MOVES2014 heavy-duty emissions report,[5] and updated the energy starts to be equivalent to diesel-fueled Urban Bus regulatory class. Likewise, the CNG transit buses are subject to the same relative HD GHG Phase 1 energy reductions as the diesel Urban Bus regulatory class.

3 Methane Emission Rates

Methane emissions in MOVES2014 are unchanged from those in MOVES2010a. These rates are based on those developed for MOVES2010, but in MOVES2010a (as documented in the Updates to the MOVES2010a report[4]) we revised the algorithm used to calculate the emissions such that methane emissions are a function of total hydrocarbon (THC) and calculated appropriate ratios from the MOVES2010 rates.

MOVES2010 used a running emission rate (in terms of grams/mile, and a start emission rate (in terms of grams/start) derived using emission test results from the Federal Test Procedure, and supplemental results from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006.[19] These rates had only one operating mode for running and start conditions and did not vary according to ambient temperature or increase with age to account for deterioration. This was in contrast to rates for total hydrocarbons (THC) for which running emissions are calculated for each of 23 operating modes (based on vehicle speed and power) and for which start emissions are calculated for each of 8 operating modes (based on vehicle soak time prior to engine start). In addition, the start THC rates varied according to ambient temperature, and increased with age to account for deterioration.

In MOVES2010a, the MOVES calculations to derive methane (CH_4) from the total hydrocarbons (THC) values were revised to be calculated as a fraction of total hydrocarbons (THC)[8]. This change more closely aligned the methane calculations with the calculation of other hydrocarbon compounds in MOVES and prevents inconsistencies that occurred in MOVES2010.

Methane and non-methane hydrocarbons in MOVES2010a and later versions are now calculated by applying a multiplicative factor (CH4THCRatio in the MethaneTHCRatio table) to the calculated THC value after all adjustments to THC have been made for all fuel types as described in the speciation report.[8] The MethaneTHCRatio stores the CH4THCratio according to the following fields:

- Vehicle source type (sourceTypeID)
- Age (ageGroupID)
- Fuel (fuelTypeID)
- Process (processID), including running, start, evaporative processes, extended idle, and APU

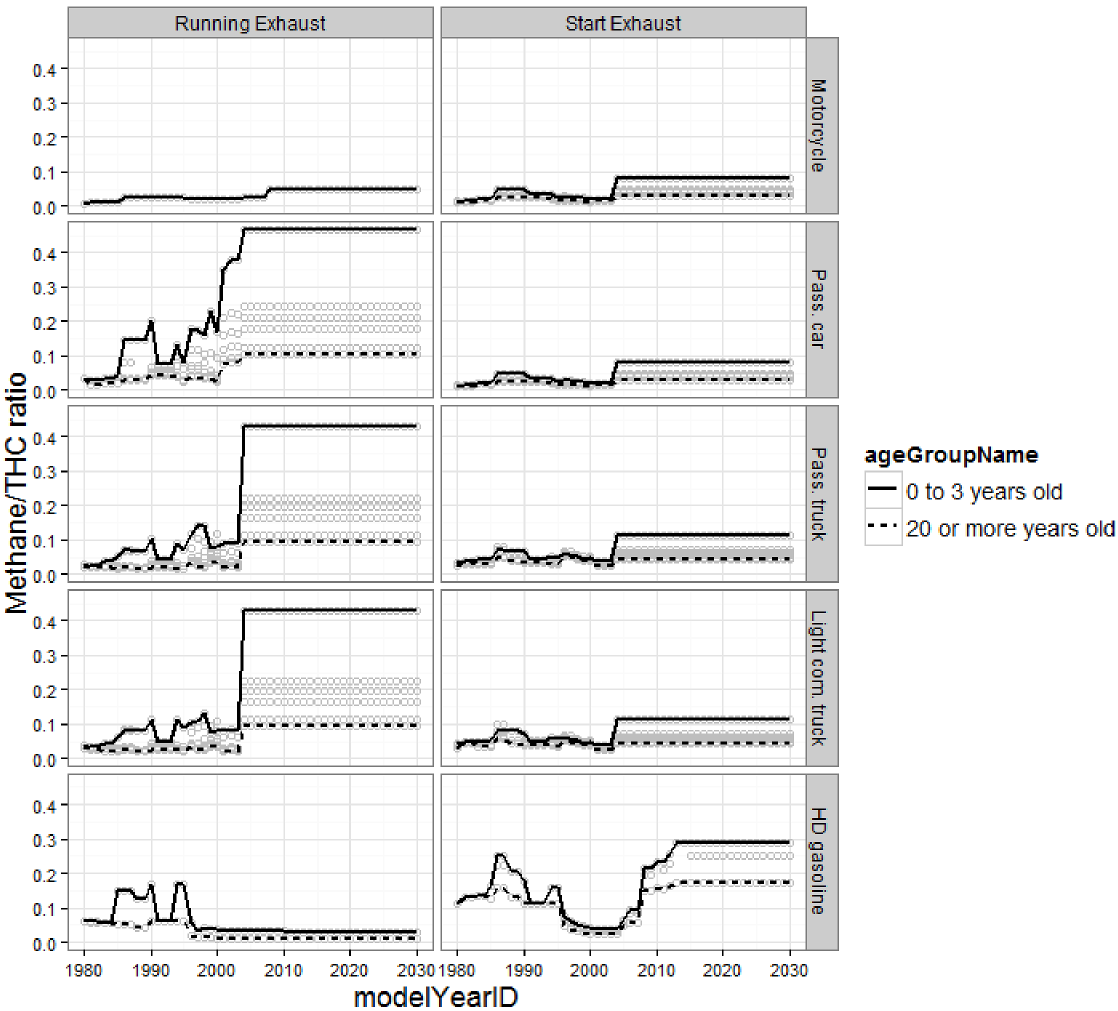
The ratios are applied to all operating modes for an emission process. The methane/THC ratio for evaporative and refueling emission processes for all vehicles is zero because methane gas is not found in liquid fuels such gasoline, diesel or E-85 fuels and is not formed during in-tank weathering.

3.1 Gasoline-fueled Vehicles

As discussed in the MOVES2010a energy updates report, a series of MOVES runs were used to create the methane/THC ratios for MOVES2010a for gasoline vehicles. These values continue to be used in MOVES2014. The MOVES2014 methane/THC values gasoline vehicles are shown in

Figure 3-1. As shown, the methane/THC values vary according to age, with the methane/THC ratios being higher for age 0-3 vehicles than for aged vehicles. This trend is an outcome of the available data and process used to derive the methane/THC emission rates for MOVES. As mentioned above, the methane emission rates in MOVES2010 did not vary according to age, while the THC emission rates increased due to deterioration effects. This caused the methane/THC ratios to decrease with age for these vehicle types. In the future, we plan on improving these ratios with additional data.

Figure 3-1. Gasoline Methane/THC ratio by model year, sourcetype, and pollutant process. 1980 and earlier fractions are equal to 1980, and 2030 and later are equal to the 2030 fractions. The grey points are all the gasoline methane/THC ratios for running and start exhaust across all vehicle source types and age groups.



3.2 E85-fueled Vehicles

MOVES2014 restored the capability of modeling methane emissions from vehicles using fuels with 70 percent or more ethanol by volume (i.e., E85 fuel). MOVES2004 included methane emission rates for ethanol fueled vehicles, but MOVES2010 did not include methane/THC values for vehicles fueled with E85.

The MOVES2014 methane/THC ratios for E85 were derived from the EPAct Phase 3 program.[9] The LA92 test cycle was used with emissions measured over three phases analogous to those in the Federal Test Procedure (FTP), at an ambient temperature of 75°F. Emissions measured include total hydrocarbons (THC) and methane (CH_4) from four Tier-2 certified flexible-fuel vehicles (FFVs) running on E85 fuel.

The methane/THC ratios were calculated separately for running exhaust and start exhaust emissions from each FFVs and then averaged by emissions processes. The age effects assumed for gasoline-fueled vehicles were applied to the methane/THC ratios for E85-fueled vehicles as shown in Table 3-1. These ratios apply to all model years.[c] Note, MOVES2014 models E85 use only for passenger cars, passenger trucks and light commercial trucks.[7]

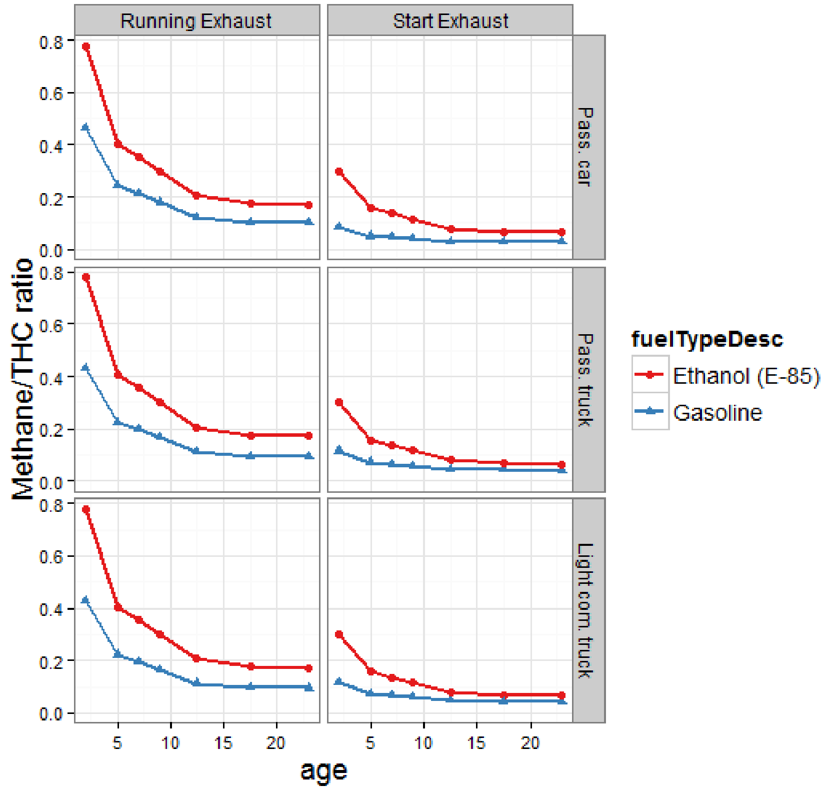
Table 3-1. Methane/THC ratios by age for Ethanol (E85) fueled vehicles in MOVES2014 for all model years, and all applicable source types (21, 31 and 32)

Age Group	Running Exhaust	Start Exhaust
0 to 3 years old	0.779	0.300
4 or 5 years old	0.404	0.155
6 or 7 years old	0.356	0.137
8 or 9 years old	0.300	0.115
10 to 14 years old	0.204	0.079
15 to 19 years old	0.174	0.067
20 or more years old	0.172	0.066

Consistent with the literature, Figure 3-2 shows that the methane/THC ratios for E85 are higher in MOVES2014 than the ratios for gasoline-fueled vehicles.[10,11]

[c] Because the data used to derive the methane/THC ratios for E85 fueled vehicles are based on Tier 2 vehicles, there is more uncertainty in the ratios for 2000 and older technology vehicles running on high ethanol blends in MOVES2014. However, pre-2001 flex-fuel vehicles are minor portion of the light-duty gasoline fleet. For example, the default MOVES2014 population indicates that less than 1-3% of the 1998-2000 model year light-duty gasoline vehicles are flex-fuel vehicles and MOVES2014 doesn't include any flex-fuel vehicles earlier than model year 1998. Additionally, the number of flex-fuel vehicles that use high ethanol blends is limited; making pre-2001 MY, high-ethanol blend fueled vehicles a small portion of the vehicle emissions inventory.

Figure 3-2. Methane/THC ratios by age, and source type for Gasoline and Ethanol (E85) fueled vehicles in model year 2005 and later

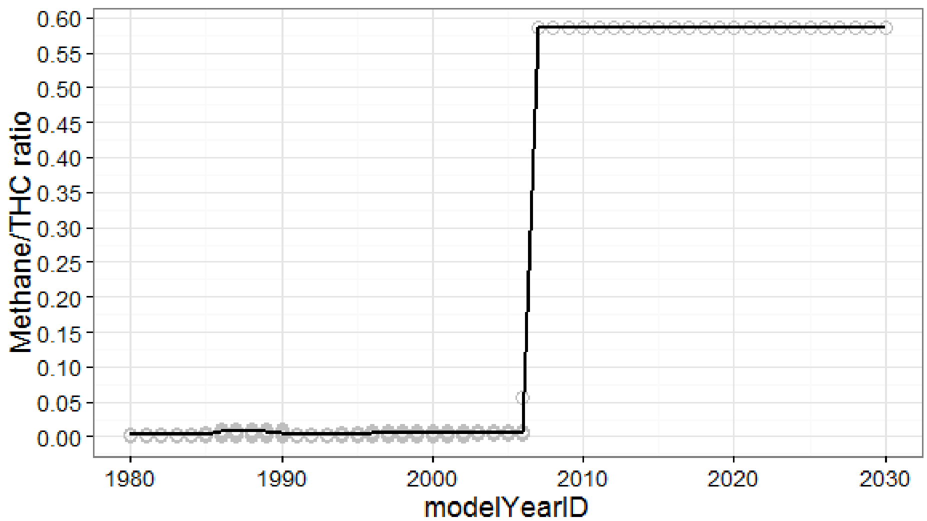


3.3 Diesel-fueled Vehicles

The methane/THC values from diesel vehicles are unchanged in MOVES2014 from MOVES2010a. Figure 3-3 displays the methane/THC values for running, start, and extended idle exhaust from diesel vehicles across all source types and ages. The methane/THC values for pre-2007 diesel vehicles were developed by calculating the ratio between the THC and methane emission rates in the MOVES2010 version, as was done for gasoline-fueled vehicles. For MY 2006 and earlier, these values are quite low, ranging from 0.001to 0.057 with an average of 0.003 as shown in Figure 3-3.

For 2007 and later, all diesel source types of all ages have the same methane/THC value of 0.5846 for start, running, and extended idling emissions. The methane ratio for 2007 and later model year diesel trucks was derived from diesel vehicle emission testing conducted in Phase I of the Health Effects Institute (HEI) Advanced Collaborative Emissions Study (ACES).[12] The methane/THC fraction for auxiliary power units is a constant 0.003 methane/THC ratio for all model years.

Figure 3-3. Diesel Methane/THC ratios for running and start exhaust. The solid line is the Methane/THC ratio for Combination Long-haul (SourceTypeID=62), running exhaust (polProcessID= 1) and between 0-3 years old (ageGroupID = 3). The grey points are all the methane/THC ratios for running and start exhaust across all diesel vehicle source types and age groups.



3.4 Compressed Natural Gas-fueled Transit Buses

MOVES2014 models emissions from CNG transit buses. The methane/THC ratios were updated in MOVES2014 based on measurements conducted on CNG transit buses from the Washington Metropolitan Area Transit Authority[13] as documented in the MOVES2014 Heavy-Duty Emission Rate Report.[5] MOVES uses two different methane/THC values for CNG transit buses that are differentiated by model year as shown in Table 3-2. The values extend back to model year 1960 and apply to all age groups, however CNG transit buses enter the fleet starting in model year 1990 in the MOVES2014 default vehicle population.

Table 3-2 Methane/THC ratios for CNG- transit buses in MOVES2014

Model Year	CH4/THC Ratio
1960-2001	0.917
2002-2050	0.950

Currently, we do not estimate evaporative or refueling emissions from CNG vehicles in MOVES and thus have no methane/THC ratios for these values. This is an area for future research.

4 Nitrous Oxide Emission Rates

4.1 Gasoline and Diesel-Fueled Vehicles

The nitrous oxide (N_2O) emission rates had only minor updates in MOVES2014. As detailed in the MOVES2010a energy and greenhouse gas emission rate report[4], the N_2O emission rates are derived from emission tests measured on the Federal Test Procedure (FTP) and supplemented with N2O emission rates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006 report.[19]

The N_2O emission rates are modeled with a single running operating mode, and a single start operating mode. The N_2O emission rates are stored in the emissionrate table, and, unlike most pollutants, the emission rates do not vary by vehicle age. As discussed in the previous energy and greenhouse gas update, the running and start emissions are derived from the composite FTP emission rates by using bag 2 of the FTP to estimate the average running emission rates (in grams per hour), and then estimating the start emissions as the remainder of the composite emissions[4].

Table 4-1 and Table 4-2 list the FTP composite N_2O emission rates, the calculated running rates (in grams per hour), and start rates (in grams per start).

Table 4-1: Composite FTP N_2O emissions, running and start for gasoline vehicles

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

Table 4-2. Composite FTP N_2O emissions, composite, running and start for diesel vehicles

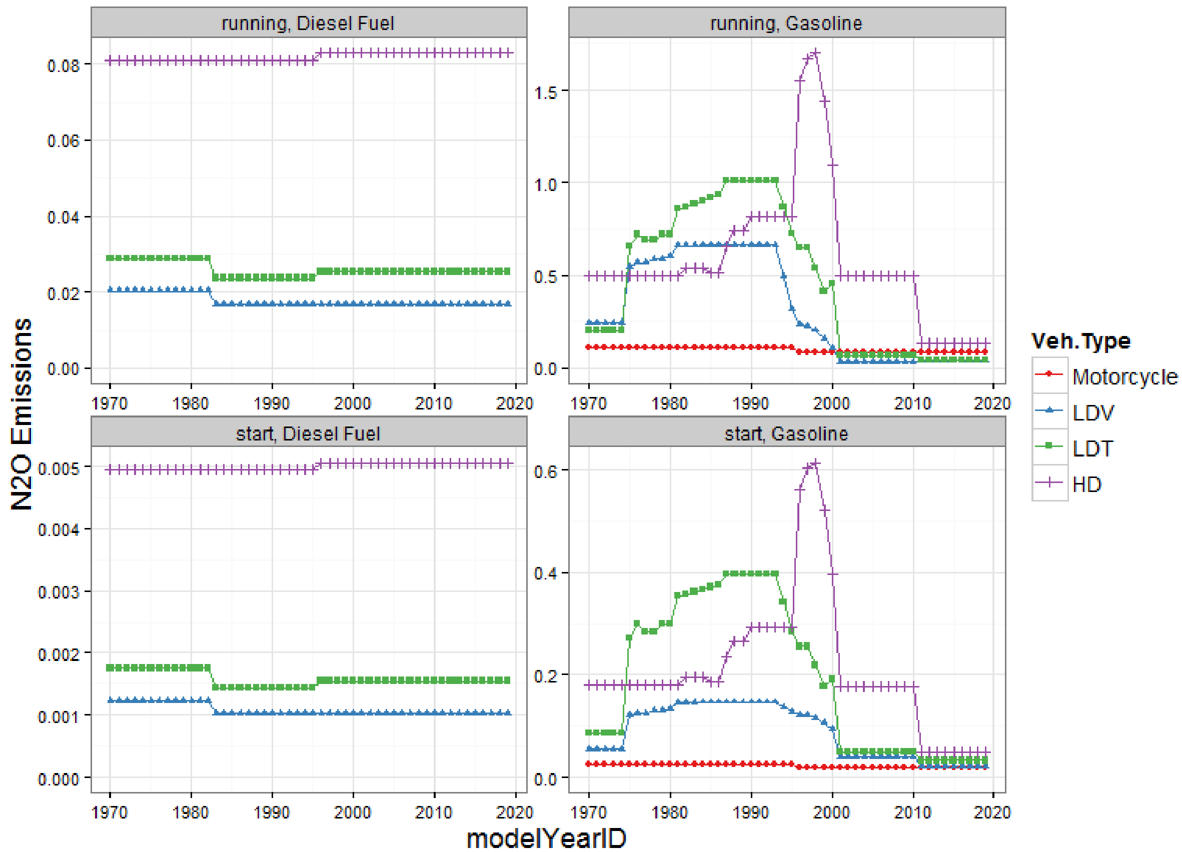
Vehicle Type / Control Technology[a]	FTP Comp (g / mile)	Running (g / hour)	Start (g / start)
Diesel Passenger Cars			
Advanced	0.0010	0.0168	0.0010
Moderate	0.0010	0.0168	0.0010
Uncontrolled	0.0012	0.0202	0.0012
Diesel Light-Duty Trucks			
Advanced	0.0015	0.0253	0.0015
Moderate	0.0014	0.0236	0.0014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

[a] Table 8-5 defines the model year group definitions of the diesel control technologies groups

The N_2O emission rates are applied in MOVES using model year group ranges that map to technology distinctions. Table 8-1 through Table 8-5 in the Appendix provide the distribution of vehicles types/technology types by model year. The running and start emission rates in Table 4-1 and Table 4-2 are multiplied by the model-year specific technology penetrations to provide model year specific emission rates in MOVES. The values in Table 8-1 through Table 8-5 are taken directly from the Inventory of the US GHG emissions and sinks, Annex Tables A-84 through A-87[19], except for the few instances as noted in the footnotes of the tables.

Figure 4-1 displays the model year-specific N_2O emission rates used in MOVES2014 for gasoline and diesel-fueled vehicles that are calculated as the product of the technology-specific rates provided in Table 4-1 and Table 4-2 and the model-year/technology penetrations provided in the Appendix. In general, MOVES2014 uses the model-year specific rates. However, for 2001-2010 MOVES has a single N_2O emission rate to represent the range of model year groups, and the emission rate for these model year groups in MOVES is the average of the model-year specific rates. MOVES2014 uses the same N_2O emission rate within vehicle class and fuel type for 2011 through 2050 model year vehicles.

Figure 4-1. N_2O emission rates for running and start processes for gasoline and diesel vehicles in MOVES2014. The N_2O emission rates are constant from 1960-1970 model year and are constant from 2011-2050 model years



4.2 Alternative-Fueled Vehicles

MOVES2004 included 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.[19] In MOVES2014, we updated the N_2O emission rates for E85-fueled vehicles to use the same emission rates as gasoline vehicles. We will revisit the N_2O E85 rates as more data becomes available.

Compressed natural gas (CNG) transit buses use the emission rates reported in Table 4-3. These rates remain unchanged from the numbers reported for MOVES2010a.[4] However, in MOVES2014, the N_2O emission rates were modified so they apply only to Urban Bus (regClassID 48) vehicles fueled by CNG, and do not apply for any other vehicle type, since in MOVES2014, CNG is an allowed fuel for transit buses only. The composite emission rate was obtained from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2006[19], and disaggregated into running and starts using the same relative running and start splits as heavy-gasoline vehicles.

Table 4-3: Nitrous oxide emission Rates for CNG-fueled transit buses

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

5 Carbon Dioxide (CO_2) Emission Rates

5.1 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 5-1.

$$CO_2 = Total\ Energy\ Consumed\ \times Carbon\ Content \times Oxidation\ Fraction \times \left(\frac{44}{12}\right) \qquad \textbf{Equation 5-1}$$

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

The carbon content and oxidation fractions used to calculate CO_2 emissions are provided in Table 5-1. The carbon content values used in MOVES were developed for MOVES2004[3] based on values derived from the life-cycle model GREET.

Table 5-1. Carbon content, xxidation fraction and energy content by fuel subtype

fuelSubtypeID	fuelTypeID	Fuel Subtype	Carbon Content (g/KJ)	Oxidation Fraction
10	1	Conventional Gasoline	0.0196	1
11	1	Reformulated Gasoline (RFG)	0.0196	1
12	1	Gasohol (E10)	0.0196	1
13	1	Gasohol (E8)	0.0196	1
14	1	Gasohol (E5)	0.0196	1
15	1	Gasohol (E15)	0.0196	1
20	2	Conventional Diesel Fuel	0.0202	1
21	2	Biodiesel	0.0201	1
22	2	Fischer-Tropsch Diesel (FTD100)	0.0207	1
30	3	Compressed Natural Gas (CNG)	0.0161	1
40	4	Liquefied Petroleum Gas (LPG)	0.0161	1
50	5	Ethanol	0.0194	1
51	5	Ethanol (E85)	0.0194	1
52	5	Ethanol (E70)	0.0194	1
18	1	Ethanol (E20)	0.0194	1
90	9	Electricity	0	0

5.2 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 5-2.

$$CO_2\ equivalent = CO_2\ \times GWP_{CO_2} + CH_4\ \times GWP_{CH_4} + N_2O\ \times GWP_{N_2O}$$ **Equation 5-2**

GWP is Global Warming Potential. MOVES uses the100-year Global Warming Potentials listed in Table 5-2 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), which is consistent with values used in recent the LD GHG 2017+ rule and the HD GHG Phase 2 NPRM.

Table 5-2. 100-year Global Warming Potentials used in MOVES

Pollutant	Global Warming Potential (GWP)
Methane (CH4)	25
Nitrous Oxide (N2O)	298
Atmospheric CO2	1

6 Fuel Consumption Calculations

MOVES reports fuel consumption in terms of energy use, but does not report fuel usage in term of volume or mass. However, MOVES calculate fuel usage in terms of volume and mass within the refueling[14] and sulfur dioxide emission calculators, respectively.[15]

MOVES uses energy content and the density of the fuel to calculate fuel volume, as presented in Equation 6-1 and the values in Table 6-1.

$$Fuel\ (gallons) = Energy\ (KJ)\ \times \left(\frac{1}{energyContent}\right)\left(\frac{g}{KJ}\right) \times \left(\frac{1}{fuelDensity}\right)\left(\frac{gallons}{g}\right) \qquad \textbf{Equation 6-1}$$

The fuel density and the energy content values are stored in the fueltype and fuelsubtype MOVES 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 MOVES fuelsupply table. The derivation of the fuelsupply table is documented in the report: MOVES2014 Fuel Supply Defaults[16].

Table 6-1. Fuel density and energy content by fuel type in MOVES2014

fuelTypeID	fuelSubtypeID	fuelSubtypeDesc	Fuel Density (g/gallons)	Energy Content (KJ/g)
1	10	Conventional Gasoline	2839	43.488
1	11	Reformulated Gasoline (RFG)	2839	42.358
1	12	Gasohol (E10)	2839	41.762
1	13	Gasohol (E8)	2839	42.1
1	14	Gasohol (E5)	2839	42.605
1	15	Gasohol (E15)	2839	40.92
1	18	Ethanol (E20)	2839	40.077
2	20	Conventional Diesel Fuel	3167	43.717
2	21	Biodiesel	3167	43.061
2	22	Fischer-Tropsch Diesel (FTD100)	3167	43.247
3	30	Compressed Natural Gas (CNG)	NULL	48.632
4	40	Liquefied Petroleum Gas (LPG)	1923	46.607
5	50	Ethanol	2944	26.592
5	51	Ethanol (E85)	2944	29.12
5	52	Ethanol (E70)	2944	31.649
9	90	Electricity	NULL	NULL

7 Appendix A. Timeline of Energy and GHG emissions in MOVES

- **MOVES2004**[3]
    - 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)[17] or interpolation.
    - Energy consumption at starts increases at temperatures < 75F
- **MOVES2009**
    - Updates of Nitrous Oxide (N2O) and methane (CH4) 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[18],[19]
    - 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 2011 Corporate Average Fuel Economy (CAFE) Standards for light trucks
- **MOVES2010a**[4]
    - 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 FE/GHG final rule projections
        - 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 reduced for 2014 and later model years vehicles to account for the Phase 1 of the Greenhouse Gas Emissions

Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles[2]

- Light Duty energy rates reduced for 2017 and later model years vehicles to account for the Light-duty EPA and NHTSA greenhouse gas and fuel economy standards[1]

8 Appendix B: Emission Control Technology Phase-In used for N2O Emission Rate Calculations.

Table 8-1 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 8-2 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 8-3 Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT) Reproduced with exceptions from Table A-85 from Inventory of US GHG Emissions and Sinks: 1990-2006.

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

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

Table 8-4 Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT) Reproduced with exceptions from Table A-86 from Inventory of US GHG Emissions and Sinks: 1990-2006.

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

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

Table 8-5 Control Technology Assignments for Diesel Highway Vehicles and Motorcycles. Reproduced with exceptions from Table A-87 from Inventory of US GHG Emissions and Sinks: 1990-2006.

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

[a]In MOVES we continue using the 1996-2006 rates for all model years beyond 2006. The 2013 US GHG Emissions and Sinks updates the Advanced Control to up to 2011 model year vehicles, and adds a new category of diesel (aftertreatment diesel). However, the N2O emission rates of aftertreatment diesel are unchanged from advanced control.[20]

9 References

[1] 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)

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

[3] 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. http://www.epa.gov/otaq/models/ngm/420p05003.pdf.

[4] 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. http://www.epa.gov/otaq/models/moves/documents/420r12025.pdf.

[5] USEPA (2015). *Exhaust Emission Rates for Heavy-Duty On-road Vehicles in MOVES2014*. EPA-420-R-15-004. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. September, 2015. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[6] 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. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[7] USEPA (2015). *Population and Activity of On-road Vehicles in MOVES2014*. EPA-420-D-15-001. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. 2015. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[8] USEPA (2014). *Speciation of Total Organic Gas and Particulate Matter Emissions from On-road Vehicles in MOVES2014*. EPA-420-R-14-020. Ann Arbor, MI. October, 2014. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[9] USEPA (2013). *Assessing the Effect of Five Gasoline Properties on Exhaust Emissions from Light-Duty Vehicles certified to Tier-2 Standards: Analysis of Data from EPAct Phase 3 (EPAct/V2/E-89). Final Report*. EPA-420-R-13-002. Assessment and Standards Division, Office of Transportation and Air Quality, Ann Arbor, MI. April, 2013.

[10] Yanowitz, J, and McCormick, R (2009). *Effect of E85 on Tailpipe Emissions from Light-Duty Vehicles.* J. Air & Waste Manage. Assoc. 59:172-182.

[11] Graham, L., Belisle, S., and Baas, C. (2008). *Emissions from Light Duty Gasoline Vehicles Operating on Low Blend Ethanol Gasoline and E85*. Atmospheric Environment. 42:4498-4516. June 2008.

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

[13] Melendez, M. T., J; Zuboy, J (2005). *Emission Testing of Washington Metropolitan Area Transit Authority (WMATA) Natural Gas and Diesel Transit Buses*. NREL/TP-540-36355. December 2005.

[14] USEPA (2014). *Evaporative Emissions from On-road Vehicles in MOVES2014*. EPA-420-R-14-014. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. September, 2014. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[15] USEPA (2015). *Fuel Effects on Exhaust Emissions from On-road Vehicles in MOVES2014*. EPA-420-R-15-001. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. 2015. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[16] USEPA (2015). *Fuel Supply Defaults: Regional Fuels and the Fuel Wizard in MOVES2014*. EPA-420-R-15-002. Assessment and Standards Division. Office of Transportation and Air Quality. US Environmental Protection Agency. Ann Arbor, MI. 2015. http://www.epa.gov/otaq/models/moves/moves-reports.htm.

[17] 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. http://www.epa.gov/otaq/models/ngm/420p05001.pdf.

[18] 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. http://www.epa.gov/otaq/models/moves/documents/420r12025.pdf.

[19] 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.

[20] 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.

http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-Annex-3-Additional-Source-or-Sink-Categories.pdf