# ANNEX 3 Methodological Descriptions for Additional Source or Sink Categories

## 3.1. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Stationary Combustion

### Estimates of $CH_4$ and $N_2O$ Emissions

Methane ($CH_4$) and nitrous oxide ($N_2O$) emissions from stationary combustion were estimated using methods from the Intergovernmental Panel on Climate Change (IPCC). Estimates were obtained by multiplying emission factors—by sector and fuel type—by fossil fuel and wood consumption data. This “top-down” methodology is characterized by two basic steps, described below. Data are presented in Table A-66 through Table A-68.

#### Step 1: Determine Energy Consumption by Sector and Fuel Type

Energy consumption from stationary combustion activities was grouped by sector: industrial, commercial, residential, electric power, and U.S. Territories. For $CH_4$ and $N_2O$ emissions from industrial, commercial, residential, and U.S. Territories, estimates were based upon consumption of coal, gas, oil, and wood. Energy consumption and wood consumption data for the United States were obtained from the Energy Information Administration’s (EIA) *Monthly Energy Review* (EIA 2025). Because the United States does not include U.S. Territories in its national energy statistics, fuel consumption data for U.S. Territories were collected from EIA’s International Energy Statistics database (EIA 2024) and Jacobs (2010).[44] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[45] Construction and agricultural fuel use was obtained from EPA (2022b) and the Federal Highway Administration (FHWA) (1996 through 2024). The energy consumption data by sector were then adjusted from higher to lower heating values by multiplying by 0.90 for natural gas and wood and by 0.95 for coal and petroleum fuel. This is a simplified convention used by the International Energy Agency (IEA). Table A-66 provides annual energy consumption data for the years 1990 through 2023.

In this *Inventory*, the energy consumption estimation methodology for the electric power sector used a Tier 2 methodology as fuel consumption by technology-type for the electric power sector was estimated based on the Acid Rain Program Dataset (EPA 2024a). Total fuel consumption in the electric power sector from EIA (2025) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2024a) data. The combustion technology and fuel use data by facility obtained from EPA (2024a) were only available from 1996 to 2023, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2024a) to the total EIA (2025) consumption for each year from 1990 to 1995.

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[44] U.S. Territories data also include combustion from mobile activities because data to allocate U.S. Territories’ energy use were unavailable. For this reason, $CH_4$ and $N_2O$ emissions from combustion by U.S. Territories are only included in the stationary combustion totals.
[45] Though emissions from construction and farm use occur due to both stationary and mobile sources, detailed data was not available to determine the magnitude from each. Currently, these emissions are assumed to be predominantly from mobile sources.

### Step 2: Determine the Amount of $CH_4$ and $N_2O$ Emitted

Activity data for industrial, commercial, residential, and U.S. Territories and fuel type for each of these sectors were then multiplied by default Tier 1 emission factors to obtain emission estimates. Emission factors for the residential, commercial, and industrial sectors were taken from the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). These $N_2O$ emission factors by fuel type (equivalent across sectors) were also assumed for U.S. Territories. The $CH_4$ emission factors by fuel type for U.S. Territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-67 provides emission factors used for each sector and fuel type. For the electric power sector, emissions were estimated by multiplying fossil fuel and wood consumption by technology- and fuel-specific Tier 2 IPCC emission factors shown in Table A-68. Emission factors were taken from U.S. EPA publications on emissions rates for combustion sources, and EPA's Compilation of Air Pollutant Emission Factors, AP-42 (EPA 1997) for combined cycle natural gas units. The EPA factors were in large part used in the *2006 IPCC Guidelines* as the factors presented.

## Estimates of $NO_x$, CO, and NMVOC Emissions

Emissions estimates for $NO_x$, CO, and NMVOCs were obtained from data published on the National Emission *Inventory* (NEI) Air Pollutant Emission Trends web site (EPA 2024b) and disaggregated based on EPA (2003).

For indirect greenhouse gases, the major source categories included coal, fuel oil, natural gas, wood, other fuels (i.e., bagasse, liquefied petroleum gases, coke, coke oven gas, and others), and stationary internal combustion, which includes emissions from internal combustion engines not used in transportation. EPA periodically estimates emissions of $NO_x$, CO, and NMVOCs by sector and fuel type using a "bottom-up" estimating procedure. In other words, the emissions were calculated either for individual sources (e.g., industrial boilers) or for many sources combined, using basic activity data (e.g., fuel consumption or deliveries) as indicators of emissions. The national activity data used to calculate the individual categories were obtained from various sources. Depending upon the category, these activity data may include fuel consumption or deliveries of fuel, tons of refuse burned, raw material processed, etc. Activity data were used in conjunction with emission factors that relate the quantity of emissions to the activity.

The basic calculation procedure for most source categories presented in EPA (2003) and EPA (2024b) is represented by the following equation:

## Equation A-7: $NO_x$, CO, and NMVOC Emissions Estimates

$$E_{p,s} = A_s \times EF_{p,s} \times (1 - C_{p,s}/100)$$

where,

| | | |
|---|---|---|
| E | = | Emissions |
| p | = | Pollutant |
| s | = | Source category |
| A | = | Activity level |
| EF | = | Emission factor |
| C | = | Percent control efficiency |

EPA currently derives the overall emission control efficiency of a category from a variety of sources, including published reports, the 1985 National Acid Precipitation and Assessment Program (NAPAP) emissions inventory, and other EPA databases. The U.S. approach for estimating emissions of $NO_x$, CO, and NMVOCs from stationary combustion as described above is similar to the methodology recommended by IPCC.

## Table A-66: Fuel Consumption by Stationary Combustion for Calculating $CH_4$ and $N_2O$ Emissions (TBtu)

| Fuel/End-Use Sector | 1990 | 1995 | 2000 | 2005 | 2010 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Coal** | **19,637** | **20,912** | **23,088** | **22,966** | **20,731** | **14,269** | **13,770** | **13,161** | **11,132** | **9,121** | **10,404** | **9,748** | **8,133** |
| Residential | 31 | 17 | 11 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Commercial | 124 | 117 | 92 | 97 | 70 | 24 | 21 | 19 | 17 | 15 | 15 | 14 | 12 |
| Industrial | 1,668 | 1,557 | 1,362 | 1,246 | 993 | 662 | 615 | 569 | 517 | 449 | 450 | 450 | 381 |
| Electric Power | 17,807 | 19,216 | 21,618 | 21,582 | 19,633 | 13,547 | 13,110 | 12,546 | 10,559 | 8,625 | 9,908 | 9,252 | 7,713 |
| U.S. Territories[a] | 5 | 5 | 5 | 33 | 35 | 35 | 25 | 28 | 39 | 33 | 31 | 32 | 28 |
| **Petroleum** | **6,388** | **5,847** | **6,640** | **6,632** | **4,958** | **4,207** | **3,932** | **4,123** | **4,078** | **3,581** | **3,644** | **3,996** | **3,756** |
| Residential | 1,376 | 1,259 | 1,425 | 1,366 | 1,100 | 805 | 774 | 955 | 995 | 864 | 875 | 929 | 876 |
| Commercial | 1,022 | 724 | 767 | 761 | 695 | 839 | 815 | 741 | 815 | 780 | 799 | 934 | 860 |
| Industrial | 2,925 | 2,713 | 2,687 | 2,852 | 2,342 | 2,135 | 1,980 | 2,055 | 1,984 | 1,685 | 1,710 | 1,840 | 1,745 |
| Electric Power | 797 | 860 | 1,269 | 1,003 | 412 | 159 | 71 | 93 | 42 | 24 | 22 | 48 | 30 |
| U.S. Territories[a] | 268 | 290 | 491 | 649 | 408 | 270 | 292 | 278 | 241 | 228 | 238 | 245 | 245 |
| **Natural Gas** | **17,229** | **19,315** | **20,900** | **20,921** | **22,897** | **26,566** | **26,111** | **28,952** | **29,967** | **29,352** | **29,329** | **30,857** | **31,051** |
| Residential | 4,487 | 4,954 | 5,105 | 4,946 | 4,878 | 4,506 | 4,563 | 5,174 | 5,208 | 4,846 | 4,889 | 5,140 | 4,677 |
| Commercial | 2,680 | 3,096 | 3,252 | 3,073 | 3,165 | 3,224 | 3,273 | 3,638 | 3,647 | 3,279 | 3,409 | 3,635 | 3,455 |
| Industrial | 7,687 | 8,701 | 8,637 | 7,315 | 7,670 | 8,770 | 8,847 | 9,325 | 9,482 | 9,284 | 9,473 | 9,629 | 9,728 |
| Electric Power | 2,376 | 2,564 | 3,894 | 5,562 | 7,157 | 10,003 | 9,381 | 10,752 | 11,559 | 11,894 | 11,484 | 12,403 | 13,107 |
| U.S. Territories[a] | 0 | 0 | 13 | 24 | 28 | 64 | 48 | 62 | 71 | 50 | 74 | 51 | 85 |
| **Wood** | **2,216** | **2,370** | **2,262** | **2,137** | **2,217** | **2,216** | **2,175** | **2,252** | **2,227** | **1,960** | **1,979** | **2,002** | **1,931** |
| Residential | 580 | 520 | 420 | 430 | 541 | 445 | 430 | 525 | 546 | 345 | 344 | 422 | 450 |
| Commercial | 66 | 72 | 71 | 70 | 72 | 74 | 74 | 74 | 74 | 73 | 73 | 73 | 72 |
| Industrial | 1,442 | 1,652 | 1,636 | 1,452 | 1,409 | 1,474 | 1,442 | 1,432 | 1,407 | 1,356 | 1,366 | 1,309 | 1,235 |
| Electric Power | 129 | 125 | 134 | 185 | 196 | 224 | 229 | 221 | 201 | 185 | 197 | 198 | 174 |
| U.S. Territories | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE | NE |

NE (Not Estimated)

[a] U.S. Territories coal is assumed to be primarily consumed in the electric power sector, natural gas in the industrial sector, and petroleum in the transportation sector.

Note: Totals may not sum due to independent rounding.

## Table A-67: $CH_4$ and $N_2O$ Emission Factors by Fuel Type and Sector (g/GJ)[a]

| Fuel/End-Use Sector | $CH_4$ | $N_2O$ |
|---|---|---|
| **Coal** | | |
| Residential | 300 | 1.5 |
| Commercial | 10 | 1.5 |
| Industrial | 10 | 1.5 |
| U.S. Territories | 1 | 1.5 |
| **Petroleum** | | |
| Residential | 10 | 0.6 |
| Commercial | 10 | 0.6 |
| Industrial | 3 | 0.6 |
| U.S. Territories | 5 | 0.6 |
| **Natural Gas** | | |
| Residential | 5 | 0.1 |
| Commercial | 5 | 0.1 |
| Industrial | 1 | 0.1 |
| U.S. Territories | 1 | 0.1 |
| **Wood** | | |
| Residential | 300 | 4.0 |
| Commercial | 300 | 4.0 |
| Industrial | 30 | 4.0 |
| U.S. Territories | NA | NA |

NA (Not Applicable)

[a] GJ (Gigajoule) = $10^9$ joules. One joule = $9.486\times10^{-4}$ Btu.

## Table A-68: $CH_4$ and $N_2O$ Emission Factors by Technology Type and Fuel Type for the Electric Power Sector (g/GJ)[a]

| Technology | Configuration | $CH_4$ | $N_2O$ |
|---|---|---|---|
| **Liquid Fuels** | | | |
| Residual Fuel Oil/Shale Oil Boilers | Normal Firing | 0.8 | 0.3 |
| | Tangential Firing | 0.8 | 0.3 |
| Gas/Diesel Oil Boilers | Normal Firing | 0.9 | 0.4 |
| | Tangential Firing | 0.9 | 0.4 |
| Large Diesel Oil Engines >600 hp (447kW) | | 4.0 | NA |
| **Solid Fuels** | | | |
| Pulverized Bituminous Combination Boilers | Dry Bottom, wall fired | 0.7 | 5.8 |
| | Dry Bottom, tangentially fired | 0.7 | 1.4 |
| | Wet bottom | 0.9 | 1.4 |
| Bituminous Spreader Stoker Boilers | With and without re-injection | 1.0 | 0.7 |
| Bituminous Fluidized Bed Combustor | Circulating Bed | 1.0 | 61 |
| | Bubbling Bed | 1.0 | 61 |
| Bituminous Cyclone Furnace | | 0.2 | 0.6 |
| Lignite Atmospheric Fluidized Bed | | NA | 71 |
| **Natural Gas** | | | |
| Boilers | | 1.0 | 0.3 |
| Gas-Fired Gas Turbines >3MW | | 3.7 | 1.3 |
| Large Dual-Fuel Engines | | 258 | NA |
| Combined Cycle | | 3.7 | 1.3 |
| **Peat** | | | |
| Peat Fluidized Bed Combustion | Circulating Bed | 3.0 | 7.0 |
| | Bubbling Bed | 3.0 | 3.0 |
| **Biomass** | | | |

| | | |
|---|---|---|
| Wood/Wood Waste Boilers | 11.0 | 7.0 |
| Wood Recovery Boilers | 1.0 | 1.0 |

NA (Not Applicable)

[a] Ibid.

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## 3.2. Methodology for Estimating Emissions of $CH_4$, $N_2O$, and Indirect Greenhouse Gases from Mobile Combustion and Methodology for and Supplemental Information on Transportation-Related Greenhouse Gas Emissions

### Estimating $CO_2$ Emissions by Transportation Mode

Transportation-related $CO_2$ emissions, as presented in the $CO_2$ Emissions from Fossil Fuel Combustion section of the Energy chapter, were calculated using the methodology described in Annex 2.1. This section provides additional information on the data sources and approach used for each transportation fuel type. As noted in Annex 2.1, $CO_2$ emissions estimates for the transportation sector were calculated directly for on-road diesel fuel and motor gasoline based on data sources for individual modes of transportation (considered a bottom-up approach). For most other fuel and energy types (aviation gasoline, residual fuel oil, natural gas, liquefied petroleum gas [LPG], and electricity), $CO_2$ emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2024b and EIA 2024c) and apportioned to individual modes (considered a "top down" approach). Carbon dioxide emissions from commercial jet fuel use are obtained directly from the Federal Aviation Administration (FAA 2024) for the years 1990 through 2022.[46]

Based on interagency discussions between the Environmental Protection Agency (EPA), EIA, and the Federal Highway Administration (FHWA) beginning in 2005, it was agreed that use of "bottom up" data would be more accurate for diesel fuel and motor gasoline consumption in the transportation sector, based on the availability of reliable data sources. A "bottom up" diesel calculation was first implemented in the 1990 through 2005 *Inventory*, and a bottom-up gasoline calculation was introduced in the 1990 through 2006 *Inventory* for the calculation of emissions from on-road vehicles. On-road fuel consumption data from FHWA Table MF-21 were used to determine total on-road use of motor gasoline and diesel fuel. (FHWA 1996 through 2024). Ratios developed from EPA's Motor Vehicle Emission Simulator (MOVES) output are then used to apportion FHWA fuel consumption data to vehicle type and fuel type.

A primary challenge to switching from a top-down approach to a bottom-up approach for the transportation sector relates to potential incompatibilities with national energy statistics. From a multi-sector national standpoint, EIA develops the most accurate estimate of total motor gasoline and diesel fuel supplied and consumed in the United States. EIA then allocates this total fuel consumption to each major end-use sector (residential, commercial, industrial and transportation) using data from EIA Monthly Energy Review for 1990-2023 for distillate fuel oil and FHWA for motor gasoline. However, the "bottom-up" approach used for the on-road and non-road fuel consumption estimate, as described above, is the most representative of the transportation sector's share of the EIA total consumption. Therefore, for years in which there was a disparity between EIA's fuel allocation estimate for the transportation sector and the "bottom-up" estimate, adjustments were made to other end-use sector fuel allocations (residential, commercial, and industrial) for the consumption of all sectors combined to equal the "top-down" EIA value.

In the case of motor gasoline, estimates of fuel use by recreational boats come from the nonroad component of EPA's MOVES5 model (EPA 2024a), and these estimates, along with those from other sectors (e.g., commercial sector, industrial sector), were adjusted for years in which the bottom-up on-road motor gasoline consumption estimate exceeded the EIA estimate for total gasoline consumption of all sectors. Similarly, to ensure consistency with EIA's total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately.

[46] For the Public Review Inventory, estimates for2023 are proxied based on 2022 data.

Estimates of diesel fuel consumption from rail were taken from: the Association of American Railroads (AAR 2008 through 2024) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2024 and APTA 2006), FTA(2024) for years 2021 to 2023, and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004), Whorton (2006 through 2014), and Railinc (2014 through 2024) for Class II and III railroads, and the U.S. Department of Energy's *Transportation Energy Data Book* (DOE 1993 through 2022) for passenger rail. Class II and III railroad diesel consumption is estimated by applying the historical average fuel usage per carload factor to yearly carloads. Estimates of diesel fuel consumption from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2022). Data for 2021, 2022 and 2023 diesel fuel consumption for ships and boats was proxied.

As noted above, for fuels other than motor gasoline and diesel, EIA's transportation sector total was apportioned to specific transportation sources. For jet fuel, estimates come from: FAA (2024) for domestic and international commercial aircraft, and DLA Energy (2023) for domestic and international military aircraft. Military fuel consumption was proxied for 2023. General aviation jet fuel consumption is calculated as the difference between total jet fuel consumption as reported by EIA and the total consumption from commercial and military jet fuel consumption. Commercial jet fuel $CO_2$ estimates are obtained directly from the Federal Aviation Administration (FAA 2024), while $CO_2$ emissions from domestic military and general aviation jet fuel consumption is determined using a top-down approach. Domestic commercial jet fuel $CO_2$ from FAA is subtracted from total domestic jet fuel $CO_2$ emissions, and this remaining value is apportioned among domestic military and domestic general aviation based on their relative proportion of energy consumption. Estimates for biofuels, including ethanol and biodiesel, were discussed separately in Section 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating $CO_2$ from Fossil Combustion, and in Section 3.10 Wood Biomass and Ethanol Consumption, and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2024b).

Table A-69 displays estimated fuel consumption by fuel and vehicle type. Table A-70 displays estimated energy consumption by fuel and vehicle type. The values in both tables correspond to the figures used to calculate $CO_2$ emissions from transportation. Except as noted above, they are estimated based on EIA transportation sector energy estimates by fuel type, with activity data used to apportion fuel consumption to the various modes of transport. The motor gasoline and diesel fuel consumption volumes published by EIA and FHWA include ethanol blended with gasoline and biodiesel blended with diesel. Biofuels blended with conventional fuels were subtracted from these consumption totals in order to be consistent with IPCC methodological guidance and national inventory report standards, for which net carbon fluxes in biogenic carbon reservoirs in croplands are accounted for in the estimates for the Land Use, Land-Use Change, and Forestry chapter, not in Energy chapter totals. Ethanol fuel volumes were removed from motor gasoline consumption estimates for years 1990 through 2022. Biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2023, as there was negligible use of biodiesel as a diesel blending component prior to 2001. The subtraction or removal of biofuels blended into motor gasoline and diesel were conducted following the methodology outlined in Step 2 ("Remove Biofuels from Petroleum") of the EIA's *Monthly Energy Review* (MER) Section 12 notes.

To remove the volume of biodiesel blended into diesel fuel, the 2009 to 2023 biodiesel and renewable diesel fuel consumption estimates from EIA (2024b) were subtracted from the transportation sector's total diesel fuel consumption volume (for both the "top-down" EIA and "bottom-up" FHWA estimates). To remove the ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2024b) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates. Total ethanol and biodiesel consumption estimates are in Table A-71.[47]

[47] Note that the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA's Petroleum Supply Annual (PSA) differs from the biodiesel volume presented in Table A-71. The PSA data is representative of the amount of biodiesel that refineries and blenders added to diesel fuel to make low level biodiesel blends. This is the appropriate value to subtract from total diesel fuel volume, as it represents the amount of biofuel blended into diesel to create low-level biodiesel blends. The biodiesel consumption value presented in Table A-69 is representative of the total biodiesel consumed and includes biodiesel components in all types of fuel formulations, from low level (<5%) to high level (6–20%, 100%) blends of biodiesel. This value is sourced from MER Table 10.4 and is calculated as biodiesel production plus biodiesel net imports minus biodiesel stock exchange.

## Table A-69: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

| Fuel/Vehicle Type | 1990 | 2000 | 2010[a] | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Motor Gasoline[b,c]** | **107,651** | **125,232** | **119,829** | **116,810** | **116,960** | **121,472** | **120,631** | **123,482** | **123,079** | **124,886** | **123,709** | **106,645** | **117,104** | **115,484** | **115,484** |
| Passenger Cars | 69,913 | 62,228 | 52,321 | 42,708 | 43,575 | 44,791 | 43,765 | 44,032 | 42,583 | 41,971 | 40,853 | 33,896 | 35,755 | 33,765 | 32,737 |
| Light-Duty Trucks | 30,500 | 56,674 | 62,665 | 69,408 | 68,650 | 71,728 | 71,877 | 74,155 | 74,971 | 77,096 | 76,872 | 67,222 | 75,003 | 75,043 | 76,086 |
| Motorcycles | 367 | 460 | 691 | 771 | 744 | 758 | 733 | 776 | 766 | 782 | 766 | 689 | 784 | 930 | 954 |
| Buses | 576 | 366 | 167 | 199 | 218 | 253 | 268 | 295 | 353 | 395 | 412 | 349 | 403 | 446 | 459 |
| Medium- and Heavy-Duty Trucks | 4,691 | 3,899 | 2,672 | 2,481 | 2,554 | 2,744 | 2,791 | 3,018 | 3,196 | 3,424 | 3,585 | 3,362 | 3,950 | 4,073 | 4,043 |
| Recreational Boats[d] | 1,604 | 1,606 | 1,315 | 1,243 | 1,220 | 1,196 | 1,197 | 1,205 | 1,211 | 1,218 | 1,220 | 1,126 | 1,209 | 1,227 | 1,205 |
| **Distillate Fuel Oil (Diesel Fuel)[b,c]** | **25,631** | **39,241** | **41,311** | **41,470** | **41,785** | **43,203** | **44,377** | **44,012** | **45,337** | **46,347** | **46,096** | **43,520** | **46,752** | **46,371** | **46,371** |
| Passenger Cars | 964 | 564 | 257 | 235 | 250 | 271 | 287 | 270 | 254 | 241 | 240 | 193 | 195 | 186 | 174 |
| Light-Duty Trucks | 799 | 1,902 | 2,708 | 3,166 | 2,983 | 3,023 | 3,138 | 3,134 | 3,125 | 3,087 | 3,116 | 2,570 | 2,708 | 2,715 | 2,706 |
| Buses | 760 | 1,483 | 1,402 | 1,577 | 1,585 | 1,714 | 1,776 | 1,762 | 1,835 | 1,948 | 1,968 | 1,584 | 1,743 | 1,894 | 1,896 |
| Medium- and Heavy-Duty Trucks | 18,722 | 29,545 | 32,089 | 31,579 | 32,014 | 33,191 | 33,783 | 34,011 | 35,245 | 36,141 | 36,268 | 35,139 | 37,919 | 37,370 | 37,507 |
| Recreational Boats | 267 | 270 | 263 | 252 | 246 | 245 | 256 | 262 | 269 | 276 | 279 | 256 | 275 | 288 | 288 |
| Ships and Non-Recreational Boats | 658 | 1,372 | 809 | 830 | 841 | 719 | 1,278 | 1,060 | 975 | 908 | 725 | 742 | 756 | 755 | 755 |
| Rail[e] | 3,461 | 4,106 | 3,783 | 3,831 | 3,866 | 4,041 | 3,858 | 3,514 | 3,635 | 3,746 | 3,501 | 3,036 | 3,157 | 3,163 | 3,044 |
| **Jet Fuel[f]** | **19,168** | **19,992** | **15,529** | **14,698** | **15,082** | **15,210** | **16,155** | **17,021** | **17,609** | **17,667** | **18,489** | **12,372** | **15,656** | **16,906** | **18,353** |
| Commercial Aircraft | 11,569 | 14,672 | 11,931 | 11,932 | 12,031 | 12,131 | 12,534 | 12,674 | 13,475 | 13,650 | 14,397 | 9,613 | 12,527 | 13,654 | 13,654 |
| General Aviation Aircraft | 3,940 | 3,107 | 2,287 | 1,629 | 2,005 | 1,751 | 2,327 | 3,152 | 2,952 | 2,880 | 2,950 | 1,659 | 1,966 | 2,105 | 3,599 |
| Military Aircraft | 3,660 | 2,213 | 1,311 | 1,137 | 1,046 | 1,327 | 1,294 | 1,194 | 1,181 | 1,138 | 1,141 | 1,100 | 1,163 | 1,147 | 1,099 |
| **Aviation Gasoline[f]** | **374** | **302** | **225** | **209** | **186** | **181** | **176** | **170** | **174** | **186** | **195** | **168** | **179** | **186** | **186** |
| General Aviation Aircraft | 374 | 302 | 225 | 209 | 186 | 181 | 176 | 170 | 174 | 186 | 195 | 168 | 179 | 186 | 186 |
| **Residual Fuel Oil[f, g]** | **2,006** | **2,963** | **1,818** | **1,410** | **1,345** | **517** | **378** | **1,152** | **1,465** | **1,246** | **1,289** | **651** | **2,155** | **2,037** | **2,037** |
| Ships and Non-Recreational Boats | 2,006 | 2,963 | 1,818 | 1,410 | 1,345 | 517 | 378 | 1,152 | 1,465 | 1,246 | 1,289 | 651 | 2,155 | 2,037 | 2,037 |
| **Natural Gas[f] (trillion cubic feet)** | **0.7** | **0.7** | **0.7** | **0.8** | **0.9** | **0.7** | **0.7** | **0.7** | **0.8** | **0.9** | **1.1** | **1.1** | **1.2** | **1.3** | **1.3** |
| Passenger Cars | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Light-Duty Trucks | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |

| Fuel/Vehicle Type | 1990 | 2000 | 2010[a] | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Medium- and Heavy-Duty Trucks | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Buses | + | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Pipelines | 0.7 | 0.7 | 0.7 | 0.8 | 0.9 | 0.7 | 0.7 | 0.7 | 0.8 | 0.9 | 1.1 | 1.1 | 1.2 | 1.3 | 1.3 |
| **LPG[f]** | **251** | **130** | **50** | **49** | **67** | **83** | **109** | **129** | **136** | **138** | **137** | **95** | **107** | **122** | **122** |
| Passenger Cars | 1 | 0.3 | + | + | + | + | + | + | + | 0 | 0 | + | + | + | + |
| Light-Duty Trucks | 25 | 9 | 2 | 1 | 1 | 2 | 2 | 1 | 2 | 8 | 8 | 6 | 7 | 10 | 12 |
| Medium- and Heavy-Duty Trucks | 225 | 84 | 21 | 19 | 26 | 27 | 31 | 34 | 31 | 119 | 116 | 80 | 87 | 94 | 90 |
| Buses | + | 37 | 27 | 30 | 40 | 54 | 77 | 94 | 103 | 11 | 12 | 9 | 12 | 17 | 20 |
| **Electricity[h,i]** | **4,751** | **5,382** | **7,735** | **7,482** | **7,965** | **8,310** | **8,433** | **8,569** | **8,928** | **9,778** | **10,405** | **9,339** | **10,116** | **11,893** | **14,178** |
| Passenger Cars | + | + | + | + | + | 0 | 5 | 26 | 54 | 102 | 145 | 185 | 484 | 960 | 1,850 |
| Light-Duty Trucks | + | + | 1 | 127 | 303 | 511 | 743 | 1,011 | 1,310 | 1,969 | 2,585 | 2,563 | 3,253 | 4,288 | 5,417 |
| Buses | + | + | 22 | 35 | 37 | 42 | 49 | 36 | 41 | 42 | 43 | 44 | 45 | 46 | 47 |
| Rail | 4,751 | 5,382 | 7,712 | 7,320 | 7,625 | 7,758 | 7,637 | 7,497 | 7,523 | 7,665 | 7,632 | 6,548 | 6,334 | 6,599 | 6,864 |

+ Does not exceed 0.05 units (trillion cubic feet, million kilowatt-hours, or million gallons, as specified).

[a] Fuel is allocated to vehicle classes using MOVES5 ratios of fuel in each vehicle class to total fuel.

[b] Figures do not include ethanol blended in motor gasoline or biodiesel blended into distillate fuel oil. Net carbon fluxes associated with ethanol are accounted for in the Land Use, Land-Use Change and Forestry chapter. This table is calculated with the heat content for gasoline without ethanol (from Table A.1 in the EIA Monthly Energy Review) rather than the annually variable quantity-weighted heat content for gasoline with ethanol, which varies by year.

[c] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. Estimates for 2023 are proxied based FHWA traffic volume trends data.

[d] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.

[e] Class II and Class III diesel consumption data for 2014-2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[f] Estimated based on EIA transportation sector energy estimates by fuel type, with bottom-up activity data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2024c). In previous *Inventory* years, data from DOE TEDB was used to estimate each vehicle class's share of the total natural gas and LPG consumption. Since TEDB does not include estimates for natural gas use by medium and heavy-duty trucks or LPG use by passenger cars, EIA Alternative Fuel Vehicle Data (Browning 2022b) is now used to determine each vehicle class's share of the total natural gas and LPG consumption.

[g] Fluctuations in reported fuel consumption may reflect data collection problems.

[h] Million kilowatt-hours

[i] Electricity consumption by passenger cars, light-duty trucks (SUVs), and buses is based on plug-in electric vehicle sales data and engine efficiencies, as outlined in Browning (2022b).

Note: Totals may not sum due to independent rounding.

## Table A-70: Energy Consumption by Fuel and Vehicle Type (TBtu)

| Fuel/Vehicle Type | 1990 | 2000 | 2010[a] | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Motor Gasoline[a,b]** | **13,464** | **15,663** | **14,899** | **14,523** | **14,542** | **15,103** | **14,999** | **15,353** | **15,303** | **15,528** | **15,381** | **13,260** | **14,560** | **14,358** | **14,358** |
| Passenger Cars | 8,744 | 7,783 | 6,505 | 5,310 | 5,418 | 5,569 | 5,441 | 5,475 | 5,294 | 5,218 | 5,079 | 4,214 | 4,445 | 4,198 | 4,070 |
| Light-Duty Trucks | 3,815 | 7,088 | 7,791 | 8,630 | 8,535 | 8,918 | 8,937 | 9,220 | 9,321 | 9,586 | 9,558 | 8,358 | 9,325 | 9,330 | 9,460 |
| Motorcycles | 46 | 57 | 86 | 96 | 92 | 94 | 91 | 97 | 95 | 97 | 95 | 86 | 98 | 116 | 119 |
| Buses | 72 | 46 | 21 | 25 | 27 | 32 | 33 | 37 | 44 | 49 | 51 | 43 | 50 | 55 | 57 |
| Medium- and Heavy-Duty Trucks | 587 | 488 | 332 | 308 | 318 | 341 | 347 | 375 | 397 | 426 | 446 | 418 | 491 | 506 | 503 |
| Recreational Boats[c] | 201 | 201 | 163 | 155 | 152 | 149 | 149 | 150 | 151 | 151 | 152 | 140 | 150 | 153 | 150 |
| **Distillate Fuel Oil (Diesel Fuel)[a,b]** | **3,555** | **5,442** | **5,729** | **5,751** | **5,795** | **5,992** | **6,155** | **6,104** | **6,288** | **6,428** | **6,393** | **6,036** | **6,484** | **6,431** | **6,431** |
| Passenger Cars | 134 | 78 | 36 | 33 | 35 | 38 | 40 | 37 | 35 | 33 | 33 | 27 | 27 | 26 | 24 |
| Light-Duty Trucks | 111 | 264 | 376 | 439 | 414 | 419 | 435 | 435 | 433 | 428 | 432 | 356 | 376 | 377 | 375 |
| Buses | 105 | 206 | 194 | 219 | 220 | 238 | 246 | 244 | 255 | 270 | 273 | 220 | 242 | 263 | 263 |
| Medium- and Heavy-Duty Trucks | 2,597 | 4,098 | 4,450 | 4,380 | 4,440 | 4,603 | 4,685 | 4,717 | 4,888 | 5,012 | 5,030 | 4,873 | 5,259 | 5,183 | 5,202 |
| Recreational Boats | 37 | 37 | 36 | 35 | 34 | 34 | 36 | 36 | 37 | 38 | 39 | 35 | 38 | 40 | 40 |
| Ships and Non-Recreational Boats | 91 | 190 | 112 | 115 | 117 | 100 | 177 | 147 | 135 | 126 | 101 | 103 | 105 | 105 | 105 |
| Rail[d] | 480 | 569 | 525 | 531 | 536 | 560 | 535 | 487 | 504 | 520 | 486 | 421 | 438 | 439 | 422 |
| **Jet Fuel[e]** | **2,588** | **2,699** | **2,096** | **1,984** | **2,036** | **2,053** | **2,181** | **2,298** | **2,377** | **2,385** | **2,496** | **1,670** | **2,114** | **2,282** | **2,282** |
| Commercial Aircraft | 1,562 | 1,981 | 1,611 | 1,611 | 1,624 | 1,638 | 1,692 | 1,711 | 1,819 | 1,843 | 1,944 | 1,298 | 1,691 | 1,843 | 1,843 |
| General Aviation Aircraft | 532 | 419 | 309 | 220 | 271 | 236 | 314 | 426 | 399 | 389 | 398 | 224 | 265 | 284 | 486 |
| Military Aircraft | 494 | 299 | 177 | 154 | 141 | 179 | 175 | 161 | 159 | 154 | 154 | 149 | 157 | 155 | 148 |
| **Aviation Gasoline** | **45** | **36** | **27** | **25** | **22** | **22** | **21** | **20** | **21** | **22** | **23** | **20** | **22** | **22** | **22** |
| General Aviation Aircraft | 45 | 36 | 27 | 25 | 22 | 22 | 21 | 20 | 21 | 22 | 23 | 20 | 22 | 22 | 22 |
| **Residual Fuel Oil[e,f,]** | **300** | **443** | **272** | **211** | **201** | **77** | **57** | **172** | **219** | **186** | **193** | **97** | **323** | **305** | **305** |
| Ships and Non-Recreational Boats | 300 | 443 | 272 | 211 | 201 | 77 | 57 | 172 | 219 | 186 | 193 | 97 | 323 | 305 | 305 |
| **Natural Gas[e]** | **679** | **672** | **719** | **780** | **887** | **760** | **745** | **757** | **799** | **962** | **1,114** | **1,111** | **1,232** | **1,367** | **1,367** |
| Passenger Cars | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | + | + | + | + |

| Fuel/Vehicle Type | 1990 | 2000 | 2010[a] | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Light-Duty Trucks | + | 0.4 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.2 | 0.2 |
| Medium- and Heavy-Duty Trucks | + | 0.2 | 0.7 | 0.9 | 1.0 | 1.1 | 1.1 | 1.4 | 1.4 | 1.5 | 1.5 | 1.6 | 1.7 | 1.8 | 1.8 |
| Buses | + | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 5 | 5 | 4 | 5 | 6 |
| Pipelines | 679 | 668 | 714 | 775 | 882 | 754 | 739 | 750 | 791 | 955 | 1,107 | 1,105 | 1,226 | 1,360 | 1,359 |
| **LPG[e]** | **23** | **12** | **5** | **5** | **6** | **8** | **10** | **12** | **12** | **13** | **12** | **9** | **10** | **11** | **11** |
| Passenger Cars | 0.1 | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| Light-Duty Trucks | 2 | 1 | 0 | + | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| Medium- and Heavy-Duty Trucks | 21 | 8 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 11 | 11 | 7 | 8 | 9 | 8 |
| Buses | + | 3.4 | 2 | 3 | 4 | 5 | 7 | 9 | 9 | 1 | 1 | 1 | 1 | 2 | 2 |
| **Electricity[g]** | **16** | **18** | **26** | **26** | **27** | **28** | **29** | **29** | **30** | **33** | **36** | **32** | **35** | **41** | **48** |
| Passenger Cars | + | + | + | + | + | + | + | 0.1 | 0.2 | 0.3 | 0.5 | 0.6 | 1.7 | 3.3 | 6.3 |
| Light-Duty Trucks | + | + | + | 0.4 | 1.0 | 1.7 | 2.5 | 3.4 | 4.5 | 6.7 | 8.8 | 8.7 | 11.1 | 14.6 | 18.5 |
| Buses | + | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.2 |
| Rail | 16 | 18 | 26 | 25 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 22 | 22 | 23 | 23 |
| **Total** | **20,670** | **24,986** | **23,774** | **23,305** | **23,518** | **24,043** | **24,195** | **24,746** | **25,049** | **25,557** | **25,648** | **22,235** | **24,778** | **24,818** | **24,826** |

Note: Totals may not sum due to independent rounding.

## Table A-71: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

| Fuel Type | 1990 | 2000 | 2010 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ethanol | 699 | 1,556 | 11,833 | 11,997 | 12,154 | 12,758 | 12,793 | 13,261 | 13,401 | 13,573 | 13,589 | 11,744 | 13,015 | 12,943 | 13,197 |
| Biodiesel | NA | NA | 260 | 899 | 1,429 | 1,417 | 1,494 | 2,085 | 1,985 | 1,904 | 1,813 | 1,873 | 1,709 | 1,608 | 1,615 |

## Estimates of $CH_4$ and $N_2O$ Emissions

Mobile source emissions of greenhouse gases other than $CO_2$ are reported by transport mode (e.g., road, rail, aviation, and waterborne), vehicle type, and fuel type. Emissions estimates of $CH_4$ and $N_2O$ were derived using a methodology like that outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Activity data were obtained from several U.S. government agencies and other publications. Depending on the category, basic activity data included fuel consumption and vehicle miles traveled (VMT). These estimates were then multiplied by emission factors, expressed as grams per unit of fuel consumed or per vehicle mile.

*Methodology for On-Road Gasoline and Diesel Vehicles*

**Step 1: Determine Vehicle Miles Traveled by Vehicle Type, Fuel Type, and Model Year**

Total VMT were obtained from the FHWA's *Highway Statistics* (FHWA 1996 through 2024). As these vehicle categories are not fuel specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) to ensure that the appropriate emission factors were applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2024) was allocated to fuel types (gasoline, diesel, other) using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. This corrects historical inconsistencies in vehicle type definitions in FHWA data[48] (Browning 2022a). VMT for alternative fuel vehicles (AFVs) was calculated separately, and the methodology is explained in the following section on AFVs. Estimates of VMT from AFVs were then subtracted from the appropriate total VMT estimates to develop the final VMT estimates by vehicle/fuel type category.[49] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-72 and Table A-73, respectively.

Total VMT for each on-road category (i.e., gasoline passenger cars, light-duty gasoline trucks, heavy-duty gasoline vehicles, diesel passenger cars, light-duty diesel trucks, medium- and heavy-duty diesel trucks, heavy-duty diesel buses, and motorcycles) were distributed across 30 model years shown for 2023 in Table A-74.

This distribution was derived by weighting the appropriate age distribution of the U.S. vehicle fleet according to vehicle registrations by the average annual age-specific vehicle mileage accumulation of U.S. vehicles. Age distribution values were obtained from EPA's MOBILE6 model for all years before 1999 (EPA 2000) and EPA's MOVES5 model for years 1999 forward (EPA 2024).[50] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES5 model (EPA 2024).[51]

**Step 2: Allocate VMT Data to Control Technology Type**

VMT by vehicle type for each model year was distributed across various control technologies as shown Table A-80 through Table A-83. The categories "EPA Tier 0" and "EPA Tier 1" were used instead of the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *Revised 1996 IPCC Guidelines*. EPA Tier 0, EPA Tier 1, EPA Tier 2, and EPA Tier 3 refer to U.S. emission regulations and California Air Resources Board (CARB) LEV, CARB LEVII, and CARB LEVII refer to California emissions regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and Tier 3 and its predecessors EPA Tier 1 and Tier 0 as well as CARB LEV, LEVII, and LEVIII apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and "advanced

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[48] VMT is allocated to vehicle classes using MOVES5 ratios of VMT in each vehicle class to total VMT.
[49] In *Inventories* through 2002, gasoline-electric hybrid vehicles were part of an "alternative fuel and advanced technology" category. However, vehicles are now separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now within the gasoline vehicle category.
[50] Age distributions were held constant for the period 1990 to 1998 and reflect a 25-year vehicle age span. EPA (2022) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.
[51] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES5 model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

three-way catalysts," as described in the *Revised 1996 IPCC Guidelines*, roughly correspond to the introduction of EPA Tier 0 and EPA Tier 1 regulations (EPA 1998).[52] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in $N_2O$ emissions compared to EPA Tier 1 emissions technology (EPA 1999). EPA Tier 3 regulations affect vehicles produced starting in 2017 and are fully phased in by 2025. CARB LEVII regulations affect California vehicles produced starting in 2004 while ARB LEVIII affect California vehicles produced starting in 2015.

EPA estimated emission control technology assignments for light- and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 in EPA (1998). Assignments for 1996 and 1997 were estimated given the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996. Assignments for 1998 through 2022 were determined using confidential engine family sales data submitted to EPA (EPA 2023b). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2023a). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, EPA Tier 2, EPA Tier 3 and CARB LEV, CARB LEVII, and CARB LEVIII standards. Tier 2 began initial phase-in by 2004. EPA Tier 3 began initial phase-in by 2017 and CARB LEV III standards began initial phase-in by 2015.

**Step 3: Determine $CH_4$ and $N_2O$ Emission Factors by Vehicle, Fuel, and Control Technology Type**

Methane and $N_2O$ emission factors (in grams of $CH_4$ and $N_2O$ per mile) for gasoline and diesel on-road vehicles utilizing EPA Tier 2, EPA Tier 3, and CARB LEV, LEVII, and LEVIII technologies were developed by Browning (2019). Motorcycle emission factors were updated for advanced technology motorcycles (Browning 2020). These emission factors were calculated based upon annual certification data submitted to EPA by vehicle manufacturers. Emission factors for earlier standards and technologies were developed by ICF (2004) based on EPA, CARB, and Environment and Climate Change Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment and Climate Change Canada tests were designed following the Federal Test Procedure (FTP). The procedure covers three separate driving segments since vehicles emit varying amounts of GHGs depending on the driving segment. These driving segments are: (1) a transient driving cycle that includes cold start and running emissions, (2) a cycle that represents running emissions only, and (3) a transient driving cycle that includes hot start and running emissions. For each test run, a bag was affixed to the tailpipe of the vehicle and the exhaust was collected; the content of this bag was later analyzed to determine quantities of gases present. The emission characteristics of driving Segment 2 was used to define running emissions. Running emissions were subtracted from the total FTP emissions to determine start emissions. These were recombined based upon MOBILE 6.2's ratio of start to running emissions for each vehicle class to approximate average driving characteristics.

**Step 4: Determine the Amount of $CH_4$ and $N_2O$ Emitted by Vehicle, Fuel, and Control Technology Type**

Emissions of $CH_4$ and $N_2O$ were calculated by multiplying total VMT by vehicle, fuel, and control technology type by the emission factors developed in Step 3.

*Methodology for Alternative Fuel Vehicles (AFVs)*

**Step 1: Determine Vehicle Miles Traveled by Vehicle and Fuel Type**

VMT for alternative fuel and advanced technology vehicles were calculated from "Updated Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Highway Vehicle Alternative Fuel Vehicles" (Browning 2017) and modified with "Updated Methodology for Estimating $CH_4$ and $N_2O$ Emissions from Highway Vehicle Alternative Fuel Vehicles" (Browning 2022b). Alternative fuels include compressed natural gas (CNG), liquid natural gas (LNG), liquefied petroleum gas (LPG), ethanol, methanol, biodiesel, hydrogen, and electricity. Most of the vehicles that use these fuels run on an internal combustion engine (ICE) powered by the alternative fuel, although many of the vehicles can

[52] For further description, see the "Definitions of Emission Control Technologies and Standards" section below.

run on either the alternative fuel or gasoline (or diesel), or some combination.[53] Except for electric vehicles and plug-in hybrid vehicles, the alternative fuel vehicle VMT were calculated using the Energy Information Administration (EIA) Alternative Fuel Vehicle Data (2023a). The EIA data provides vehicle counts and fuel use for fleet vehicles used by electricity providers, federal agencies, natural gas providers, propane providers, state agencies and transit agencies, for calendar years 2003 through 2017. For 1992 to 2002, EIA data tables were used to estimate fuel consumption and vehicle counts by vehicle type. These tables include total vehicle fuel use and vehicle counts by fuel and calendar year for the United States over the period 1992 through 2010. Breakdowns by vehicle type for 1992 through 2002 (both fuel consumed and vehicle counts) were assumed to be at the same ratio as for 2003 where data existed. For 1990 and 1991, fuel consumed by alternative fuel and vehicle type were extrapolated based on a regression analysis using the best curve fit based upon $R^2$ using the nearest five years of data. Fuel consumption for vehicles from 2018 onward was determined using the same ratio of annual AFV VMT to annual conventional vehicle VMT, as was calculated for 2017 using EIA data and GREET 2023 Energy Efficiency Ratios.

For 2018 to 2023, counts of electric, plug-in electric and fuel cell vehicles were determined from confidential sales data while electric and fuel cell heavy-duty bus counts were determined from Smart Cities Dive (2022). A regression analysis of vehicle counts was used for other fuels for the 2018 to 2023 period. Annual VMT for those vehicles are assumed to be less than the annual VMT of conventional fueled vehicles of the same class.

Counts of electric vehicles (EVs) and plug-in hybrid-electric vehicles (PHEVs) were taken from data compiled by Hybridcars.com from 2010 to 2018 (Hybridcars.com 2019). For 2019 through 2023, EV and PHEV sales were taken from Wards Intelligence U.S. Light Vehicle Sales Report (Wards Intelligence 2023). EVs were divided into cars and trucks using vehicle type information from fueleconomy.gov publications (EPA 2010-2023). Fuel use per vehicle for personal EVs and PHEVs were calculated from fuel economies listed in the fueleconomy.gov publications multiplied by the average light duty car and truck mileage accumulation rates determined from MOVES5. PHEV VMT was divided into gasoline and electric VMT using the Society of Automotive Engineers Utility Factor Standard J2841 (SAE 2010).

Because AFVs run on different fuel types, their fuel use characteristics are not directly comparable. Accordingly, fuel economy for each vehicle type is expressed in gasoline equivalent terms, i.e., how much gasoline contains the equivalent amount of energy as the alternative fuel. Energy economy ratios (the ratio of the gasoline equivalent fuel economy of a given technology to that of conventional gasoline or diesel vehicles) were taken from the Argonne National Laboratory's GREET2022 model (ANL 2022). These ratios were used to estimate fuel economy in miles per gasoline gallon equivalent for each alternative fuel and vehicle type. Energy use per fuel type was then divided among the various weight categories and vehicle technologies that use that fuel. Total VMT per vehicle type for each calendar year was then determined by dividing the energy usage by the fuel economy. For AFVs capable of running on both/either traditional or alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2017). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-73, while more detailed estimates of VMT by control technology are shown Table A-74.

**Step 2: Determine $CH_4$ and $N_2O$ Emission Factors by Vehicle and Alternative Fuel Type**

Methane and $N_2O$ emission factors for alternative fuel vehicles (AFVs) were calculated using Argonne National Laboratory's GREET model (ANL 2023). These emission factors are shown in Table A-85 and Table A-86.

[53] Fuel types used in combination depend on the vehicle class. For light-duty vehicles, gasoline is generally blended with ethanol and diesel is blended with biodiesel; dual-fuel vehicles can run on gasoline or an alternative fuel – either natural gas or LPG – but not at the same time, while flex-fuel vehicles are designed to run on E85 (85 percent ethanol) or gasoline, or any mixture of the two in between. Heavy-duty vehicles are more likely to run on diesel fuel, natural gas, or LPG.

**Step 3: Determine the Amount of $CH_4$ and $N_2O$ Emitted by Vehicle and Fuel Type**

Emissions of $CH_4$ and $N_2O$ were calculated by multiplying total VMT for each vehicle and fuel type (Step 1) by the appropriate emission factors (Step 2).

## Methodology for Non-Road Mobile Sources

Methane and $N_2O$ emissions from non-road mobile sources were estimated by applying emission factors to the amount of fuel consumed by mode and vehicle type.

Activity data for non-road vehicles include annual fuel consumption statistics by transportation mode and fuel type, as shown in Table A-79. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2022) for distillate fuel, and DHS (2008) and EIA (2024b) for residual fuel; marine transport fuel consumption data for U.S. Territories (EIA 2017) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[54] Fuel consumption data and emissions for ships and non-recreational boats are not further disaggregated by vessel type or vocation. Gasoline consumption by recreational boats was obtained from the nonroad component of EPA's MOVES5 model (EPA 2024). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2024), diesel consumption from commuter rail was obtained from APTA (2007 through 2024) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2014).[55] It is estimated that an average of 41 gallons of diesel consumption per Class II and III carload originated from 2000-2009 based on carload data reported from AAR (2008 through 2023) and fuel consumption data provided by Whorton, D. (2006 through 2014). Class II and Class III diesel consumption for 2014-2022 is estimated by multiplying this average historical fuel usage per carload factor by the number of shortline carloads originated each year (RailInc 2014 through 2024). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2022). Data for 2021-2023 was obtained from the National Transit Database "Fuel and Energy" table (FTA 2023). Diesel consumption for Intercity Rail for 2019 through 2023 was obtained from the Bureau of Transportation Statistics "Amtrak Fuel Consumption and Travel Data" table. Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2024a) and FAA (2023), as described in Annex 2.1: Methodology for Estimating Emissions of $CO_2$ from Fossil Fuel Combustion and were reduced by the amount allocated to international bunker fuels (DLA 2023 and FAA 2023). Pipeline fuel consumption was obtained from EIA (2024c) (note: pipelines are a transportation source but are stationary, not mobile sources). Data on fuel consumption by non-transportation mobile sources were obtained from the Nonroad component of EPA's MOVES5 model (EPA 2024) for gasoline and diesel powered equipment, and from FHWA (1996 through 2024) for gasoline consumption by off-road trucks used in the agriculture, industrial, commercial, and construction sectors.[56] Specifically, this *Inventory* uses FHWA's Agriculture, Construction, and Commercial/Industrial MF-24 fuel volumes along with the MOVES-Nonroad model gasoline volumes to estimate non-road mobile source $CH_4$ and $N_2O$ emissions for these categories. For agriculture, the MF-24 gasoline volume is used directly because it includes both off-road trucks and equipment. For construction and commercial/industrial gasoline estimates, the 2014 and older MF-24 volumes represented off-road trucks only; therefore, the MOVES-Nonroad gasoline volumes for construction and commercial/industrial are added to the respective categories in the *Inventory*. Beginning in 2015, this addition is no longer necessary since the FHWA updated its method for estimating on-road and non-road

[54] See International Bunker Fuels section of the Energy chapter.

[55] Diesel consumption from Class II and Class III railroad were unavailable for 2014-2023. Diesel consumption data for 2014-2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[56] "Non-transportation mobile sources" are defined as any vehicle or equipment not used on the traditional road system, but excluding aircraft, rail and watercraft. This category includes snowmobiles, golf carts, riding lawn mowers, agricultural equipment, and trucks used for off-road purposes, among others. This category is similar to the IPCC's "Off-road" category (1 A 3 e ii) described in Chapter 3: Mobile Combustion *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, in Table 3.1.1.

gasoline consumption. Among the method updates, FHWA now incorporates MOVES-Nonroad equipment gasoline volumes in the construction and commercial/industrial categories.

Since the nonroad component of EPA's MOVES5 model does not account for the COVID-19 pandemic and associated restrictions, fuel consumption for non-transportation mobile sources for 2021 were developed by adjusting 2019 and 2020 consumption. Sector specific adjustments were applied to the 2019 consumption for agricultural equipment (-1.6 percent) and airport equipment (-38 percent) to estimate 2020 volumes. An adjustment factor for agricultural equipment was derived using employment data from the Bureau of Labor and Statistics (BLS 2022). An adjustment factor for airport equipment was derived based on the decline in commercial aviation fuel consumption. For all other nonroad equipment sectors, a 7.7 percent reduction factor was applied to 2019 values to estimate 2020. This is based on the reduction in transportation diesel consumption from 2019 to 2020 (EIA 2023b). In a similar fashion, trends in all these variables between 2020 and 2021 were used to estimate 2021 values.

Emissions of $CH_4$ and $N_2O$ from non-road mobile sources were calculated using the updated 2006 IPCC Tier 3 guidance and estimates of activity from EPA's MOVES5 model. $CH_4$ and $N_2O$ emission factors were calculated from engine certification data by engine and fuel type and weighted by activity estimates calculated by MOVES5 to determine overall emission factors in grams per kg of fuel consumed by fuel type (Browning 2020).

## Estimates of $NO_x$, CO, and NMVOC Emissions

The emission estimates of $NO_x$, CO, and NMVOCs from mobile combustion (transportation) were obtained from EPA's National Emission *Inventory* (NEI) Air Pollutant Emission Trends web site (EPA 2024c). This EPA report provides emission estimates for these gases by fuel type using a procedure whereby emissions were calculated using basic activity data, such as amount of fuel delivered or miles traveled, as indicators of emissions. Emissions for heavy-duty diesel trucks and heavy-duty diesel buses were calculated by distributing the total heavy-duty diesel vehicle emissions in the ratio of VMT for each individual category.

### Table A-72: Vehicle Miles Traveled for Gasoline On-Road Vehicles (billion miles)

| Year | Passenger Cars[b] | Light-Duty Trucks[b] | Heavy-Duty Vehicles[a,b] | Motorcycles[b] |
|---|---|---|---|---|
| 1990 | 1,474.4 | 409.3 | 46.6 | 11.4 |
| 1991 | 1,457.4 | 448.3 | 46.2 | 11.5 |
| 1992 | 1,470.4 | 498.7 | 46.9 | 11.8 |
| 1993 | 1,464.4 | 545.2 | 46.9 | 12.0 |
| 1994 | 1,464.3 | 596.4 | 47.1 | 12.3 |
| 1995 | 1,464.5 | 650.4 | 47.4 | 12.5 |
| 1996 | 1,461.3 | 706.0 | 47.5 | 12.8 |
| 1997 | 1,463.4 | 767.3 | 47.9 | 13.1 |
| 1998 | 1,459.5 | 829.1 | 48.0 | 13.4 |
| 1999 | 1,447.8 | 889.6 | 48.0 | 13.6 |
| 2000 | 1,455.7 | 939.5 | 44.8 | 12.2 |
| 2001 | 1,459.9 | 977.1 | 43.4 | 11.1 |
| 2002 | 1,472.0 | 1,020.4 | 42.9 | 11.2 |
| 2003 | 1,465.5 | 1,051.3 | 43.0 | 11.4 |
| 2004 | 1,470.9 | 1,116.8 | 40.6 | 15.0 |
| 2005 | 1,459.6 | 1,153.6 | 37.9 | 13.8 |
| 2006 | 1,432.8 | 1,182.6 | 40.3 | 19.2 |
| 2007 | 1,427.5 | 1,200.3 | 37.3 | 21.4 |
| 2008 | 1,401.4 | 1,168.9 | 38.2 | 20.8 |
| 2009 | 1,396.4 | 1,178.3 | 35.7 | 20.8 |
| 2010 | 1,390.6 | 1,200.4 | 32.5 | 18.5 |

| | | | | |
|---|---|---|---|---|
| 2011 | 1,320.7 | 1,271.2 | 29.7 | 18.6 |
| 2012 | 1,194.8 | 1,406.9 | 30.0 | 21.4 |
| 2013 | 1,217.3 | 1,399.2 | 29.8 | 20.4 |
| 2014 | 1,217.3 | 1,431.3 | 30.4 | 20.0 |
| 2015 | 1,225.6 | 1,489.4 | 30.7 | 19.7 |
| 2016 | 1,233.8 | 1,549.3 | 31.9 | 20.5 |
| 2017 | 1,211.1 | 1,598.8 | 33.6 | 20.2 |
| 2018 | 1,183.5 | 1,644.0 | 35.0 | 20.2 |
| 2019 | 1,168.5 | 1,684.4 | 36.4 | 19.8 |
| 2020 | 991.1 | 1,518.8 | 34.2 | 18.1 |
| 2021 | 1,023.7 | 1,679.3 | 39.2 | 19.9 |
| 2022 | 997.5 | 1,743.7 | 41.2 | 24.0 |
| 2023 | 985.4 | 1,808.2 | 41.7 | 24.8 |

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.
[b] VMT is allocated to vehicle classes using MOVES5 ratios.
Notes: In 2015, EIA changed its methods for estimating AFV fuel consumption. These methodological changes included how vehicle counts are estimated, moving from estimates based on modeling to one that is based on survey data. EIA now publishes data about fuel use and number of vehicles for only four types of AFV fleets: federal government, state government, transit agencies, and fuel providers. These changes were first incorporated in the 1990 through 2014 *Inventory* and apply to the 1990 through 2023 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates are allocated to vehicle type using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. VMT for 2023 is proxied based on FHWA's Traffic Volume Trends data.
Source: Derived from FHWA (1996 through 2024), DOE (1990 through 2022), Browning (2022a), Browning (2018a), and Browning (2017).

## Table A-73: Vehicle Miles Traveled for Diesel On-Road Vehicles (billion miles)

| Year | Passenger Cars[b] | Light-Duty Trucks[b] | Heavy-Duty Trucks[a,b] | Heavy-Duty Buses[b] |
|---|---|---|---|---|
| 1990 | 40.7 | 18.7 | 136.7 | 6.0 |
| 1991 | 39.0 | 20.3 | 142.5 | 6.5 |
| 1992 | 37.9 | 22.4 | 151.6 | 7.1 |
| 1993 | 36.3 | 24.3 | 159.0 | 7.6 |
| 1994 | 34.8 | 26.4 | 167.6 | 8.3 |
| 1995 | 33.2 | 28.6 | 176.7 | 8.9 |
| 1996 | 31.4 | 30.9 | 185.8 | 9.5 |
| 1997 | 29.7 | 33.4 | 196.2 | 10.3 |
| 1998 | 27.7 | 35.9 | 206.3 | 11.0 |
| 1999 | 25.5 | 38.4 | 215.9 | 11.7 |
| 2000 | 23.2 | 39.8 | 219.0 | 11.9 |
| 2001 | 21.6 | 41.9 | 230.7 | 10.6 |
| 2002 | 19.5 | 43.4 | 233.9 | 11.1 |
| 2003 | 17.6 | 44.6 | 244.4 | 11.2 |
| 2004 | 16.1 | 47.9 | 244.6 | 11.4 |
| 2005 | 14.6 | 49.5 | 247.5 | 11.2 |
| 2006 | 13.2 | 51.7 | 259.9 | 12.0 |
| 2007 | 11.7 | 51.4 | 266.0 | 12.5 |
| 2008 | 10.5 | 48.5 | 271.8 | 12.8 |

| | | | | |
|---|---|---|---|---|
| 2009 | 9.9 | 47.5 | 251.8 | 12.4 |
| 2010 | 9.5 | 45.9 | 253.6 | 11.9 |
| 2011 | 8.7 | 47.8 | 233.9 | 11.9 |
| 2012 | 7.7 | 52.2 | 235.3 | 12.7 |
| 2013 | 8.2 | 49.2 | 238.4 | 12.9 |
| 2014 | 8.7 | 49.2 | 241.8 | 13.5 |
| 2015 | 9.1 | 51.3 | 241.6 | 13.6 |
| 2016 | 8.5 | 52.9 | 244.8 | 13.5 |
| 2017 | 7.9 | 53.5 | 253.5 | 14.0 |
| 2018 | 7.4 | 53.7 | 259.6 | 14.6 |
| 2019 | 7.0 | 53.0 | 254.2 | 14.1 |
| 2020 | 5.7 | 45.2 | 254.1 | 11.2 |
| 2021 | 5.9 | 49.1 | 280.7 | 12.5 |
| 2022 | 5.7 | 50.3 | 283.2 | 13.7 |
| 2023 | 5.2 | 49.8 | 282.1 | 13.5 |

[a] Heavy-Duty Trucks includes Medium-Duty Trucks and Heavy-Duty Trucks.

[b] VMT is allocated to vehicle classes using MOVES5 ratios.

Notes: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates were then allocated using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT. VMT for 2023 is proxied based on FHWA's Traffic Volume Trends data.

Sources: Derived from FHWA (1996 through 2024), DOE (1993 through 2022), and Browning (2017), Browning (2018a), Browning (2022a).

**Table A-74: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (billion miles)**

| Year | Passenger Cars | Light-Duty Trucks | Heavy-Duty Trucks[a] | Buses |
|---|---|---|---|---|
| 1990 | 0.0 | 0.1 | 0.4 | 0.0 |
| 1991 | 0.0 | 0.1 | 0.4 | 0.0 |
| 1992 | 0.0 | 0.1 | 0.4 | 0.0 |
| 1993 | 0.0 | 0.1 | 0.4 | 0.0 |
| 1994 | 0.0 | 0.1 | 0.4 | 0.0 |
| 1995 | 0.0 | 0.1 | 0.4 | 0.1 |
| 1996 | 0.0 | 0.1 | 0.4 | 0.1 |
| 1997 | 0.0 | 0.1 | 0.4 | 0.1 |
| 1998 | 0.0 | 0.1 | 0.5 | 0.1 |
| 1999 | 0.0 | 0.1 | 0.5 | 0.2 |
| 2000 | 0.1 | 0.2 | 0.6 | 0.2 |
| 2001 | 0.1 | 0.2 | 0.6 | 0.2 |
| 2002 | 0.2 | 0.3 | 0.7 | 0.2 |
| 2003 | 0.1 | 0.6 | 0.7 | 0.3 |
| 2004 | 0.1 | 0.7 | 0.7 | 0.3 |
| 2005 | 0.1 | 0.6 | 1.1 | 0.3 |
| 2006 | 0.2 | 0.6 | 2.0 | 0.4 |
| 2007 | 0.2 | 0.5 | 2.5 | 0.4 |
| 2008 | 0.2 | 1.3 | 2.2 | 0.4 |
| 2009 | 0.2 | 1.5 | 2.3 | 0.4 |
| 2010 | 0.2 | 2.1 | 2.0 | 0.4 |
| 2011 | 0.5 | 1.9 | 5.5 | 0.6 |
| 2012 | 0.8 | 2.1 | 5.5 | 0.6 |
| 2013 | 1.5 | 2.9 | 8.5 | 0.8 |
| 2014 | 2.1 | 2.7 | 8.5 | 0.9 |
| 2015 | 2.9 | 2.5 | 9.1 | 0.9 |
| 2016 | 3.8 | 2.7 | 12.7 | 1.2 |
| 2017 | 4.6 | 2.8 | 12.3 | 1.2 |
| 2018 | 6.8 | 3.1 | 12.4 | 1.6 |
| 2019 | 9.0 | 3.4 | 11.9 | 1.6 |
| 2020 | 9.0 | 4.1 | 12.1 | 1.4 |
| 2021 | 11.3 | 6.8 | 11.7 | 1.4 |
| 2022 | 14.7 | 10.6 | 11.5 | 1.6 |
| 2023 | 19.3 | 19.5 | 14.0 | 1.9 |

[a] Heavy-Duty Trucks includes medium-duty trucks and heavy-duty trucks.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2023c).

Notes: In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2005 to 2023 time period.

## Table A-75: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (Million Miles)

| Vehicle Type/Year | 1990 | 2000 | 2010 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Light-Duty Cars** | **3.4** | **82.6** | **246.4** | **2,874.0** | **3,757.2** | **4,646.1** | **6,817.1** | **9,037.2** | **9,003.1** | **11,302.8** | **14,705.1** | **19,283.1** |
| Methanol-Flex Fuel ICE | + | + | + | + | + | + | + | + | + | + | + | + |
| Ethanol-Flex Fuel ICE | + | 17.0 | 104.4 | 102.4 | 115.1 | 79.9 | 79.0 | 74.2 | 61.6 | 61.2 | 58.1 | 54.9 |
| CNG ICE | + | 4.5 | 9.2 | 10.0 | 11.6 | 10.7 | 10.9 | 10.5 | 9.0 | 9.3 | 9.1 | 9.0 |
| CNG Bi-fuel | + | 14.6 | 6.8 | 1.6 | 1.3 | 1.4 | 0.9 | 0.6 | 0.2 | + | + | + |
| LPG ICE | 1.0 | 1.0 | + | 0.1 | 0.2 | 0.2 | 0.2 | 0.1 | + | + | + | + |
| LPG Bi-fuel | 2.4 | 2.4 | 1.0 | 0.1 | 0.1 | + | + | + | + | + | + | + |
| Biodiesel (BD100) | + | 1.6 | 59.0 | 339.3 | 432.1 | 372.6 | 329.4 | 315.7 | 246.3 | 232.2 | 208.2 | 257.6 |
| NEVs | + | 40.8 | 63.4 | 155.1 | 111.4 | 128.7 | 135.4 | 144.2 | 148.7 | 153.1 | 157.6 | 170.7 |
| Electric Vehicle | + | 0.7 | 0.7 | 1,354.7 | 1,827.9 | 2,373.9 | 4,020.1 | 5,925.2 | 6,119.7 | 8,077.3 | 11,339.4 | 15,661.0 |
| SI PHEV - Electricity | + | + | 1.9 | 910.1 | 1,251.7 | 1,655.5 | 2,205.6 | 2,515.5 | 2,369.2 | 2,698.9 | 2,845.2 | 3,023.2 |
| Fuel Cell Hydrogen | + | + | + | 0.7 | 6.0 | 23.1 | 35.6 | 51.2 | 48.4 | 70.9 | 87.4 | 106.6 |
| | | | | | | | | | | | | |
| **Light-Duty Trucks** | **66.4** | **152.8** | **2,067.5** | **2,461.7** | **2,708.3** | **2,835.5** | **3,086.5** | **3,405.3** | **4,125.6** | **6,835.1** | **10,567.1** | **19,503.8** |
| Ethanol-Flex Fuel ICE | + | 17.9 | 111.1 | 195.1 | 247.9 | 369.0 | 400.7 | 420.2 | 379.3 | 432.9 | 484.1 | 540.0 |
| CNG ICE | + | 4.3 | 7.3 | 4.0 | 3.5 | 4.8 | 3.4 | 2.9 | 2.0 | 1.7 | 1.2 | 0.7 |
| CNG Bi-fuel | + | 36.2 | 17.4 | 18.2 | 23.4 | 21.4 | 21.5 | 21.4 | 18.2 | 19.7 | 20.9 | 22.2 |
| LPG ICE | 19.2 | 21.1 | 8.5 | 4.9 | 4.9 | 5.0 | 5.3 | 5.4 | 4.8 | 5.3 | 5.8 | 6.3 |
| LPG Bi-fuel | 47.2 | 51.9 | 21.7 | 8.1 | 6.1 | 7.3 | 8.2 | 8.2 | 7.0 | 7.6 | 8.1 | 8.7 |
| LNG | + | 0.1 | + | + | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Biodiesel (BD100) | + | 17.2 | 1,899.2 | 2,201.2 | 2,196.0 | 1,962.3 | 1,859.1 | 1,868.3 | 2,100.6 | 2,399.1 | 2,562.1 | 3,472.3 |
| Electric Vehicle | + | 4.0 | 2.3 | 21.9 | 183.2 | 360.4 | 581.4 | 776.8 | 1,220.6 | 2,952.9 | 5,610.2 | 12,096.9 |
| SI PHEV - Electricity | + | + | + | 7.5 | 42.1 | 96.0 | 197.6 | 290.9 | 381.4 | 1,000.1 | 1,855.4 | 3,335.4 |
| Fuel Cell Hydrogen | + | + | + | 0.7 | 1.3 | 9.2 | 9.3 | 11.1 | 11.6 | 15.7 | 19.0 | 21.1 |
| | | | | | | | | | | | | |
| **Medium-Duty Trucks** | **176.0** | **175.1** | **473.2** | **2,623.3** | **3,743.1** | **3,596.8** | **3,498.4** | **3,412.5** | **3,514.1** | **3,423.9** | **3,328.0** | **4,112.5** |
| CNG ICE | + | 0.7 | 5.5 | 11.2 | 13.3 | 14.0 | 14.1 | 15.8 | 16.2 | 17.7 | 18.5 | 18.8 |
| CNG Bi-fuel | + | 6.9 | 6.2 | 11.1 | 12.1 | 13.3 | 13.8 | 15.4 | 15.7 | 17.1 | 17.7 | 18.1 |
| LPG ICE | 142.6 | 128.9 | 27.9 | 18.2 | 15.8 | 14.3 | 11.3 | 9.6 | 7.1 | 5.1 | 2.9 | 0.8 |
| LPG Bi-fuel | 33.5 | 31.5 | 13.1 | 19.8 | 24.9 | 24.4 | 25.9 | 28.6 | 29.2 | 31.6 | 32.7 | 33.2 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LNG | + | + | + | 0.2 | 0.2 | 0.4 | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.6 |
| Biodiesel (BD100) | + | 7.2 | 420.5 | 2,562.8 | 3,676.7 | 3,530.6 | 3,433.0 | 3,342.7 | 3,445.4 | 3,351.9 | 3,255.6 | 4,041.1 |
| | | | | | | | | | | | | |
| **Heavy-Duty Trucks** | **201.1** | **201.0** | **1,115.2** | **5,510.3** | **7,751.0** | **7,532.8** | **7,247.8** | **6,892.3** | **7,233.5** | **6,886.5** | **6,573.1** | **7,992.0** |
| Neat Methanol ICE | 100.6 | 110.3 | 1,030.0 | 5,450.2 | 7,681.4 | 7,461.2 | 7,179.2 | 6,830.1 | 7,175.1 | 6,829.4 | 6,520.0 | 7,941.7 |
| Neat Ethanol ICE | + | + | + | + | + | + | + | + | + | + | + | + |
| CNG ICE | + | + | + | 1.1 | 4.0 | 9.6 | 8.0 | 6.3 | 3.6 | 1.7 | 1.0 | 0.5 |
| LPG ICE | + | 0.8 | 13.1 | 19.9 | 28.9 | 29.3 | 32.3 | 33.2 | 35.8 | 39.7 | 40.8 | 42.6 |
| LPG Bi-fuel | 94.5 | 84.3 | 58.5 | 30.2 | 28.2 | 24.6 | 20.5 | 15.9 | 12.5 | 9.3 | 5.5 | 2.0 |
| LNG | 6.1 | 5.4 | 10.1 | 5.3 | 5.3 | 5.2 | 5.1 | 4.6 | 4.5 | 4.4 | 4.1 | 3.9 |
| Biodiesel (BD100) | + | + | 3.6 | 3.6 | 3.1 | 2.9 | 2.7 | 2.3 | 2.1 | 1.9 | 1.6 | 1.3 |
| | | | | | | | | | | | | |
| **Buses** | **31.5** | **209.2** | **379.7** | **923.5** | **1,187.9** | **1,175.1** | **1,640.5** | **1,620.2** | **1,385.4** | **1,432.4** | **1,610.9** | **1,862.5** |
| Neat Methanol ICE | 15.7 | 104.6 | 189.8 | 461.9 | 594.1 | 587.8 | 820.6 | 810.6 | 693.2 | 717.3 | 807.4 | 934.1 |
| Neat Ethanol ICE | 3.6 | + | + | + | + | + | + | + | + | + | + | + |
| CNG ICE | + | + | + | 2.8 | 2.6 | 1.9 | 199.8 | 201.4 | 173.1 | 196.5 | 219.1 | 221.0 |
| LPG ICE | + | 79.7 | 130.6 | 160.1 | 173.8 | 185.3 | 4.6 | 4.8 | 4.2 | 4.8 | 5.5 | 5.5 |
| LNG | 12.1 | 10.8 | 6.7 | 2.8 | 4.8 | 3.6 | 2.2 | 1.4 | 0.6 | + | + | + |
| Biodiesel (BD100) | + | 11.5 | 6.6 | 4.1 | 3.8 | 2.8 | 195.2 | 187.6 | 158.9 | 153.7 | 161.1 | 193.6 |
| Electric | + | 1.2 | 43.5 | 289.4 | 402.5 | 386.2 | 381.2 | 366.5 | 310.4 | 300.2 | 314.6 | 378.1 |
| Fuel Cell Hydrogen | + | 1.3 | 2.4 | 2.3 | 6.2 | 7.6 | 36.9 | 48.0 | 45.0 | 59.9 | 103.3 | 130.1 |
| **Total VMT** | **478.5** | **820.7** | **4,281.9** | **14,392.7** | **19,147.5** | **19,786.3** | **22,290.3** | **24,367.5** | **25,261.8** | **29,880.6** | **36,784.1** | **52,753.9** |

+ Does not exceed 0.05 million vehicle miles traveled.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2024a).

Notes: Throughout the rest of this *Inventory*, medium-duty trucks are grouped with heavy-duty trucks; they are reported separately here because these two categories may run on a slightly different range of fuel types. In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2005 to 2023 time period. Totals may not sum due to independent rounding.

## Table A-76: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles[a] 2023

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC | HDDB |
|---|---|---|---|---|---|---|---|---|
| 0 | 3.8% | 6.3% | 6.3% | 0.0% | 4.9% | 5.5% | 5.9% | 4.5% |
| 1 | 2.7% | 5.6% | 8.4% | 0.0% | 5.1% | 6.9% | 5.7% | 3.2% |
| 2 | 3.0% | 6.1% | 6.1% | 0.0% | 5.3% | 4.7% | 6.3% | 4.1% |
| 3 | 3.6% | 5.7% | 6.1% | 0.0% | 3.7% | 6.4% | 4.4% | 4.8% |
| 4 | 4.5% | 6.7% | 6.0% | 0.1% | 5.5% | 6.1% | 4.2% | 5.7% |
| 5 | 4.9% | 6.2% | 3.9% | 0.8% | 5.8% | 4.5% | 4.0% | 5.6% |
| 6 | 5.8% | 6.1% | 5.4% | 1.0% | 5.7% | 4.5% | 3.9% | 5.6% |
| 7 | 5.9% | 5.4% | 5.0% | 1.0% | 6.1% | 5.3% | 4.0% | 5.7% |
| 8 | 6.4% | 5.2% | 4.7% | 12.6% | 6.3% | 4.8% | 3.7% | 5.3% |
| 9 | 6.1% | 4.4% | 2.9% | 15.6% | 3.8% | 3.3% | 3.6% | 4.7% |
| 10 | 6.3% | 3.9% | 2.9% | 16.3% | 2.7% | 3.1% | 3.2% | 3.9% |
| 11 | 5.5% | 3.3% | 3.4% | 13.3% | 3.2% | 3.6% | 3.0% | 3.9% |
| 12 | 4.1% | 3.3% | 2.7% | 9.3% | 2.9% | 2.5% | 2.1% | 4.0% |
| 13 | 4.1% | 2.6% | 1.3% | 8.3% | 1.3% | 1.4% | 1.7% | 4.2% |
| 14 | 3.5% | 1.9% | 1.7% | 5.2% | 1.2% | 1.9% | 3.6% | 3.5% |
| 15 | 4.2% | 3.1% | 2.9% | 0.5% | 3.6% | 3.0% | 4.3% | 3.3% |
| 16 | 4.3% | 3.2% | 2.3% | 0.4% | 3.3% | 4.5% | 5.5% | 3.1% |
| 17 | 3.6% | 2.9% | 3.0% | 4.7% | 4.8% | 4.1% | 5.3% | 3.0% |
| 18 | 3.2% | 2.8% | 2.4% | 3.0% | 3.8% | 3.5% | 4.8% | 2.2% |
| 19 | 2.6% | 2.8% | 2.1% | 1.7% | 4.1% | 2.4% | 3.7% | 2.3% |
| 20 | 2.4% | 2.3% | 1.8% | 1.9% | 3.3% | 2.2% | 3.9% | 2.1% |
| 21 | 1.9% | 2.0% | 1.8% | 1.7% | 2.6% | 1.9% | 2.9% | 2.2% |
| 22 | 1.6% | 1.7% | 2.1% | 1.0% | 2.6% | 2.4% | 2.4% | 2.1% |
| 23 | 1.4% | 1.5% | 2.1% | 0.8% | 1.7% | 2.8% | 1.9% | 2.0% |
| 24 | 1.0% | 1.2% | 3.5% | 0.4% | 1.8% | 2.1% | 1.4% | 2.0% |
| 25 | 0.8% | 0.9% | 1.7% | 0.3% | 0.5% | 1.3% | 1.1% | 1.7% |
| 26 | 0.7% | 0.9% | 1.9% | 0.1% | 1.5% | 1.3% | 0.9% | 1.4% |
| 27 | 0.5% | 0.6% | 1.4% | 0.1% | 0.9% | 1.2% | 0.8% | 1.2% |
| 28 | 0.5% | 0.6% | 1.9% | 0.1% | 0.9% | 1.3% | 0.6% | 1.1% |
| 29 | 0.4% | 0.5% | 1.1% | 0.0% | 0.6% | 1.0% | 0.5% | 0.9% |
| 30 | 0.3% | 0.4% | 1.0% | 0.0% | 0.6% | 0.8% | 0.5% | 0.8% |
| **Total** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** |

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and HDDB (heavy-duty diesel buses).

Note: This year's *Inventory* includes updated vehicle population data based on the MOVES5 Model. Totals may not sum due to independent rounding.

Source: EPA (2024).

## Table A-77: Annual Average Vehicle Mileage Accumulation per Vehicles[a] (miles) 2023

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC[b] | HDDB |
|---|---|---|---|---|---|---|---|---|
| 0 | 14,772 | 15,489 | 20,214 | - | 15,489 | 48,058 | 10,667 | 24,835 |
| 1 | 14,268 | 15,005 | 21,328 | - | 15,005 | 41,681 | 5,696 | 20,403 |
| 2 | 13,790 | 14,453 | 20,475 | - | 14,454 | 41,910 | 4,309 | 21,398 |
| 3 | 13,339 | 14,007 | 20,595 | - | 14,007 | 46,215 | 3,563 | 21,189 |
| 4 | 12,912 | 13,588 | 19,763 | 12,912 | 13,588 | 43,137 | 3,083 | 21,657 |
| 5 | 12,507 | 13,181 | 17,357 | 12,507 | 13,181 | 39,625 | 2,741 | 19,892 |
| 6 | 12,124 | 12,786 | 17,878 | 12,124 | 12,786 | 37,453 | 2,485 | 18,863 |

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC[b] | HDDB |
|---|---|---|---|---|---|---|---|---|
| 7 | 11,761 | 12,406 | 16,229 | 11,761 | 12,406 | 41,175 | 2,283 | 20,080 |
| 8 | 11,416 | 12,037 | 15,041 | 11,416 | 12,037 | 36,594 | 2,112 | 18,985 |
| 9 | 11,089 | 11,676 | 13,551 | 11,089 | 11,676 | 34,644 | 1,973 | 18,545 |
| 10 | 10,776 | 11,329 | 12,600 | 10,776 | 11,329 | 32,404 | 1,856 | 17,782 |
| 11 | 10,478 | 10,986 | 11,881 | 10,478 | 10,986 | 26,364 | 1,749 | 16,471 |
| 12 | 10,192 | 10,657 | 10,608 | 10,192 | 10,657 | 20,730 | 1,664 | 15,338 |
| 13 | 9,918 | 10,333 | 9,412 | 9,918 | 10,333 | 23,075 | 1,579 | 15,843 |
| 14 | 9,653 | 10,014 | 8,148 | 9,653 | 10,014 | 20,853 | 1,504 | 16,521 |
| 15 | 9,397 | 9,703 | 6,838 | 9,397 | 9,703 | 11,897 | 1,440 | 15,867 |
| 16 | 9,148 | 9,399 | 5,561 | 9,148 | 9,399 | 15,459 | 1,387 | 15,526 |
| 17 | 8,904 | 9,101 | 5,377 | 8,904 | 9,101 | 11,728 | 1,333 | 15,719 |
| 18 | 8,663 | 8,810 | 4,907 | 8,664 | 8,810 | 11,172 | 1,280 | 13,445 |
| 19 | 8,425 | 8,527 | 4,651 | 8,425 | 8,527 | 9,425 | 1,237 | 12,761 |
| 20 | 8,188 | 8,250 | 4,448 | 8,188 | 8,250 | 8,948 | 1,195 | 14,504 |
| 21 | 7,951 | 7,978 | 4,149 | 7,951 | 7,978 | 7,294 | 1,163 | 13,296 |
| 22 | 7,712 | 7,713 | 3,769 | 7,712 | 7,713 | 7,652 | 1,131 | 12,653 |
| 23 | 7,469 | 7,453 | 3,463 | 7,469 | 7,453 | 8,422 | 1,067 | 13,093 |
| 24 | 7,223 | 7,195 | 3,050 | 7,223 | 7,195 | 7,845 | 1,003 | 13,338 |
| 25 | 6,968 | 6,941 | 2,942 | 6,968 | 6,941 | 7,370 | 939 | 13,171 |
| 26 | 6,707 | 6,697 | 2,600 | 6,707 | 6,697 | 5,454 | 864 | 12,119 |
| 27 | 6,437 | 6,458 | 2,474 | 6,437 | 6,458 | 5,334 | 800 | 12,165 |
| 28 | 6,156 | 6,222 | 2,114 | 6,156 | 6,222 | 4,085 | 757 | 11,757 |
| 29 | 5,863 | 5,991 | 2,094 | 5,863 | 5,991 | 3,428 | 704 | 12,688 |
| 30 | 2,616 | 4,611 | 1,034 | 1,526 | 4,395 | 1,041 | 266 | 10,732 |

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and HDDB (heavy-duty diesel buses).
[b] Because of a lack of data, all motorcycles over 12 years old are considered to have the same emissions and travel characteristics, and therefore are presented in aggregate.
Source: EPA (2024).

## Table A-78: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2023

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC | HDDB |
|---|---|---|---|---|---|---|---|---|
| 0 | 5.29% | 8.39% | 9.78% | 0.00% | 6.80% | 9.40% | 23.60% | 19.39% |
| 1 | 3.64% | 7.17% | 13.86% | 0.00% | 6.80% | 10.17% | 12.01% | 7.39% |
| 2 | 3.88% | 7.48% | 9.64% | 0.00% | 6.81% | 7.00% | 10.18% | 7.09% |
| 3 | 4.51% | 6.85% | 9.74% | 0.00% | 4.56% | 10.52% | 5.89% | 6.88% |
| 4 | 5.43% | 7.76% | 9.20% | 0.09% | 6.63% | 9.30% | 4.79% | 7.03% |
| 5 | 5.69% | 7.02% | 5.17% | 1.00% | 6.83% | 6.31% | 4.10% | 6.10% |
| 6 | 6.53% | 6.62% | 7.50% | 1.20% | 6.50% | 6.01% | 3.62% | 5.52% |
| 7 | 6.51% | 5.74% | 6.28% | 1.12% | 6.73% | 7.71% | 3.37% | 5.17% |
| 8 | 6.84% | 5.34% | 5.45% | 13.93% | 6.72% | 6.28% | 2.94% | 4.47% |
| 9 | 6.30% | 4.40% | 3.05% | 16.72% | 3.91% | 4.09% | 2.63% | 3.74% |
| 10 | 6.35% | 3.73% | 2.77% | 17.02% | 2.76% | 3.52% | 2.23% | 2.92% |
| 11 | 5.41% | 3.10% | 3.14% | 13.48% | 3.16% | 3.40% | 1.97% | 2.70% |
| 12 | 3.93% | 3.01% | 2.24% | 9.14% | 2.76% | 1.83% | 1.33% | 2.67% |
| 13 | 3.79% | 2.29% | 0.94% | 7.93% | 1.17% | 1.11% | 1.01% | 2.65% |
| 14 | 3.17% | 1.63% | 1.04% | 4.87% | 1.09% | 1.38% | 2.02% | 2.11% |
| 15 | 3.66% | 2.59% | 1.55% | 0.49% | 3.08% | 1.26% | 2.32% | 1.87% |
| 16 | 3.64% | 2.54% | 0.96% | 0.33% | 2.72% | 2.46% | 2.82% | 1.69% |
| 17 | 2.99% | 2.27% | 1.24% | 4.08% | 3.90% | 1.69% | 2.64% | 1.58% |

| Vehicle Age | LDGV | LDGT | HDGV | LDDV | LDDT | HDDV | MC | HDDB |
|---|---|---|---|---|---|---|---|---|
| 18 | 2.57% | 2.12% | 0.92% | 2.48% | 2.94% | 1.39% | 2.27% | 1.11% |
| 19 | 2.04% | 2.01% | 0.75% | 1.35% | 3.13% | 0.80% | 1.72% | 1.15% |
| 20 | 1.80% | 1.63% | 0.63% | 1.47% | 2.40% | 0.69% | 1.72% | 0.99% |
| 21 | 1.41% | 1.37% | 0.58% | 1.28% | 1.83% | 0.48% | 1.28% | 1.00% |
| 22 | 1.11% | 1.12% | 0.61% | 0.73% | 1.76% | 0.65% | 1.00% | 0.95% |
| 23 | 0.98% | 0.95% | 0.56% | 0.59% | 1.10% | 0.82% | 0.76% | 0.85% |
| 24 | 0.70% | 0.77% | 0.83% | 0.26% | 1.18% | 0.59% | 0.54% | 0.79% |
| 25 | 0.54% | 0.56% | 0.39% | 0.23% | 0.28% | 0.35% | 0.37% | 0.64% |
| 26 | 0.42% | 0.51% | 0.39% | 0.07% | 0.87% | 0.25% | 0.28% | 0.48% |
| 27 | 0.30% | 0.33% | 0.26% | 0.07% | 0.54% | 0.22% | 0.23% | 0.39% |
| 28 | 0.28% | 0.32% | 0.30% | 0.05% | 0.48% | 0.19% | 0.18% | 0.34% |
| 29 | 0.20% | 0.26% | 0.17% | 0.01% | 0.34% | 0.12% | 0.14% | 0.24% |
| 30 | 0.08% | 0.14% | 0.08% | 0.01% | 0.22% | 0.03% | 0.05% | 0.09% |
| **Total** | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |

[a] The following abbreviations correspond to vehicle types: LDGV (light-duty gasoline vehicles), LDGT (light-duty gasoline trucks), HDGV (heavy-duty gasoline vehicles), LDDV (light-duty diesel vehicles), LDDT (light-duty diesel trucks), HDDV (heavy-duty diesel vehicles), MC (motorcycles) and HDDB (heavy-duty diesel buses).

Notes: Estimated by weighting data in Table A-77. This year's *Inventory* includes updated vehicle population data based on the MOVES5 model that affects this distribution. Totals may not sum due to independent rounding.

## Table A-79: Fuel Consumption for Non-Road Sources by Fuel Type (million gallons unless otherwise noted)

| Vehicle Type/Year | 1990 | 2000 | 2010 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Aircraft[a]** | **19,542** | **20,294** | **15,754** | **14,907** | **15,268** | **15,390** | **16,331** | **17,191** | **17,783** | **17,854** | **18,683** | **12,540** | **15,835** | **17,092** | **18,529** |
| Aviation Gasoline | 374 | 302 | 225 | 209 | 186 | 181 | 176 | 170 | 174 | 186 | 195 | 168 | 179 | 186 | 176 |
| Jet Fuel | 19,168 | 19,992 | 15,529 | 14,698 | 15,082 | 15,210 | 16,155 | 17,021 | 17,609 | 17,667 | 18,489 | 12,372 | 15,656 | 16,906 | 18,353 |
| *Commercial Aviation[b]* | *11,569* | *14,672* | *11,931* | *11,932* | *12,031* | *12,131* | *12,534* | *12,674* | *13,475* | *13,650* | *14,397* | *9,613* | *12,527* | *13,654* | *13,654* |
| **Ships and Boats** | **4,826** | **6,544** | **4,693** | **4,239** | **4,175** | **3,191** | **3,652** | **4,235** | **4,469** | **4,190** | **4,053** | **3,312** | **4,945** | **4,871** | **4,336** |
| Diesel | 1,156 | 1,882 | 1,361 | 1,389 | 1,414 | 1,284 | 1,881 | 1,680 | 1,593 | 1,525 | 1,342 | 1,342 | 1,377 | 1,401 | 1,421 |
| Gasoline | 1,611 | 1,636 | 1,446 | 1,372 | 1,349 | 1,323 | 1,325 | 1,335 | 1,344 | 1,352 | 1,355 | 1,251 | 1,345 | 1,366 | 1,370 |
| Residual | 2,060 | 3,027 | 1,886 | 1,477 | 1,413 | 584 | 445 | 1,219 | 1,532 | 1,313 | 1,356 | 719 | 2,222 | 2,104 | 1,545 |
| **Construction/Mining Equipment[c]** | | | | | | | | | | | | | | | |
| Diesel | 4,317 | 5,181 | 5,727 | 5,533 | 5,447 | 5,313 | 5,200 | 5,483 | 5,978 | 6,262 | 6,464 | 5,966 | 6,414 | 6,782 | 6,829 |
| Gasoline | 472 | 357 | 678 | 651 | 1,100 | 710 | 367 | 375 | 375 | 385 | 387 | 389 | 363 | 290 | 290 |
| CNG (million cubic feet) | 5,082 | 6,032 | 6,219 | 5,957 | 5,802 | 5,598 | 5,430 | 5,629 | 6,018 | 6,204 | 6,321 | 5,834 | 6,272 | 6,477 | 6,499 |
| LPG | 22 | 27 | 26 | 24 | 24 | 23 | 22 | 23 | 25 | 26 | 27 | 25 | 27 | 28 | 28 |
| **Agricultural Equipment[d]** | | | | | | | | | | | | | | | |
| Diesel | 3,514 | 3,278 | 3,942 | 3,932 | 3,900 | 3,925 | 3,862 | 3,760 | 3,728 | 3,732 | 3,742 | 3,682 | 3,741 | 3,689 | 3,689 |
| Gasoline | 813 | 652 | 692 | 875 | 655 | 644 | 159 | 168 | 168 | 160 | 129 | 135 | 147 | 148 | 148 |
| CNG (million cubic feet) | 1,758 | 1,678 | 1,647 | 1,611 | 1,588 | 1,590 | 1,561 | 1,517 | 1,503 | 1,502 | 1,507 | 1,483 | 1,506 | 1,485 | 1,487 |
| LPG | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Rail** | **3,461** | **4,106** | **3,807** | **3,921** | **4,025** | **4,201** | **4,020** | **3,715** | **3,832** | **3,936** | **3,696** | **3,225** | **3,354** | **3,394** | **3,325** |
| Diesel | 3,461 | 4,106 | 3,807 | 3,921 | 4,025 | 4,201 | 4,020 | 3,715 | 3,832 | 3,936 | 3,696 | 3,225 | 3,354 | 3,394 | 3,325 |
| **Other[e]** | | | | | | | | | | | | | | | |
| Diesel | 2,095 | 2,047 | 2,450 | 2,639 | 2,725 | 2,811 | 2,832 | 2,851 | 2,919 | 3,027 | 3,110 | 2,849 | 3,071 | 3,348 | 3,442 |
| Gasoline | 4,371 | 4,673 | 5,525 | 5,189 | 5,201 | 5,281 | 5,083 | 5,137 | 5,178 | 5,238 | 5,287 | 5,041 | 5,268 | 5,515 | 5,539 |
| CNG (million cubic feet) | 20,894 | 25,035 | 29,891 | 35,085 | 37,436 | 39,705 | 38,069 | 37,709 | 38,674 | 40,390 | 41,474 | 38,280 | 41,151 | 44,451 | 45,699 |
| LPG | 1,412 | 2,191 | 2,165 | 2,181 | 2,213 | 2,248 | 2,279 | 2,316 | 2,408 | 2,526 | 2,616 | 2,415 | 2,596 | 2,891 | 3,003 |
| **Total (gallons)** | **44,845** | **49,351** | **45,459** | **44,092** | **44,734** | **43,737** | **43,808** | **45,254** | **46,864** | **47,335** | **48,195** | **39,579** | **45,762** | **48,047** | **49,158** |
| **Total (million cubic feet)** | **27,735** | **32,745** | **37,757** | **42,653** | **44,826** | **46,893** | **45,060** | **44,854** | **46,194** | **48,097** | **49,301** | **45,597** | **48,929** | **52,413** | **53,684** |

**Table A-80: Emissions Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)**

| Model Years | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | CARB LEV | CARB LEV 2 | EPA Tier 2 | CARB LEV 3 | EPA Tier 3 |
|---|---|---|---|---|---|---|---|---|---|
| 1973-1975 | 100% | - | - | - | - | - | - | - | - |
| 1976 | 20% | 80% | - | - | - | - | - | - | - |
| 1977-1978 | 15% | 85% | - | - | - | - | - | - | - |
| 1979-1980 | 10% | 90% | - | - | - | - | - | - | - |
| 1981 | - | 15% | 85% | - | - | - | - | - | - |
| 1982 | - | 14% | 86% | - | - | - | - | - | - |
| 1983 | - | 12% | 88% | - | - | - | - | - | - |
| 1984-1993 | - | - | 100% | - | - | - | - | - | - |
| 1994 | - | - | 80% | 20% | - | - | - | - | - |
| 1995 | - | - | 60% | 40% | - | - | - | - | - |
| 1996 | - | - | 40% | 54% | 6% | - | - | - | - |
| 1997 | - | - | 20% | 68% | 12% | - | - | - | - |
| 1998 | - | - | <1% | 82% | 18% | - | - | - | - |
| 1999 | - | - | <1% | 67% | 33% | - | - | - | - |
| 2000 | - | - | - | 44% | 56% | - | - | - | - |
| 2001 | - | - | - | 3% | 97% | - | - | - | - |
| 2002 | - | - | - | 1% | 99% | - | - | - | - |
| 2003 | - | - | - | <1% | 85% | 2% | 12% | - | - |
| 2004 | - | - | - | <1% | 24% | 16% | 60% | - | - |
| 2005 | - | - | - | - | 13% | 27% | 60% | - | - |
| 2006 | - | - | - | - | 18% | 35% | 47% | - | - |
| 2007 | - | - | - | - | 4% | 43% | 53% | - | - |
| 2008 | - | - | - | - | 2% | 42% | 56% | - | - |
| 2009 | - | - | - | - | <1% | 43% | 57% | - | - |
| 2010 | - | - | - | - | - | 44% | 56% | - | - |
| 2011 | - | - | - | - | - | 42% | 58% | - | - |
| 2012 | - | - | - | - | - | 41% | 59% | - | - |
| 2013 | - | - | - | - | - | 40% | 60% | - | - |
| 2014 | - | - | - | - | - | 37% | 62% | 1% | - |
| 2015 | - | - | - | - | - | 33% | 56% | 11% | <1% |
| 2016 | - | - | - | - | - | 25% | 50% | 18% | 6% |
| 2017 | - | - | - | - | - | 14% | 0% | 29% | 56% |
| 2018 | - | - | - | - | - | 7% | 0% | 42% | 52% |
| 2019 | - | - | - | - | - | 3% | 0% | 44% | 53% |
| 2020 | - | - | - | - | - | 0% | 0% | 50% | 50% |
| 2021 | - | - | - | - | - | 2% | 0% | 48% | 50% |
| 2022 | - | - | - | - | - | 1% | 0% | 49% | 50% |
| 2023 | - | - | - | - | - | 1% | | 49% | 50% |

**-** (Not Applicable)

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex. In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.

Sources: EPA (1998), EPA (2024a), and EPA (2024b).

## Table A-81: Emissions Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

| Model Years | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | CARB LEV[b] | CARB LEV 2 | EPA Tier 2 | CARB LEV 3 | EPA Tier 3 |
|---|---|---|---|---|---|---|---|---|---|
| 1973-1975 | 100% | - | - | - | - | - | - | - | - |
| 1976 | 30% | 70% | - | - | - | - | - | - | - |
| 1977 | 20% | 80% | - | - | - | - | - | - | - |
| 1978-1979 | 25% | 75% | - | - | - | - | - | - | - |
| 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 | - | - | - | 87% | 13% | - | - | - | - |
| 1999 | - | - | - | 61% | 39% | - | - | - | - |
| 2000 | - | - | - | 63% | 37% | - | - | - | - |
| 2001 | - | - | - | 24% | 76% | - | - | - | - |
| 2002 | - | - | - | 31% | 69% | - | - | - | - |
| 2003 | - | - | - | 25% | 69% | - | 6% | - | - |
| 2004 | - | - | - | 1% | 26% | 8% | 65% | - | - |
| 2005 | - | - | - | - | 17% | 17% | 66% | - | - |
| 2006 | - | - | - | - | 24% | 22% | 54% | - | - |
| 2007 | - | - | - | - | 14% | 25% | 61% | - | - |
| 2008 | - | - | - | - | <1% | 34% | 66% | - | - |
| 2009 | - | - | - | - | - | 34% | 66% | - | - |
| 2010 | - | - | - | - | - | 30% | 70% | - | - |
| 2011 | - | - | - | - | - | 27% | 73% | - | - |
| 2012 | - | - | - | - | - | 24% | 76% | - | - |
| 2013 | - | - | - | - | - | 31% | 69% | - | - |
| 2014 | - | - | - | - | - | 26% | 73% | 1% | - |
| 2015 | - | - | - | - | - | 22% | 72% | 6% | - |
| 2016 | - | - | - | - | - | 20% | 62% | 16% | 2% |
| 2017 | - | - | - | - | - | 9% | 14% | 28% | 48% |
| 2018 | - | - | - | - | - | 7% | - | 38% | 55% |
| 2019 | - | - | - | - | - | 3% | - | 44% | 53% |
| 2020 | - | - | - | - | - | - | - | 50% | 50% |
| 2021 | - | - | - | - | - | - | - | 50% | 50% |
| 2022 | - | - | - | - | - | - | - | 50% | 50% |
| 2023 | - | - | - | - | - | 0% | - | 49% | 50% |

- (Not Applicable)

[a] Detailed descriptions of emissions control technologies are provided in the following section of this Annex.

[b] The proportion of LEVs as a whole has decreased since 2001, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a carmaker can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

Notes: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.
Sources: EPA (1998), EPA (2023a), and EPA (2024b).

## Table A-82: Emissions Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

| Model Years | Uncontrolled | Non-catalyst | Oxidation | EPA Tier 0 | EPA Tier 1 | CARB LEV[b] | CARB LEV 2 | EPA Tier 2 | CARB LEV 3 | EPA Tier 3 |
|---|---|---|---|---|---|---|---|---|---|---|
| ≤1980 | 100% | - | - | - | - | - | - | - | - | - |
| 1981-1984 | 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 | - | - | - | - | 100% | - | - | - | - | - |
| 1999 | - | - | - | - | 98% | 2% | - | - | - | - |
| 2000 | - | - | - | - | 93% | 7% | - | - | - | - |
| 2001 | - | - | - | - | 78% | 22% | - | - | - | - |
| 2002 | - | - | - | - | 94% | 6% | - | - | - | - |
| 2003 | - | - | - | - | 85% | 14% | - | 1% | - | - |
| 2004 | - | - | - | - | - | 33% | - | 67% | - | - |
| 2005 | - | - | - | - | - | 15% | - | 85% | - | - |
| 2006 | - | - | - | - | - | 50% | - | 50% | - | - |
| 2007 | - | - | - | - | - | - | 27% | 73% | - | - |
| 2008 | - | - | - | - | - | - | 46% | 54% | - | - |
| 2009 | - | - | - | - | - | - | 45% | 55% | - | - |
| 2010 | - | - | - | - | - | - | 24% | 76% | - | - |
| 2011 | - | - | - | - | - | - | 7% | 93% | - | - |
| 2012 | - | - | - | - | - | - | 17% | 83% | - | - |
| 2013 | - | - | - | - | - | - | 17% | 83% | - | - |
| 2014 | - | - | - | - | - | - | 19% | 81% | - | - |
| 2015 | - | - | - | - | - | - | 31% | 64% | 5% | - |
| 2016 | - | - | - | - | - | - | 24% | 10% | 21% | 44% |
| 2017 | - | - | - | - | - | - | 8% | 8% | 39% | 45% |
| 2018 | - | - | - | - | - | - | 13% | - | 35% | 52% |
| 2019 | - | - | - | - | - | - | 10% | - | 40% | 50% |
| 2020 | - | - | - | - | - | - | - | - | 50% | 50% |
| 2021 | - | - | - | - | - | - | - | - | 50% | 50% |
| 2022 | - | - | - | - | - | - | - | - | 50% | 50% |
| 2023 | - | - | - | - | - | - | - | - | 45% | 55% |

- (Not Applicable)
[a] Detailed descriptions of emissions control technologies are provided in the following section of this Annex.
[b] The proportion of LEVs as a whole has decreased since 2000, as carmakers have been able to achieve greater emission reductions with certain types of LEVs, such as ULEVs. Because ULEVs emit about half the emissions of LEVs, a manufacturer can reduce the total number of LEVs they need to build to meet a specified emission average for all of their vehicles in a given model year.

Notes: In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, which emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore were not included in the engine technology breakouts. For this *Inventory*, HEVs are now classified as gasoline vehicles across the entire time series.
Sources: EPA (1998), EPA (2023a), and EPA (2024b).

## Table A-83: Emissions Control Technology Assignments for Diesel On-Road Vehicles and Motorcycles

| Vehicle Type/Control Technology | Model Years |
|---|---|
| **Diesel Passenger Cars and Light-Duty Trucks** | |
| Uncontrolled | 1960–1982 |
| Moderate Control | 1983–1995 |
| Advanced Control | 1996–2006 |
| Aftertreatment | 2007-2023 |
| **Diesel Medium- and Heavy-Duty Trucks and Buses** | |
| Uncontrolled | 1960–1989 |
| Moderate Control | 1990–2003 |
| Advanced Control | 2004–2006 |
| Aftertreatment | 2007–2023 |
| **Motorcycles** | |
| Uncontrolled | 1960–1995 |
| Non-Catalyst Controls | 1996–2005 |
| Advanced | 2006-2023 |

Note: Detailed descriptions of emissions control technologies are provided in the following section of this Annex.
Source: EPA (1998) and Browning (2005).

## Table A-84: Emission Factors for $CH_4$ and $N_2O$ for On-Road Vehicles

| Vehicle Type/Control Technology | $N_2O$ (g/mi) | $CH_4$ (g/mi) |
|---|---|---|
| **Gasoline Passenger Cars** | | |
| EPA Tier 3 | 0.0015 | 0.0055 |
| ARB LEV III | 0.0012 | 0.0045 |
| EPA Tier 2 | 0.0048 | 0.0072 |
| ARB LEV II | 0.0043 | 0.0070 |
| ARB LEV | 0.0205 | 0.0100 |
| EPA Tier 1[a] | 0.0429 | 0.0271 |
| EPA Tier 0[a] | 0.0647 | 0.0704 |
| Oxidation Catalyst | 0.0504 | 0.1355 |
| Non-Catalyst Control | 0.0197 | 0.1696 |
| Uncontrolled | 0.0197 | 0.1780 |
| **Gasoline Light-Duty Trucks** | | |
| EPA Tier 3 | 0.0012 | 0.0092 |
| ARB LEV III | 0.0012 | 0.0065 |
| EPA Tier 2 | 0.0025 | 0.0100 |
| ARB LEV II | 0.0057 | 0.0084 |
| ARB LEV | 0.0223 | 0.0148 |
| EPA Tier 1[a] | 0.0871 | 0.0452 |
| EPA Tier 0[a] | 0.1056 | 0.0776 |

| | | |
|---|---|---|
| Oxidation Catalyst | 0.0639 | 0.1516 |
| Non-Catalyst Control | 0.0218 | 0.1908 |
| Uncontrolled | 0.0220 | 0.2024 |
| **Gasoline Heavy-Duty Vehicles** | | |
| EPA Tier 3 | 0.0063 | 0.0252 |
| ARB LEV III | 0.0136 | 0.0411 |
| EPA Tier 2 | 0.0015 | 0.0297 |
| ARB LEV II | 0.0049 | 0.0391 |
| ARB LEV | 0.0466 | 0.0300 |
| EPA Tier 1[a] | 0.1750 | 0.0655 |
| EPA Tier 0[a] | 0.2135 | 0.2630 |
| Oxidation Catalyst | 0.1317 | 0.2356 |
| Non-Catalyst Control | 0.0473 | 0.4181 |
| Uncontrolled | 0.0497 | 0.4604 |
| **Diesel Passenger Cars** | | |
| Aftertreatment | 0.0192 | 0.0302 |
| Advanced | 0.0010 | 0.0005 |
| Moderate | 0.0010 | 0.0005 |
| Uncontrolled | 0.0012 | 0.0006 |
| **Diesel Light-Duty Trucks** | | |
| Aftertreatment | 0.0214 | 0.0290 |
| Advanced | 0.0014 | 0.0009 |
| Moderate | 0.0014 | 0.0009 |
| Uncontrolled | 0.0017 | 0.0011 |
| **Diesel Medium- and Heavy-Duty Trucks and Buses** | | |
| Aftertreatment | 0.0431 | 0.0095 |
| Advanced | 0.0048 | 0.0051 |
| Moderate | 0.0048 | 0.0051 |
| Uncontrolled | 0.0048 | 0.0051 |
| **Motorcycles** | | |
| Advanced | 0.0179 | 0.0661 |
| Non-Catalyst Control | 0.0069 | 0.0672 |
| Uncontrolled | 0.0087 | 0.0899 |

[a] The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *2006 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this Annex.

Source: ICF (2006 and 2017), Browning (2022a).

## Table A-85: Emission Factors for $N_2O$ for Alternative Fuel Vehicles (g/mi)

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Light-Duty Cars** | | | | | | | | | | | | | | |
| Methanol-Flex Fuel ICE | 0.040 | 0.027 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| Ethanol-Flex Fuel ICE | 0.040 | 0.027 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| CNG ICE | 0.024 | 0.022 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| CNG Bi-fuel | 0.024 | 0.022 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| LPG ICE | 0.024 | 0.022 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| LPG Bi-fuel | 0.024 | 0.022 | 0.006 | 0.006 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| Biodiesel (BD100) | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| **Light-Duty Trucks** | | | | | | | | | | | | | | |
| Ethanol-Flex Fuel ICE | 0.077 | 0.056 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| CNG ICE | 0.046 | 0.045 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| CNG Bi-fuel | 0.046 | 0.045 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| LPG ICE | 0.046 | 0.045 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| LPG Bi-fuel | 0.046 | 0.045 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| LNG | 0.046 | 0.045 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.006 | 0.006 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| Biodiesel (BD100) | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| **Medium-Duty Trucks** | | | | | | | | | | | | | | |
| CNG ICE | 0.127 | 0.127 | 0.106 | 0.108 | 0.109 | 0.110 | 0.088 | 0.067 | 0.045 | 0.023 | 0.001 | 0.001 | 0.001 | 0.001 |
| CNG Bi-fuel | 0.127 | 0.127 | 0.106 | 0.108 | 0.109 | 0.110 | 0.088 | 0.067 | 0.045 | 0.023 | 0.001 | 0.001 | 0.001 | 0.001 |
| LPG ICE | 0.127 | 0.127 | 0.106 | 0.108 | 0.109 | 0.110 | 0.092 | 0.073 | 0.055 | 0.037 | 0.018 | 0.018 | 0.018 | 0.018 |
| LPG Bi-fuel | 0.127 | 0.127 | 0.106 | 0.108 | 0.109 | 0.110 | 0.092 | 0.073 | 0.055 | 0.037 | 0.018 | 0.018 | 0.018 | 0.018 |
| LNG | 0.127 | 0.127 | 0.106 | 0.108 | 0.109 | 0.110 | 0.088 | 0.067 | 0.045 | 0.023 | 0.001 | 0.001 | 0.001 | 0.001 |
| Biodiesel (BD100) | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 | 0.005 |
| **Heavy-Duty Trucks** | | | | | | | | | | | | | | |
| Neat Methanol ICE | 0.128 | 0.128 | 0.121 | 0.124 | 0.127 | 0.130 | 0.110 | 0.089 | 0.069 | 0.048 | 0.028 | 0.027 | 0.026 | 0.026 |
| Neat Ethanol ICE | 0.128 | 0.128 | 0.121 | 0.124 | 0.127 | 0.130 | 0.110 | 0.089 | 0.069 | 0.048 | 0.028 | 0.027 | 0.026 | 0.026 |
| CNG ICE | 0.077 | 0.077 | 0.109 | 0.108 | 0.108 | 0.108 | 0.086 | 0.065 | 0.043 | 0.022 | 0.000 | 0.000 | 0.000 | 0.000 |
| LPG ICE | 0.077 | 0.077 | 0.109 | 0.108 | 0.108 | 0.108 | 0.090 | 0.073 | 0.055 | 0.038 | 0.020 | 0.017 | 0.014 | 0.012 |
| LPG Bi-fuel | 0.077 | 0.077 | 0.109 | 0.108 | 0.108 | 0.108 | 0.087 | 0.067 | 0.047 | 0.027 | 0.007 | 0.006 | 0.006 | 0.006 |
| LNG | 0.077 | 0.077 | 0.109 | 0.108 | 0.108 | 0.108 | 0.086 | 0.065 | 0.043 | 0.022 | 0.000 | 0.000 | 0.000 | 0.000 |
| Biodiesel (BD100) | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 |
| **Buses** | | | | | | | | | | | | | | |
| Neat Methanol ICE | 0.198 | 0.198 | 0.141 | 0.139 | 0.137 | 0.136 | 0.114 | 0.093 | 0.072 | 0.051 | 0.029 | 0.029 | 0.029 | 0.028 |

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Neat Ethanol ICE | 0.198 | 0.198 | 0.141 | 0.139 | 0.137 | 0.136 | 0.114 | 0.093 | 0.072 | 0.051 | 0.029 | 0.029 | 0.029 | 0.028 |
| CNG ICE | 0.119 | 0.119 | 0.084 | 0.083 | 0.082 | 0.081 | 0.065 | 0.049 | 0.033 | 0.017 | 0.001 | 0.001 | 0.001 | 0.001 |
| LPG ICE | 0.119 | 0.119 | 0.084 | 0.083 | 0.082 | 0.081 | 0.070 | 0.059 | 0.048 | 0.036 | 0.025 | 0.022 | 0.018 | 0.015 |
| LNG | 0.119 | 0.119 | 0.084 | 0.083 | 0.082 | 0.081 | 0.065 | 0.049 | 0.033 | 0.017 | 0.001 | 0.001 | 0.001 | 0.001 |
| Biodiesel (BD100) | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicles (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.

Source: Developed by ICF (Browning 2022b) using ANL (2022).

## Table A-86: Emission Factors for $CH_4$ for Alternative Fuel Vehicles (g/mi)

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Light-Duty Cars** | | | | | | | | | | | | | | |
| Methanol-Flex Fuel ICE | 0.126 | 0.083 | 0.020 | 0.018 | 0.017 | 0.016 | 0.016 | 0.015 | 0.015 | 0.015 | 0.015 | 0.013 | 0.012 | 0.011 |
| Ethanol-Flex Fuel ICE | 0.126 | 0.083 | 0.020 | 0.018 | 0.017 | 0.016 | 0.016 | 0.015 | 0.015 | 0.015 | 0.015 | 0.013 | 0.012 | 0.011 |
| CNG ICE | 1.793 | 1.103 | 0.198 | 0.185 | 0.171 | 0.158 | 0.156 | 0.153 | 0.151 | 0.149 | 0.146 | 0.133 | 0.120 | 0.106 |
| CNG Bi-fuel | 1.793 | 1.103 | 0.198 | 0.185 | 0.171 | 0.158 | 0.156 | 0.153 | 0.151 | 0.149 | 0.146 | 0.133 | 0.120 | 0.106 |
| LPG ICE | 0.179 | 0.110 | 0.020 | 0.018 | 0.017 | 0.016 | 0.016 | 0.015 | 0.015 | 0.015 | 0.015 | 0.013 | 0.012 | 0.011 |
| LPG Bi-fuel | 0.179 | 0.110 | 0.020 | 0.018 | 0.017 | 0.016 | 0.016 | 0.015 | 0.015 | 0.015 | 0.015 | 0.013 | 0.012 | 0.011 |
| Biodiesel (BD100) | - | - | 0.012 | 0.018 | 0.024 | 0.030 | 0.019 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 | 0.030 |
| **Light-Duty Trucks** | | | | | | | | | | | | | | |
| Ethanol-Flex Fuel ICE | 0.184 | 0.118 | 0.021 | 0.019 | 0.018 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.014 | 0.013 | 0.012 |
| CNG ICE | 2.632 | 1.580 | 0.211 | 0.195 | 0.179 | 0.164 | 0.162 | 0.161 | 0.160 | 0.159 | 0.158 | 0.144 | 0.130 | 0.116 |
| CNG Bi-fuel | 2.632 | 1.580 | 0.211 | 0.195 | 0.179 | 0.164 | 0.162 | 0.161 | 0.160 | 0.159 | 0.158 | 0.144 | 0.130 | 0.116 |
| LPG ICE | 0.263 | 0.158 | 0.021 | 0.019 | 0.018 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.014 | 0.013 | 0.012 |
| LPG Bi-fuel | 0.263 | 0.158 | 0.021 | 0.019 | 0.018 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.016 | 0.014 | 0.013 | 0.012 |
| LNG | 2.632 | 1.580 | 0.211 | 0.195 | 0.179 | 0.164 | 0.162 | 0.161 | 0.160 | 0.159 | 0.158 | 0.144 | 0.130 | 0.116 |
| Biodiesel (BD100) | - | - | 0.012 | 0.017 | 0.023 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 | 0.029 |
| **Medium-Duty Trucks** | | | | | | | | | | | | | | |
| CNG ICE | 6.800 | 6.800 | 5.697 | 5.762 | 5.827 | 5.893 | 5.052 | 4.212 | 3.372 | 2.532 | 1.691 | 1.675 | 1.658 | 1.641 |
| CNG Bi-fuel | 6.800 | 6.800 | 5.697 | 5.762 | 5.827 | 5.893 | 5.052 | 4.212 | 3.372 | 2.532 | 1.691 | 1.675 | 1.658 | 1.641 |
| LPG ICE | 0.680 | 0.680 | 0.570 | 0.576 | 0.583 | 0.589 | 0.473 | 0.357 | 0.241 | 0.125 | 0.009 | 0.009 | 0.009 | 0.009 |

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LPG Bi-fuel | 0.680 | 0.680 | 0.570 | 0.576 | 0.583 | 0.589 | 0.473 | 0.357 | 0.241 | 0.125 | 0.009 | 0.009 | 0.009 | 0.009 |
| LNG | 6.800 | 6.800 | 5.697 | 5.762 | 5.827 | 5.893 | 5.052 | 4.212 | 3.372 | 2.532 | 1.691 | 1.675 | 1.658 | 1.641 |
| Biodiesel (BD100) | 0.287 | 0.009- | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
| **Heavy-Duty Trucks** | | | | | | | | | | | | | | |
| Neat Methanol ICE | 0.287 | 0.287 | 0.271 | 0.278 | 0.285 | 0.292 | 0.249 | 0.205 | 0.162 | 0.118 | 0.075 | 0.073 | 0.072 | 0.070 |
| Neat Ethanol ICE | 0.287 | 0.287 | 0.271 | 0.278 | 0.285 | 0.292 | 0.249 | 0.205 | 0.162 | 0.118 | 0.075 | 0.073 | 0.072 | 0.070 |
| CNG ICE | 4.100 | 4.100 | 5.827 | 5.805 | 5.783 | 5.761 | 4.785 | 3.808 | 2.832 | 1.855 | 0.879 | 0.879 | 0.879 | 0.879 |
| LPG ICE | 0.410 | 0.410 | 0.583 | 0.581 | 0.578 | 0.576 | 0.462 | 0.347 | 0.232 | 0.119 | 0.003 | 0.003 | 0.003 | 0.002 |
| LPG Bi-fuel | 0.410 | 0.410 | 0.583 | 0.581 | 0.578 | 0.576 | 0.462 | 0.347 | 0.232 | 0.119 | 0.003 | 0.003 | 0.003 | 0.002 |
| LNG | 4.100 | 4.100 | 5.827 | 5.805 | 5.783 | 5.761 | 4.785 | 3.808 | 2.832 | 1.855 | 0.879 | 0.879 | 0.879 | 0.879 |
| Biodiesel (BD100) | - | - | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |
| **Buses** | | | | | | | | | | | | | | |
| Neat Methanol ICE | 1.316 | 1.316 | 0.937 | 0.926 | 0.915 | 0.904 | 0.762 | 0.620 | 0.478 | 0.337 | 0.195 | 0.193 | 0.190 | 0.188 |
| Neat Ethanol ICE | 1.316 | 1.316 | 0.937 | 0.926 | 0.915 | 0.904 | 0.762 | 0.620 | 0.478 | 0.337 | 0.195 | 0.193 | 0.190 | 0.188 |
| CNG ICE | 18.800 | 18.800 | 13.389 | 13.229 | 13.068 | 12.908 | 10.801 | 8.694 | 6.588 | 4.481 | 2.734 | 2.348 | 2.321 | 2.295 |
| LPG ICE | 1.880 | 1.880 | 1.339 | 1.323 | 1.307 | 1.291 | 1.034 | 0.778 | 0.522 | 0.265 | 0.009 | 0.008 | 0.006 | 0.005 |
| LNG | 18.800 | 18.800 | 13.389 | 13.229 | 13.068 | 12.908 | 10.801 | 8.694 | 6.588 | 4.481 | 2.374 | 2.348 | 2.321 | 2.295 |
| Biodiesel (BD100) | - | - | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 | 0.009 |

Note: When driven in all-electric mode, plug-in electric vehicles have zero tailpipe emissions. Therefore, emissions factors for battery electric vehicles (BEVs) and the electric portion of plug-in hybrid electric vehicles (PHEVs) are not included in this table.
Source: Developed by ICF (Browning 2022b) using ANL (2022).

## Table A-87: Emission Factors for $N_2O$ Emissions from Non-Road Mobile Combustion (g/kg fuel)

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ships and Boats** | | | | | | | | | | | | | | |
| Residual Fuel Oil | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 | 0.088 |
| Gasoline | | | | | | | | | | | | | | |
| *2 Stroke* | 0.021 | 0.021 | 0.025 | 0.026 | 0.026 | 0.026 | 0.027 | 0.027 | 0.027 | 0.027 | 0.027 | 0.028 | 0.028 | 0.028 |
| *4 Stroke* | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.002 | 0.003 | 0.003 | 0.003 | 0.003 | 0.003 |
| Distillate Fuel Oil | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 | 0.054 |
| **Rail** | | | | | | | | | | | | | | |
| Diesel | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 | 0.080 |
| **Aircraft** | | | | | | | | | | | | | | |
| Jet Fuel | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| Aviation Gasoline | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 | 0.040 |

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Agricultural Equipment[a]** | | | | | | | | | | | | | | |
| Gasoline-Equipment | | | | | | | | | | | | | | |
| *2 Stroke* | 0.103 | 0.118 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.170 | 0.169 |
| *4 Stroke* | 0.355 | 0.365 | 0.415 | 0.417 | 0.420 | 0.422 | 0.423 | 0.425 | 0.427 | 0.429 | 0.431 | 0.433 | 0.433 | 0.431 |
| Gasoline-Off-road Trucks | 0.355 | 0.365 | 0.415 | 0.417 | 0.420 | 0.422 | 0.423 | 0.425 | 0.427 | 0.429 | 0.431 | 0.433 | 0.430 | 0.430 |
| Diesel-Equipment | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.336 | 0.335 |
| Diesel-Off-Road Trucks | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.175 |
| CNG | 0.061 | 0.061 | 0.075 | 0.075 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 | 0.076 |
| LPG | 0.389 | 0.389 | 0.444 | 0.446 | 0.449 | 0.451 | 0.452 | 0.454 | 0.456 | 0.458 | 0.460 | 0.462 | 0.462 | 0.460 |
| **Construction/Mining Equipment[b]** | | | | | | | | | | | | | | |
| Gasoline-Equipment | | | | | | | | | | | | | | |
| *2 Stroke* | 0.028 | 0.030 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 | 0.042 |
| *4 Stroke* | 0.408 | 0.450 | 0.521 | 0.523 | 0.524 | 0.525 | 0.526 | 0.527 | 0.527 | 0.528 | 0.528 | 0.528 | 0.528 | 0.530 |
| Gasoline-Off-road Trucks | 0.41 | 0.45 | 0.52 | 0.52 | 0.52 | 0.52 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 | 0.53 |
| Diesel-Equipment | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.295 | 0.296 |
| Diesel-Off-Road Trucks | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.174 | 0.175 |
| CNG | 0.367 | 0.367 | 0.398 | 0.402 | 0.405 | 0.409 | 0.416 | 0.424 | 0.431 | 0.437 | 0.442 | 0.445 | 0.445 | 0.446 |
| LPG | 0.197 | 0.197 | 0.229 | 0.231 | 0.233 | 0.235 | 0.237 | 0.239 | 0.240 | 0.242 | 0.243 | 0.243 | 0.243 | 0.244 |
| **Lawn and Garden Equipment** | | | | | | | | | | | | | | |
| Gasoline-Residential | | | | | | | | | | | | | | |
| *2 Stroke* | 0.107 | 0.120 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.172 | 0.174 |
| *4 Stroke* | 0.519 | 0.578 | 0.690 | 0.692 | 0.693 | 0.694 | 0.695 | 0.695 | 0.695 | 0.696 | 0.696 | 0.696 | 0.696 | 0.701 |
| Gasoline-Commercial | | | | | | | | | | | | | | |
| *2 Stroke* | 0.071 | 0.079 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.110 | 0.111 |
| *4 Stroke* | 0.409 | 0.476 | 0.532 | 0.533 | 0.534 | 0.534 | 0.534 | 0.535 | 0.535 | 0.535 | 0.535 | 0.535 | 0.535 | 0.539 |
| Diesel-Residential | 0.167 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.154 |
| Diesel-Commercial | 0.167 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.154 |
| LPG | 0.245 | 0.245 | 0.300 | 0.302 | 0.303 | 0.304 | 0.305 | 0.306 | 0.306 | 0.306 | 0.306 | 0.306 | 0.306 | 0.308 |
| **Airport Equipment** | | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | | |
| *4 Stroke* | 0.299 | 0.316 | 0.378 | 0.380 | 0.381 | 0.382 | 0.382 | 0.383 | 0.383 | 0.383 | 0.383 | 0.383 | 0.383 | 0.400 |
| Diesel | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.364 | 0.380 |
| LPG | 0.346 | 0.346 | 0.424 | 0.427 | 0.429 | 0.430 | 0.431 | 0.431 | 0.432 | 0.432 | 0.432 | 0.432 | 0.432 | 0.451 |
| **Industrial/Commercial Equipment** | | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | | |

| | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *2 Stroke* | 0.107 | 0.123 | 0.177 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.178 | 0.182 |
| *4 Stroke* | 0.425 | 0.473 | 0.548 | 0.550 | 0.551 | 0.552 | 0.553 | 0.553 | 0.552 | 0.551 | 0.551 | 0.550 | 0.550 | 0.563 |
| Diesel | 0.183 | 0.180 | 0.190 | 0.191 | 0.192 | 0.190 | 0.190 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.189 | 0.195 |
| CNG | 0.034 | 0.031 | 0.043 | 0.044 | 0.044 | 0.044 | 0.043 | 0.043 | 0.043 | 0.043 | 0.043 | 0.042 | 0.042 | 0.043 |
| LPG | 0.250 | 0.250 | 0.303 | 0.305 | 0.307 | 0.308 | 0.309 | 0.310 | 0.311 | 0.311 | 0.311 | 0.312 | 0.312 | 0.324 |
| **Logging Equipment** | | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | | |
| *2 Stroke* | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| *4 Stroke* | 0.579 | 0.604 | 0.688 | 0.699 | 0.709 | 0.719 | 0.725 | 0.730 | 0.733 | 0.735 | 0.736 | 0.737 | 0.737 | 0.733 |
| Diesel | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.398 | 0.395 |
| **Railroad Equipment** | | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | | |
| *4 Stroke* | 0.498 | 0.555 | 0.646 | 0.647 | 0.648 | 0.649 | 0.649 | 0.650 | 0.650 | 0.650 | 0.650 | 0.650 | 0.650 | 0.665 |
| Diesel | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.297 | 0.304 |
| LPG | 0.005 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 | 0.004 |
| **Recreational Equipment** | | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | | |
| *2 Stroke* | 0.034 | 0.034 | 0.036 | 0.036 | 0.037 | 0.037 | 0.037 | 0.038 | 0.038 | 0.039 | 0.039 | 0.039 | 0.039 | 0.039 |
| *4 Stroke* | 0.487 | 0.503 | 0.535 | 0.536 | 0.536 | 0.536 | 0.536 | 0.536 | 0.536 | 0.537 | 0.537 | 0.531 | 0.531 | 0.535 |
| Diesel | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.207 | 0.208 |
| LPG | 0.255 | 0.255 | 0.275 | 0.277 | 0.279 | 0.281 | 0.284 | 0.286 | 0.288 | 0.290 | 0.293 | 0.295 | 0.295 | 0.297 |

- Not applicable

[a] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[b] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

Source: IPCC (2006) and Browning, L (2018b), EPA (2024).

### Table A-88: Emission Factors for $CH_4$ Emissions from Non-Road Mobile Combustion (g/kg fuel)

| | 1990 | 2000 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Ships and Boats** | | | | | | | | | | | | | |
| Residual Fuel Oil | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 | 0.309 |
| Gasoline | | | | | | | | | | | | | |
| *2 Stroke* | 1.255 | 1.270 | 1.536 | 1.557 | 1.578 | 1.597 | 1.615 | 1.629 | 1.642 | 1.652 | 1.661 | 1.672 | 1.672 |
| *4 Stroke* | 0.717 | 0.725 | 0.773 | 0.777 | 0.783 | 0.788 | 0.793 | 0.797 | 0.801 | 0.805 | 0.808 | 0.813 | 0.813 |
| Distillate Fuel Oil | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.008 | 2.039 | 2.039 |
| **Rail** | | | | | | | | | | | | | |

| | 1990 | 2000 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 | 0.250 |
| **Aircraft** | | | | | | | | | | | | | |
| Jet Fuel[a] | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| Aviation Gasoline | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 | 2.640 |
| **Agricultural Equipment[b]** | | | | | | | | | | | | | |
| Gasoline-Equipment | | | | | | | | | | | | | |
| *2 Stroke* | 1.500 | 1.720 | 2.480 | 2.480 | 2.480 | 2.480 | 2.480 | 2.480 | 2.480 | 2.480 | 2.480 | 2.471 | 2.471 |
| *4 Stroke* | 0.570 | 0.586 | 0.670 | 0.674 | 0.677 | 0.679 | 0.682 | 0.686 | 0.689 | 0.692 | 0.695 | 0.692 | 0.692 |
| Gasoline-Off-road Trucks | 0.570 | 0.586 | 0.670 | 0.674 | 0.677 | 0.679 | 0.682 | 0.686 | 0.689 | 0.692 | 0.695 | 0.692 | 0.692 |
| Diesel-Equipment | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.397 | 0.396 | 0.396 |
| Diesel-Off-Road Trucks | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.287 | 0.287 |
| CNG | 1.391 | 1.391 | 1.719 | 1.726 | 1.731 | 1.734 | 1.736 | 1.736 | 1.736 | 1.736 | 1.736 | 1.730 | 1.730 |
| LPG | 0.135 | 0.135 | 0.155 | 0.156 | 0.157 | 0.157 | 0.158 | 0.158 | 0.159 | 0.160 | 0.160 | 0.160 | 0.160 |
| **Construction/Mining Equipment[c]** | | | | | | | | | | | | | |
| Gasoline-Equipment | | | | | | | | | | | | | |
| *2 Stroke* | 1.868 | 1.997 | 2.858 | 2.858 | 2.858 | 2.858 | 2.858 | 2.858 | 2.858 | 2.858 | 2.858 | 2.866 | 2.866 |
| *4 Stroke* | 0.789 | 0.871 | 1.011 | 1.013 | 1.015 | 1.017 | 1.019 | 1.020 | 1.021 | 1.022 | 1.022 | 1.025 | 1.025 |
| Gasoline-Off-road Trucks | 0.789 | 0.871 | 1.011 | 1.013 | 1.015 | 1.017 | 1.019 | 1.020 | 1.021 | 1.022 | 1.022 | 1.025 | 1.025 |
| Diesel-Equipment | 0.317 | 0.317 | 0.316 | 0.316 | 0.316 | 0.316 | 0.317 | 0.317 | 0.317 | 0.317 | 0.317 | 0.318 | 0.318 |
| Diesel-Off-Road Trucks | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.286 | 0.287 | 0.287 |
| CNG | 1.322 | 1.322 | 1.447 | 1.459 | 1.473 | 1.499 | 1.529 | 1.554 | 1.574 | 1.595 | 1.605 | 1.609 | 1.609 |
| LPG | 0.233 | 0.233 | 0.273 | 0.276 | 0.278 | 0.280 | 0.283 | 0.285 | 0.286 | 0.287 | 0.288 | 0.289 | 0.289 |
| **Lawn and Garden Equipment** | | | | | | | | | | | | | |
| Gasoline-Residential | | | | | | | | | | | | | |
| *2 Stroke* | 1.489 | 1.666 | 2.381 | 2.381 | 2.382 | 2.382 | 2.382 | 2.382 | 2.383 | 2.383 | 2.384 | 2.403 | 2.403 |
| *4 Stroke* | 0.803 | 0.894 | 1.070 | 1.072 | 1.073 | 1.074 | 1.075 | 1.075 | 1.075 | 1.076 | 1.076 | 1.084 | 1.084 |
| Gasoline-Commercial | | | | | | | | | | | | | |
| *2 Stroke* | 1.685 | 1.859 | 2.609 | 2.609 | 2.609 | 2.609 | 2.610 | 2.610 | 2.610 | 2.611 | 2.611 | 2.631 | 2.631 |
| *4 Stroke* | 0.821 | 0.956 | 1.071 | 1.072 | 1.072 | 1.073 | 1.073 | 1.073 | 1.073 | 1.073 | 1.074 | 1.082 | 1.082 |
| Diesel-Residential | 0.236 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.209 | 0.209 |
| Diesel-Commercial | 0.236 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.208 | 0.209 | 0.209 |
| LPG | 0.137 | 0.137 | 0.169 | 0.170 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.179 | 0.179 |
| **Airport Equipment** | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | |
| *4 Stroke* | 0.287 | 0.303 | 0.364 | 0.365 | 0.366 | 0.366 | 0.366 | 0.367 | 0.367 | 0.367 | 0.367 | 0.383 | 0.383 |
| Diesel | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.593 | 0.619 | 0.619 |

| | 1990 | 2000 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LPG | 0.137 | 0.137 | 0.169 | 0.170 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.171 | 0.179 | 0.179 |
| **Industrial/Commercial Equipment** | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | |
| *2 Stroke* | 1.541 | 1.774 | 2.550 | 2.551 | 2.552 | 2.553 | 2.553 | 2.554 | 2.554 | 2.554 | 2.555 | 2.617 | 2.617 |
| *4 Stroke* | 0.758 | 0.837 | 0.984 | 0.987 | 0.987 | 0.987 | 0.987 | 0.986 | 0.985 | 0.984 | 0.983 | 1.006 | 1.006 |
| Diesel | 0.120 | 0.106 | 0.140 | 0.143 | 0.141 | 0.139 | 0.135 | 0.134 | 0.133 | 0.133 | 0.132 | 0.135 | 0.135 |
| CNG | 2.334 | 2.420 | 2.837 | 2.832 | 2.854 | 2.867 | 2.877 | 2.885 | 2.892 | 2.897 | 2.904 | 2.986 | 2.986 |
| LPG | 0.174 | 0.174 | 0.212 | 0.213 | 0.214 | 0.215 | 0.215 | 0.216 | 0.216 | 0.216 | 0.216 | 0.225 | 0.225 |
| **Logging Equipment** | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | |
| *2 Stroke* | 2.289 | 2.423 | 3.468 | 3.468 | 3.468 | 3.468 | 3.468 | 3.468 | 3.468 | 3.468 | 3.468 | 3.446 | 3.446 |
| *4 Stroke* | 0.914 | 0.950 | 1.114 | 1.127 | 1.137 | 1.143 | 1.149 | 1.153 | 1.157 | 1.159 | 1.161 | 1.153 | 1.153 |
| Diesel | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.153 | 0.152 | 0.152 |
| **Railroad Equipment** | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | |
| *4 Stroke* | 0.897 | 0.990 | 1.155 | 1.157 | 1.158 | 1.158 | 1.159 | 1.160 | 1.160 | 1.160 | 1.160 | 1.190 | 1.19 |
| Diesel | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.125 | 0.130 | 0.13 |
| LPG | 0.784 | 0.787 | 0.919 | 0.927 | 0.936 | 0.943 | 0.956 | 0.962 | 0.966 | 0.970 | 0.973 | 1.000 | 1.00 |
| **Recreational Equipment** | | | | | | | | | | | | | |
| Gasoline | | | | | | | | | | | | | |
| *2 Stroke* | 5.170 | 5.252 | 5.781 | 5.862 | 5.944 | 6.024 | 6.100 | 6.176 | 6.244 | 6.310 | 3.510 | 3.534 | 3.534 |
| *4 Stroke* | 0.935 | 0.965 | 1.029 | 1.030 | 1.030 | 1.030 | 1.031 | 1.031 | 1.031 | 1.032 | 0.975 | 0.982 | 0.982 |
| Diesel | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.228 | 0.230 | 0.230 |
| LPG | 0.182 | 0.182 | 0.198 | 0.200 | 0.201 | 0.203 | 0.204 | 0.206 | 0.208 | 0.209 | 0.211 | 0.213 | 0.213 |

## Definitions of Emission Control Technologies and Standards

The $N_2O$ and $CH_4$ emission factors used depend on the emission standards in place and the corresponding level of control technology for each vehicle type. Table A-80 through Table A-83 show the years in which these technologies or standards were in place and the penetration level for each vehicle type. These categories are defined below and were compiled from EPA (1998, 1999) and IPCC/UNEP/OECD/IEA (1997).

**Uncontrolled**

Vehicles manufactured prior to the implementation of pollution control technologies are designated as uncontrolled. Gasoline passenger cars and light-duty trucks (pre-1973), gasoline heavy-duty vehicles (pre-1984), diesel vehicles (pre-1983), and motorcycles (pre-1996) are assumed to have no control technologies in place.

**Gasoline Emission Controls**

Below are the control technologies and emissions standards applicable to gasoline vehicles.

*Non-catalyst*

These emission controls were common in gasoline passenger cars and light-duty gasoline trucks during model years (1973-1974) but phased out thereafter, in heavy-duty gasoline vehicles beginning in the mid-1980s, and in motorcycles from 1996 to 2005. This technology reduces hydrocarbon (HC) and carbon monoxide (CO) emissions through adjustments to ignition timing and air-fuel ratio, air injection into the exhaust manifold, and exhaust gas recirculation (EGR) valves, which also helps meet vehicle $NO_x$ standards.

*Oxidation Catalyst*

This control technology designation represents the introduction of the catalytic converter, which was the most common technology in gasoline passenger cars and light-duty gasoline trucks made from 1975 to 1980 (cars) and 1975 to 1985 (trucks). This technology was also used in some heavy-duty gasoline vehicles between 1982 and 1997. The two-way catalytic converter oxidizes HC and CO, significantly reducing emissions over 80 percent beyond non-catalyst-system capacity. One reason unleaded gasoline was introduced in 1975 was due to the fact that oxidation catalysts cannot function properly with leaded gasoline.

*Advanced Control*

Motorcycles built after 2005 are assumed to have advanced emission control systems to better capture emissions from motorcycles. This can include fuel injection, closed loop control, and three-way catalysts.

*EPA Tier 0*

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, a technology used in gasoline passenger cars and light-duty gasoline trucks beginning in the early 1980s which remained common until 1994. This more sophisticated emission control system improves the efficiency of the catalyst by converting CO and HC to $CO_2$ and $H_2O$, reducing $NO_x$ to nitrogen and oxygen, and using an on-board diagnostic computer and oxygen sensor. In addition, this type of catalyst includes a fuel metering system (carburetor or fuel injection) with electronic "trim" (also known as a "closed-loop system"). New cars with three-way catalysts met the Clean Air Act's amended standards (enacted in 1977) of reducing HC to 0.41 g/mile by 1980, CO to 3.4 g/mile by 1981 and $NO_x$ to 1.0 g/mile by 1981.

*EPA Tier 1*

This emission standard created through the 1990 amendments to the Clean Air Act limited passenger car $NO_x$ emissions to 0.4 g/mi, and HC emissions to 0.25 g/mi. These bounds amounted to a 60 and 40 percent reduction respectively from the EPA Tier 0 standard set in 1981. For light-duty trucks, this standard set emissions at 0.4 to 1.1 g/mi for $NO_x$, and 0.25 to 0.39 g/mi for HCs, depending on the weight of the truck. Emission reductions were met through the use of more advanced emission control systems applied to light-duty gasoline vehicles beginning in

1994. These advanced emission control systems included advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

*EPA Tier 2*

This emission standard was specified in the 1990 amendments to the Clean Air Act, limiting passenger car $NO_x$ emissions to 0.07 g/mi on average and aligning emissions standards for passenger cars and light-duty trucks. Manufacturers can meet this average emission level by producing vehicles in eleven emission "Bins," the three highest of which expired in 2006. These emission standards represent a 77 to 95 percent reduction in emissions from the EPA Tier 1 standard set in 1994. Emission reductions were met via more advanced emission control systems and lower sulfur fuels and applied to vehicles beginning in 2004. These advanced emission control systems include improved combustion, advanced three-way catalysts, electronically controlled fuel injection and ignition timing, EGR, and air injection.

*EPA Tier 3*

These standards begin in 2017 and will fully phase-in by 2025, although some Tier 3-compliant vehicles were produced prior to 2017. This emission standard reduces both tailpipe and evaporative emissions from passenger cars, light-duty trucks, medium-duty passenger vehicles, and some heavy-duty vehicles. It is combined with a gasoline sulfur standard that will enable more stringent vehicle emissions standards and will make emissions control systems more effective.

*CARB Low Emission Vehicles (LEV)*

This emission standard requires a much higher emission control level than the Tier 1 standard. Applied to light-duty gasoline passenger cars and trucks beginning in small numbers in the mid-1990s, LEV includes multi-port fuel injection with adaptive learning, an advanced computer diagnostics systems and advanced and close coupled catalysts with secondary air injection. LEVs as defined here include transitional low-emission vehicles (TLEVs), low emission vehicles, ultra-low emission vehicles (ULEVs). In this analysis, all categories of LEVs are treated the same given there are limited $CH_4$ or $N_2O$ emission factor data for LEVs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

*CARB LEVII*

This emission standard builds upon ARB's LEV emission standards. They represent a significant strengthening of the emission standards and require light trucks under 8500 lbs. gross vehicle weight to meet passenger car standards. It also introduces a super ultra-low vehicle (SULEV) emission standard. The LEVII standards decreased emission requirements for LEV and ULEV vehicles as well as increasing the useful life of the vehicle to 150,000. These standards began with 2004 vehicles. In this analysis, all categories of LEVIIs are treated the same given there are limited $CH_4$ or $N_2O$ emission factor data for LEVIIs to distinguish among the different types of vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

*CARB LEVIII*

These standards begin in 2015 and are fully phased in by 2025, although some LEVIII-compliant vehicles were produced prior to 2017. LEVIII set new vehicle emissions standards and lowered the sulfur content of gasoline, considering the vehicle and its fuel as an integrated system. These new tailpipe standards apply to all light-duty vehicles, medium duty, and some heavy-duty vehicles. Zero emission vehicles (ZEVs) are incorporated into the alternative fuel and advanced technology vehicle assessments.

## Diesel Emission Controls

Below are the three levels of emissions control for diesel vehicles.

**Moderate control**

Improved injection timing technology and combustion system design for light- and heavy-duty diesel vehicles (in place in model years 1983 to 1995) are considered moderate control technologies. These controls were implemented to meet emission standards for diesel trucks and buses adopted by the EPA in 1985 to be met in 1991 and 1994.

**Advanced control**

EGR and modern electronic control of the fuel injection system are designated as advanced control technologies. These technologies provide diesel vehicles with the level of emission control necessary to comply with standards in place from 1996 through 2006.

**Aftertreatment**

Use of diesel particulate filters (DPFs), oxidation catalysts and $NO_x$ absorbers or selective catalytic reduction (SCR) systems are designated as aftertreatment control. These technologies provide diesel vehicles with a level of emission control necessary to comply with standards in place from 2007 on.

## Supplemental Information on Greenhouse Gas Emissions from Transportation and Other Mobile Sources

This section of this Annex includes supplemental information on the contribution of transportation and other mobile sources to U.S. greenhouse gas emissions. In the main body of the *Inventory* report, emission estimates are presented by greenhouse gas, with separate discussions of the methodologies used to estimate $CO_2$, $N_2O$, $CH_4$, and HFC emissions. The purpose of this sub-annex, within the Annex that details the calculation methods and data used for non-$CO_2$ calculations, is to consolidate all transportation estimates presented throughout the report.

This section of this Annex reports total greenhouse gas emissions from transportation and other (non-transportation) mobile sources in $CO_2$ equivalents, with information on the contribution by greenhouse gas and by mode, vehicle type, and fuel type. Additional analyses were conducted to develop estimates of $CO_2$ from non-transportation mobile sources (e.g., agricultural equipment, construction/mining equipment, recreational vehicles), and to provide more detailed breakdowns of emissions by source.

**Estimation of $CO_2$ from Non-Transportation Mobile Sources**

The estimates of $N_2O$ and $CH_4$ from fuel combustion presented in the Energy chapter of the *Inventory* include both transportation sources and other mobile sources. Other mobile sources include construction/mining equipment, agricultural equipment, vehicles used off-road, and other sources that have utility associated with their movement but do not have a primary purpose of transporting people or goods (e.g., snowmobiles, riding lawnmowers, etc.). Estimates of $CO_2$ from non-transportation mobile sources, based on EIA fuel consumption estimates, are included in the industrial and commercial sectors of the *Inventory*. In order to provide comparable information on transportation and mobile sources, Table A-89 provides estimates of $CO_2$ from these other mobile sources, developed from the Nonroad component of EPA's MOVES5 model and FHWA's Highway Statistics. These other mobile source estimates were developed using the same fuel consumption data utilized in developing the $N_2O$ and $CH_4$ estimates (see Table A-79). Note that the method used to estimate fuel consumption volumes for $CO_2$ emissions from non-transportation mobile sources for the supplemental information presented in Table A-89, Table A-91, and Table A-92 differs from the method used to estimate fuel consumption volumes for $CO_2$ in the industrial and commercial sectors in this *Inventory*, which include $CO_2$ emissions from all non-transportation mobile sources (see Section 3.1 for a discussion of that methodology).

**Estimation of HFC Emissions from Transportation Sources**

In addition to $CO_2$, $N_2O$ and $CH_4$ emissions, transportation sources also result in emissions of HFCs. HFCs are emitted to the atmosphere during equipment manufacture and operation (because of component failure, leaks, and purges), as well as at servicing and disposal events. There are three categories of transportation-related HFC emissions: Mobile air-conditioning represents the emissions from air conditioning units in passenger cars, light-duty trucks, and heavy-duty vehicles; Comfort Cooling represents the emissions from air conditioning units in passenger trains and buses; and Refrigerated Transport represents the emissions from units used to cool freight during transportation Table A-90 below presents these HFC emissions. Table A-91 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

### Table A-89: $CO_2$ Emissions from Non-Transportation Mobile Sources (MMT $CO_2$ Eq.)[a]

| Fuel Type/ Vehicle Type | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agricultural Equipment[a] | 43.4 | 39.9 | 48.0 | 45.8 | 45.9 | 41.1 | 40.2 | 39.8 | 39.8 | 39.7 | 39.1 | 39.8 | 39.3 | 39.3 |
| Construction/Mining Equipment[b] | 48.9 | 57.4 | 62.9 | 65.9 | 61.1 | 57.0 | 60.0 | 65.1 | 68.2 | 70.3 | 65.1 | 69.5 | 72.7 | 73.2 |
| Other Sources[c] | 69.6 | 76.3 | 85.9 | 87.0 | 88.8 | 87.4 | 88.3 | 89.9 | 92.3 | 94.1 | 88.0 | 93.4 | 100.2 | 102.1 |
| **Total** | **161.9** | **173.6** | **196.8** | **198.7** | **195.9** | **185.6** | **188.4** | **194.8** | **200.3** | **204.1** | **192.2** | **202.8** | **212.2** | **214.6** |

### Table A-90: HFC Emissions from Transportation Sources (MMT $CO_2$ Eq.)

| Vehicle Type | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mobile AC** | **+** | **50.2** | **47.9** | **42.4** | **39.4** | **36.8** | **33.6** | **30.2** | **28.2** | **26.2** | **24.2** | **22.4** | **20.4** | **18.4** |
| Passenger Cars | + | 25.5 | 18.7 | 15.7 | 14.4 | 13.3 | 12.0 | 10.4 | 9.4 | 8.4 | 7.6 | 7.0 | 6.6 | 5.7 |
| Light-Duty Trucks | + | 23.3 | 26.6 | 24.1 | 22.4 | 20.9 | 19.2 | 17.5 | 16.4 | 15.4 | 14.2 | 13.0 | 11.4 | 10.4 |
| Heavy-Duty Vehicles | + | 1.5 | 2.7 | 2.6 | 2.6 | 2.6 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.4 | 2.3 |
| **Comfort Cooling for Trains and Buses** | **+** | **0.1** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.4** | **0.5** |
| School and Tour Buses | + | 0.1 | 0.4 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 |
| Transit Buses | + | + | + | + | + | + | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Rail | + | + | + | + | + | + | + | + | + | + | + | + | + | + |
| **Refrigerated Transport** | **+** | **0.8** | **3.9** | **4.4** | **4.9** | **5.4** | **5.9** | **6.4** | **6.9** | **7.4** | **7.9** | **8.4** | **8.8** | **9.0** |
| Medium- and Heavy-Duty Trucks | + | 0.4 | 2.0 | 2.3 | 2.5 | 2.6 | 2.8 | 3.0 | 3.2 | 3.4 | 3.6 | 3.8 | 3.9 | 3.9 |
| Rail | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Ships and Boats | + | 0.3 | 1.7 | 2.0 | 2.3 | 2.6 | 2.9 | 3.2 | 3.6 | 3.9 | 4.2 | 4.5 | 4.8 | 5.1 |
| **Total** | **+** | **51.1** | **52.3** | **47.3** | **44.7** | **42.6** | **39.9** | **37.0** | **35.5** | **34.0** | **32.5** | **31.2** | **29.6** | **27.9** |

+ Does not exceed 0.05 MMT $CO_2$ Eq.
Note: Totals may not sum due to independent rounding.

## Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Mode/Vehicle Type/Fuel Type

Table A-91 presents estimates of greenhouse gas emissions from an expanded analysis including all transportation and additional mobile sources, as well as emissions from electricity generation by the consuming category, in $CO_2$ equivalents. In total, transportation and non-transportation mobile sources emitted 2,049.1 MMT $CO_2$ Eq. in 2023, an increase of 21 percent from 1990.[57] Transportation sources account for 1,827.5 MMT $CO_2$ Eq.

[57] Recommended Best Practice for Quantifying Speciated Organic Gas Emissions from Aircraft Equipped with Turbofan, Turbojet and Turboprop Engines," EPA-420-R-09-901, May 27, 2009 (see https://www.epa.gov/regulations-emissions-vehicles-and-engines/organic-gas-speciation-profile-aircraft).

while non-transportation mobile sources account for 221.7 MMT $CO_2$ Eq. These estimates include HFC emissions for mobile AC, comfort cooling for trains and buses, and refrigerated transport. These estimates were generated using the estimates of $CO_2$ emissions from transportation sources reported in Section 3.1 $CO_2$ Emissions from Fossil Fuel Combustion, and $CH_4$ emissions and $N_2O$ emissions reported in the Mobile Combustion section of the Energy chapter; information on HFCs from mobile air conditioners, comfort cooling for trains and buses, and refrigerated transportation from the Substitution of Ozone Depleting Substances section of the IPPU chapter; and estimates of $CO_2$ emitted from non-transportation mobile sources reported in Table A-89 above.

Although all emissions reported here are based on estimates reported throughout this *Inventory*, some additional calculations were performed to provide a detailed breakdown of emissions by mode and vehicle category. In the case of $N_2O$ and $CH_4$, additional calculations were performed to develop emission estimates by type of aircraft and type of heavy-duty vehicle (i.e., medium- and heavy-duty trucks or buses) to match the level of detail for $CO_2$ emissions. $N_2O$ estimates for both jet fuel and aviation gasoline, and $CH_4$ estimates for aviation gasoline were developed for individual aircraft types by multiplying the emissions estimates for each fuel type (jet fuel and aviation gasoline) by the portion of fuel used by each aircraft type (from FAA 2024 and DLA 2022). Emissions of $CH_4$ from jet fuels are no longer considered to be emitted from aircraft gas turbine engines burning jet fuel A at higher power settings. This update applies to the entire time series.[58] Recent research indicates that modern aircraft jet engines are typically net consumers of methane (Santoni et al. 2011). Methane is emitted at low power and idle operation, but at higher power modes aircraft engines consume methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, $CH_4$ emission factors for jet aircraft were reported as zero to reflect the latest emissions testing data.

Similarly, $N_2O$ and $CH_4$ estimates were developed for medium- and heavy-duty trucks by multiplying the emission estimates for heavy-duty vehicles for each fuel type (gasoline, diesel) from the Mobile Combustion section in the Energy chapter, by the portion of fuel used by each vehicle type (from DOE 1993 through 2022). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from the Nonroad component of EPA's MOVES5 model (EPA 2024). Otherwise, the table and figure are drawn directly from emission estimates presented elsewhere in the *Inventory*, and are dependent on the methodologies presented in Annex 2.1 (for $CO_2$), Chapter 4, and Annex 3.10 (for HFCs), and earlier in this Annex (for $CH_4$ and $N_2O$).

Transportation sources include on-road vehicles, aircraft, boats and ships, rail, and pipelines (note: pipelines are a transportation source but are stationary, not mobile, emissions sources). In addition, transportation-related greenhouse gas emissions also include HFC released from mobile air-conditioners and refrigerated transport, and the release of $CO_2$ from lubricants (such as motor oil) used in transportation. Together, transportation sources were responsible for 1,827.5 MMT $CO_2$ Eq. in 2023.

On-road vehicles were responsible for about 73 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2023. Although light-duty vehicles make up the largest component of on-road vehicle greenhouse gas emissions, medium- and heavy-duty trucks have been the primary sources of growth in on-road vehicle emissions. Greenhouse gas emissions from passenger cars decreased 54 percent between 1990 and 2023. Greenhouse gas emissions from light-duty trucks increased by 151 percent between 1990 and 2023. Overall, between 1990 and 2023, greenhouse gas emissions from passenger cars and light-duty trucks together increased by 8.5 percent. Greenhouse gas emissions from medium- and heavy-duty trucks increased 81 percent between 1990 and 2023, reflecting the increased volume of total freight movement and an increasing share of freight transported by trucks.

Greenhouse gas emissions from aircraft decreased 4 percent between 1990 and 2023. Emissions from military aircraft decreased 66 percent between 1990 and 2023. Commercial aircraft emissions increased 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, dropped another 33 percent from 2019 to 2020,

[58] VMT is allocated to vehicle classes using MOVES5 ratios of VMT in each vehicle class to total VMT.

followed by an increase of 42 percent from 2020 to 2023. Overall, this represents a change of approximately 18 percent between 1990 and 2023.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 221.7 MMT $CO_2$ Eq. in 2023. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased, growing approximately 34 percent between 1990 and 2023. Methane and $N_2O$ emissions from these sources are included in the "Mobile Combustion" section and $CO_2$ emissions are included in the relevant economic sectors.

## Contribution of Transportation and Mobile Sources to Greenhouse Gas Emissions, by Gas

Table A-92 presents estimates of greenhouse gas emissions from transportation and other mobile sources broken down by greenhouse gas. As this table shows, $CO_2$ accounts for most transportation greenhouse gas emissions (approximately 98 percent in 2023). Emissions of $CO_2$ from transportation and mobile sources increased by 357 MMT $CO_2$ Eq. between 1990 and 2023. In contrast, the combined emissions of $CH_4$ and $N_2O$ decreased by 26.2 MMT $CO_2$ Eq. over the same period, due largely to the introduction of emission control technologies designed to reduce criteria pollutant emissions.[59] HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 27.9 MMT $CO_2$ Eq. in 2023 as these chemicals were phased in as substitutes for ozone depleting substances. It should be noted, however, that the ozone depleting substances that HFCs replaced are also powerful greenhouse gases but are not included in national greenhouse gas inventories per national inventory reporting standards.

## Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A-93 and Table A-94 present greenhouse gas estimates from transportation, broken down into the passenger and freight categories. Passenger modes include light-duty vehicles, buses, passenger rail, aircraft (general aviation and commercial aircraft), recreational boats, and mobile air conditioners, and are illustrated in Table A-93. Freight modes include medium- and heavy-duty trucks, freight rail, refrigerated transport, waterborne freight vessels, pipelines, and commercial aircraft and are illustrated in Table A-94. Commercial aircraft do carry some freight, in addition to passengers, and emissions have been split between passenger and freight transportation. The amount of commercial aircraft emissions allocated to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned (DOT 1991 through 2025). Each passenger was considered to weigh an average of 150 pounds, with a luggage weight of 50 pounds. The total freight weight and total passenger weight carried were used to determine percent shares which were used to split the total commercial aircraft emission estimates. The remaining transportation and mobile emissions were from sources not considered to be either freight or passenger modes (e.g., construction/mining and agricultural equipment, lubricants).

The estimates in these tables are derived from the estimates presented in Table A-91. In addition, estimates of fuel consumption from DOE (1993 through 2022) were used to allocate rail emissions between passenger and freight categories.

In 2023, passenger transportation modes emitted 1,232.0 MMT $CO_2$ Eq., while freight transportation modes emitted 575.1 MMT $CO_2$ Eq. Between 1990 and 2023, the percentage growth of greenhouse gas emissions from freight sources was 62 percent. Emissions from passenger sources increased by 10 percent from 1990 to 2023. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

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[59] The decline in CFC emissions is not captured in the official transportation estimates.

## Table A-91: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT $CO_2$ Eq.)

| Mode / Vehicle Type / Fuel Type | 1990 | 2000 | 2010 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | % of total | % Change 1990 - 2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Transportation Total[a]** | **1,523.9** | **1,910.0** | **1,801.9** | **1,752.5** | **1,787.3** | **1,795.6** | **1,830.7** | **1,848.2** | **1,878.2** | **1,878.5** | **1,628.8** | **1,809.5** | **1,808.6** | **1,827.5** | **90%** | **19%** |
| **On-Road Vehicles** | **1,201.4** | **1,550.9** | **1,510.0** | **1,462.1** | **1,510.9** | **1,507.5** | **1,531.0** | **1,537.1** | **1,559.6** | **1,548.0** | **1,373.2** | **1,495.1** | **1,474.6** | **1,490.1** | **73%** | **24%** |
| **Passenger Cars** | **658.7** | **610.6** | **501.8** | **407.9** | **416.4** | **405.6** | **406.0** | **391.2** | **383.9** | **372.7** | **309.6** | **325.4** | **307.3** | **303.3** | **15%** | **-54%** |
| Gasoline[b] | 648.8 | 579.2 | 474.2 | 389.7 | 399.2 | 389.3 | 391.2 | 378.2 | 372.0 | 361.7 | 300.0 | 316.2 | 298.4 | 295.1 | **14%** | **-55%** |
| Diesel[b] | 9.9 | 5.9 | 2.6 | 2.6 | 2.8 | 3.0 | 2.8 | 2.6 | 2.5 | 2.5 | 2.0 | 2.0 | 1.9 | 1.8 | **0%** | **-82%** |
| AFVs[c] | + | + | + | + | + | + | + | + | + | 0.1 | 0.1 | 0.2 | 0.4 | 0.7 | **0%** | **13782%** |
| HFCs from Mobile AC | - | 25.5 | 25.0 | 15.7 | 14.4 | 13.3 | 12.0 | 10.4 | 9.4 | 8.4 | 7.6 | 7.0 | 6.6 | 5.7 | **0%** | **NA** |
| **Light-Duty Trucks** | **289.7** | **571.4** | **624.8** | **669.3** | **693.7** | **693.8** | **711.7** | **717.0** | **733.3** | **729.8** | **636.9** | **705.8** | **704.5** | **726.2** | **35%** | **151%** |
| Gasoline[b] | 281.3 | 528.3 | 565.8 | 614.2 | 639.8 | 640.1 | 659.7 | 666.6 | 684.0 | 681.0 | 595.1 | 663.4 | 663.3 | 686.0 | **33%** | **144%** |
| Diesel[b] | 8.2 | 19.7 | 27.9 | 30.8 | 31.2 | 32.4 | 32.4 | 32.3 | 32.0 | 32.3 | 26.6 | 28.1 | 28.2 | 27.8 | **1%** | **239%** |
| AFVs[c] | 0.1 | 0.1 | + | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.9 | 1.1 | 1.0 | 1.3 | 1.7 | 2.0 | **0%** | **1283%** |
| HFCs from Mobile AC | - | 23.3 | 31.0 | 24.1 | 22.4 | 20.9 | 19.2 | 17.5 | 16.4 | 15.4 | 14.2 | 13.0 | 11.4 | 10.4 | **1%** | **NA** |
| **Medium- and Heavy-Duty Trucks** | **236.6** | **345.5** | **360.4** | **359.2** | **373.3** | **379.9** | **384.4** | **398.8** | **411.1** | **414.0** | **400.3** | **434.6** | **430.2** | **427.6** | **21%** | **81%** |
| Gasoline[b] | 43.0 | 36.4 | 24.4 | 22.9 | 24.5 | 24.9 | 26.8 | 28.4 | 30.3 | 31.7 | 29.7 | 34.9 | 35.9 | 36.4 | **2%** | **-15%** |
| Diesel[b] | 192.2 | 306.7 | 331.4 | 330.9 | 343.2 | 349.4 | 351.8 | 364.5 | 374.2 | 375.5 | 363.9 | 392.9 | 387.3 | 384.4 | **19%** | **100%** |
| AFVs[c] | 1.3 | 0.5 | 0.2 | 0.4 | 0.4 | 0.5 | 0.6 | 0.5 | 0.9 | 0.9 | 0.6 | 0.7 | 0.7 | 0.7 | **0%** | **-47%** |
| HFCs from Refrigerated Transport and Mobile AC[e] | - | 1.9 | 4.4 | 4.9 | 5.1 | 5.2 | 5.3 | 5.4 | 5.6 | 5.8 | 6.1 | 6.3 | 6.3 | 6.1 | **0.0** | **NA** |
| **Buses** | **13.1** | **19.3** | **16.8** | **19.2** | **21.0** | **21.9** | **22.1** | **23.4** | **24.5** | **24.8** | **20.2** | **22.3** | **24.4** | **24.4** | **1%** | **86%** |
| Gasoline[b] | 5.3 | 3.4 | 1.5 | 2.0 | 2.3 | 2.4 | 2.6 | 3.1 | 3.5 | 3.6 | 3.1 | 3.6 | 3.9 | 4.1 | **0%** | **-22%** |
| Diesel[b] | 7.8 | 15.4 | 14.5 | 16.4 | 17.7 | 18.4 | 18.2 | 19.0 | 20.2 | 20.4 | 16.4 | 18.1 | 19.6 | 19.4 | **1%** | **149%** |
| AFVs[c] | + | 0.4 | 0.4 | 0.5 | 0.6 | 0.8 | 0.9 | 0.9 | 0.5 | 0.4 | 0.3 | 0.3 | 0.4 | 0.5 | **0%** | **5287%** |
| HFCs from Comfort Cooling | - | 0.1 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | **0%** | **NA** |
| **Motorcycles** | **3.3** | **4.2** | **6.2** | **6.7** | **6.8** | **6.6** | **6.9** | **6.9** | **7.0** | **6.8** | **6.2** | **7.0** | **8.3** | **8.7** | **0%** | **159%** |
| Gasoline[b] | 3.3 | 4.2 | 6.2 | 6.7 | 6.8 | 6.6 | 6.9 | 6.9 | 7.0 | 6.8 | 6.2 | 7.0 | 8.3 | 8.7 | **0%** | **159%** |
| **Aircraft** | **188.8** | **199.1** | **154.6** | **149.8** | **151.0** | **160.3** | **168.8** | **174.6** | **175.3** | **183.4** | **123.0** | **155.4** | **167.8** | **181.9** | **9%** | **-4%** |
| **General Aviation Aircraft** | **42.0** | **35.3** | **26.3** | **23.3** | **20.5** | **26.5** | **34.8** | **32.9** | **32.4** | **33.3** | **19.2** | **22.8** | **24.5** | **39.5** | **2%** | **-6%** |
| Jet Fuel[f] | 38.8 | 32.7 | 24.4 | 21.7 | 19.0 | 25.0 | 33.3 | 31.5 | 30.8 | 31.7 | 17.8 | 21.3 | 22.9 | 38.0 | **2%** | **-2%** |
| Aviation Gasoline | 3.2 | 2.6 | 1.9 | 1.6 | 1.5 | 1.5 | 1.5 | 1.5 | 1.6 | 1.7 | 1.4 | 1.5 | 1.6 | 1.5 | **0%** | **-53%** |
| **Commercial Aircraft** | **110.8** | **140.5** | **114.2** | **115.2** | **116.1** | **120.0** | **121.4** | **129.0** | **130.7** | **137.8** | **92.0** | **120.0** | **130.8** | **130.8** | **6%** | **18%** |
| Jet Fuel[f] | 110.8 | 140.5 | 114.2 | 115.2 | 116.1 | 120.0 | 121.4 | 129.0 | 130.7 | 137.8 | 92.0 | 120.0 | 130.8 | 130.8 | **6%** | **18%** |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Military Aircraft** | **36.0** | **23.3** | **14.0** | **11.3** | **14.4** | **13.9** | **12.6** | **12.6** | **12.2** | **12.3** | **11.8** | **12.6** | **12.5** | **11.6** | **1%** | **-68%** |
| Jet Fuel[f] | 36.0 | 23.3 | 14.0 | 11.3 | 14.4 | 13.9 | 12.6 | 12.6 | 12.2 | 12.3 | 11.8 | 12.6 | 12.5 | 11.6 | **1%** | **-68%** |
| **Ships and Boats[d]** | **47.0** | **65.9** | **45.0** | **39.7** | **29.1** | **33.8** | **40.7** | **43.8** | **41.1** | **40.0** | **32.2** | **50.7** | **49.9** | **43.8** | **2%** | **-7%** |
| Gasoline | 14.4 | 14.5 | 11.8 | 10.9 | 10.7 | 10.7 | 10.7 | 10.8 | 10.9 | 10.9 | 10.0 | 10.8 | 11.0 | 11.0 | **1%** | **-24%** |
| Distillate Fuel | 9.8 | 17.4 | 11.3 | 11.5 | 10.2 | 16.2 | 14.0 | 13.1 | 12.5 | 10.6 | 10.6 | 10.9 | 11.0 | 10.9 | **1%** | **12%** |
| Residual Fuel[e] | 22.8 | 33.6 | 20.7 | 15.3 | 5.9 | 4.3 | 13.1 | 16.6 | 14.2 | 14.6 | 7.4 | 24.5 | 23.1 | 16.8 | **1%** | **-26%** |
| HFCs from Refrigerated Transport[e] | + | 0.3 | 1.2 | 2.0 | 2.3 | 2.6 | 2.9 | 3.2 | 3.6 | 3.9 | 4.2 | 4.5 | 4.8 | 5.1 | **0%** | **NA** |
| **Rail** | **39.0** | **46.6** | **44.0** | **44.4** | **46.2** | **44.0** | **40.2** | **41.3** | **42.5** | **39.7** | **34.2** | **35.5** | **35.6** | **33.8** | **2%** | **-13%** |
| Distillate Fuel[f] | 35.8 | 42.9 | 39.3 | 40.1 | 41.9 | 40.0 | 36.5 | 37.7 | 38.9 | 36.3 | 31.5 | 32.8 | 32.8 | 31.2 | **2%** | **-13%** |
| Electricity | 3.1 | 3.5 | 4.5 | 4.1 | 4.1 | 3.8 | 3.5 | 3.4 | 3.4 | 3.2 | 2.5 | 2.5 | 2.5 | 2.5 | **0%** | **-19%** |
| Other Emissions from Rail Electricity Use[g] | 0.1 | + | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | **0%** | **9%** |
| HFCs from Comfort Cooling | - | + | + | + | + | + | + | + | + | + | + | + | + | + | **0%** | **NA** |
| HFCs from Refrigerated Transport[e] | - | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | + | **0%** | **NA** |
| **Pipelines[h]** | **36.0** | **35.5** | **37.9** | **46.8** | **39.9** | **39.1** | **39.7** | **41.9** | **50.5** | **58.5** | **58.5** | **64.9** | **72.0** | **71.3** | **3%** | **98%** |
| Natural Gas | 36.0 | 35.5 | 37.9 | 46.8 | 39.9 | 39.1 | 39.7 | 41.9 | 50.5 | 58.5 | 58.5 | 64.9 | 72.0 | 71.3 | **3%** | **98%** |
| **Other Transportation** | **11.8** | **12.1** | **10.4** | **9.6** | **10.0** | **11.0** | **10.4** | **9.6** | **9.2** | **8.8** | **7.8** | **8.0** | **8.7** | **6.6** | **0%** | **-45%** |
| Lubricants | **11.8** | **12.1** | **10.4** | **9.6** | **10.0** | **11.0** | **10.4** | **9.6** | **9.2** | **8.8** | **7.8** | **8.0** | **8.7** | **6.6** | **0%** | **-45%** |
| **Non-Transportation Mobile[i] Total** | **166.9** | **179.1** | **205.3** | **205.6** | **202.8** | **192.0** | **194.9** | **201.4** | **207.0** | **210.9** | **198.7** | **209.5** | **2192** | **221.7** | **11%** | **34%** |
| **Agricultural Equipment[i,j]** | **44.7** | **41.1** | **48.1** | **47.3** | **47.4** | **42.4** | **41.4** | **41.1** | **41.1** | **40.9** | **40.3** | **41.0** | **40.5** | **40.5** | **2%** | **-9%** |
| Gasoline | 7.5 | 6.0 | 6.2 | 5.8 | 5.7 | 1.4 | 1.5 | 1.5 | 1.4 | 1.1 | 1.2 | 1.3 | 1.3 | 1.3 | **0%** | **-82%** |
| Diesel | 37.2 | 35.0 | 41.8 | 41.4 | 41.6 | 40.9 | 39.8 | 39.5 | 39.6 | 39.7 | 39.0 | 39.6 | 39.1 | 39.1 | **2%** | **6%** |
| CNG | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | **0%** | **-14%** |
| LPG | + | + | + | + | + | + | + | + | + | + | + | + | + | + | **0%** | **-10%** |
| **Construction/Mining Equipment[i,k]** | **50.2** | **58.9** | **67.1** | **67.8** | **62.9** | **58.6** | **61.6** | **66.9** | **70.0** | **72.2** | **66.9** | **71.4** | **74.6** | **75.1** | **4%** | **51%** |
| Gasoline | 4.4 | 3.3 | 6.1 | 9.9 | 6.4 | 3.3 | 3.4 | 3.4 | 3.5 | 3.5 | 3.5 | 3.3 | 2.6 | 2.6 | **0%** | **-40%** |
| Diesel | 45.4 | 55.1 | 60.5 | 57.5 | 56.1 | 54.8 | 57.8 | 63.0 | 66.0 | 68.2 | 62.9 | 67.6 | 71.5 | 72.4 | **4%** | **59%** |
| CNG | 0.3 | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.4 | 0.4 | 0.4 | **0%** | **31%** |
| LPG | 0.1 | 0.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.2 | 0.2 | 0.1 | 0.2 | 0.2 | 0.2 | **0%** | **27%** |
| **Other Equipment[i,l]** | **71.9** | **79.1** | **90.1** | **90.5** | **92.4** | **90.9** | **91.8** | **93.5** | **96.0** | **97.9** | **91.6** | **97.0** | **104.1** | **106.1** | **5%** | **48%** |
| Gasoline | 40.5 | 43.2 | 50.0 | 46.8 | 47.5 | 45.6 | 46.1 | 46.5 | 47.1 | 47.5 | 45.3 | 47.2 | 49.4 | 49.6 | **2%** | **23%** |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Diesel | 21.9 | 21.6 | 25.7 | 28.5 | 29.4 | 29.6 | 29.8 | 30.5 | 31.7 | 32.5 | 29.8 | 32.1 | 35.0 | 36.0 | **2%** | **65%** |
| CNG | 1.2 | 1.4 | 1.7 | 2.1 | 2.2 | 2.2 | 2.1 | 2.2 | 2.3 | 2.4 | 2.2 | 2.3 | 2.5 | 2.6 | **0%** | **123%** |
| LPG | 8.3 | 12.9 | 12.8 | 13.1 | 13.3 | 13.5 | 13.7 | 14.3 | 15.0 | 15.5 | 14.3 | 15.4 | 17.1 | 17.8 | **1%** | **116%** |
| **Transportation and Non-Transportation Mobile Total**[l] | **1,690.8** | **2,089.0** | **2,007.2** | **1,958.3** | **1,990.2** | **1,987.8** | **2,025.6** | **2,049.6** | **2,085.2** | **2,089.4** | **1,827.6** | **2,019.0** | **2,027.9** | **2,049.3** | **100%** | **21%** |

+ Does not exceed 0.05 MMT $CO_2$ Eq.

NA (Not Applicable), as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

[a] Not including emissions from international bunker fuels.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop $CO_2$ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. MOVES5 ratios of fuel use by vehicle class to total fuel use are used to allocate fuel consumption between each on-road vehicle class. For mobile $CH_4$ and $N_2O$ emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). Total VMT estimates are allocated to vehicle type using EPA's MOVES5 model ratios of VMT per vehicle class to total VMT.

[c] In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes were incorporated into this year's *Inventory* and apply to the 2003 to 2017 time period. For 2017 and later, estimates were made using available data (Browning 2022b).

[d] Fluctuations in emission estimates reflect data collection problems. Note that $CH_4$ and $N_2O$ from U.S. Territories are included in this value, but not $CO_2$ emissions from U.S. Territories, which are estimated separately in the section on U.S. Territories.

[e] Domestic residual fuel for ships and boats is estimated by taking the total amount of residual fuel and subtracting out an estimate of international bunker fuel use.

[f] Class II and Class III diesel consumption data for 2014 to 2023 is not available. Diesel consumption data for 2014 to 2023 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[g] Other emissions from electricity generation are a result of waste incineration (as the majority of municipal solid waste is combusted in "trash-to-steam" electricity generation plants), electrical transmission and distribution, and a portion of other process uses of carbonates (from pollution control equipment installed in electricity generation plants).

[h] Includes only $CO_2$ from natural gas used to power natural gas pipelines; does not include emissions from electricity use or non-$CO_2$ gases.

[i] Note that the method used to estimate $CO_2$ emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate $CO_2$ in the industrial and commercial sectors in the *Inventory*, which include $CO_2$ emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating $CO_2$ emissions from fossil fuel combustion in this *Inventory*).

[j] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[k] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.

[l] "Other" includes snowmobiles and other recreational equipment, logging equipment, lawn and garden equipment, railroad equipment, airport equipment, commercial equipment, and industrial equipment, as well as fuel consumption from trucks that are used off-road for commercial/industrial purposes.

Notes: Increases to $CH_4$ and $N_2O$ emissions from mobile combustion relative to previous *Inventories* are largely due to updates made to the Motor Vehicle Emissions Simulator (MOVES5) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series, as well as non-transportation mobile fuel consumption. See Section 3.1 $CH_4$ and $N_2O$ from Mobile Combustion for more detail. This year's *Inventory* uses the Nonroad component of MOVES5 for years 1999 through 2023. In 2016, historical confidential vehicle sales data were re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

### Table A-92: Transportation and Mobile Source Emissions by Gas (MMT $CO_2$ Eq.)

| Year | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | Percent Change 1990-2023 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $CO_2$ [a] | 1,645.7 | 1,981.3 | 1,869.2 | 1,881.5 | 1,917.7 | 1,919.0 | 1,960.7 | 1,988.7 | 2,026.9 | 2,033.8 | 1,776.5 | 1,968.3 | 1,979.0 | 2,002.6 | 22% |
| $N_2O$ | 37.8 | 49.8 | 27.4 | 25.8 | 24.3 | 22.7 | 21.8 | 20.8 | 19.7 | 18.7 | 16.0 | 16.8 | 16.5 | 16.2 | -57% |
| $CH_4$ | 7.2 | 6.7 | 3.5 | 3.4 | 3.2 | 3.2 | 3.1 | 3.0 | 2.9 | 2.8 | 2.5 | 2.5 | 2.6 | 2.5 | -65% |
| HFC | + | 51.1 | 52.3 | 47.3 | 44.7 | 42.6 | 39.9 | 37.0 | 35.5 | 34.0 | 32.5 | 31.2 | 29.6 | 27.9 | NA |
| **Total** [b] | **1,690.7** | **2,089.0** | **1,952.4** | **1,958.0** | **1,989.9** | **1,987.5** | **2,025.5** | **2,049.6** | **2,085.1** | **2,089.3** | **1,827.5** | **2,018.8** | **2,027.7** | **2,049.2** | **21%** |

+ Does not exceed 0.05 MMT $CO_2$ Eq.

NA (Not Applicable), as there were no HFC emissions allocated to the transport sector in 1990, and thus a growth rate cannot be calculated.

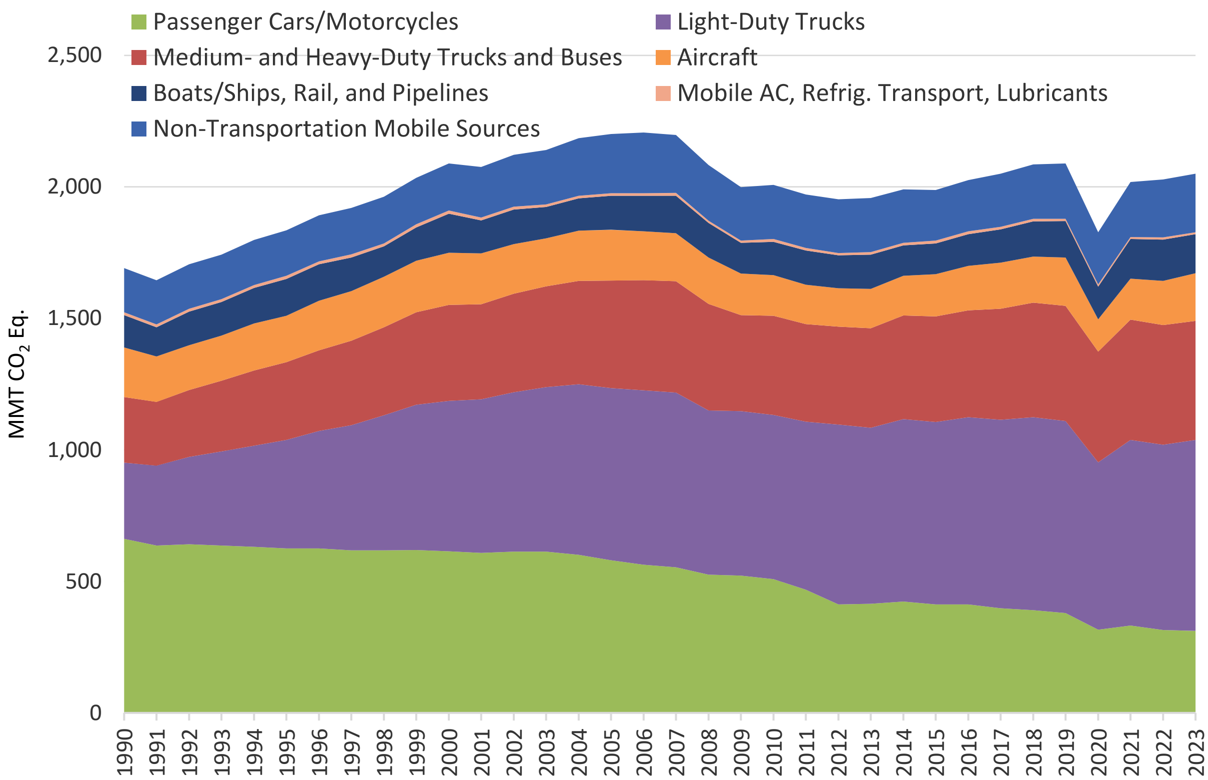
[a] The method used to estimate $CO_2$ emissions from non-transportation mobile sources in this supplementary information table differs from the method used to estimate $CO_2$ in the industrial and commercial sectors in the *Inventory*, which include $CO_2$ emissions from all non-transportation mobile sources (see Section 3.1 for the methodology for estimating $CO_2$ emissions from fossil fuel combustion in this *Inventory*).

[b] Total excludes other emissions from electricity generation and $CH_4$ and $N_2O$ emissions from electric rail.

Notes: Gasoline and diesel highway vehicle fuel consumption estimates used to develop $CO_2$ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile $CH_4$ and $N_2O$ emissions estimates, gasoline and diesel highway vehicle miles travelled estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024). VMT estimates are allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES5 model.

In 2016, historical confidential vehicle sales data was re-evaluated to determine the engine technology assignments. First several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

**Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2023**



## Table A-93: Greenhouse Gas Emissions from Passenger Transportation (MMT $CO_2$ Eq.)

| Vehicle Type | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | % Change 90-23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **On-Road Vehicles[a,b]** | **964.8** | **1,205.5** | **1,114.8** | **1,103.1** | **1,137.9** | **1,127.9** | **1,146.8** | **1,138.5** | **1,148.7** | **1,134.2** | **972.9** | **1,060.5** | **1,044.5** | **1,062.6** | **10%** |
| Passenger Cars | 658.7 | 610.6 | 405.2 | 407.9 | 416.4 | 405.6 | 406.0 | 391.2 | 383.9 | 372.7 | 309.6 | 325.4 | 307.3 | 303.3 | -54% |
| Light-Duty Trucks | 289.7 | 571.4 | 683.7 | 669.3 | 693.7 | 693.8 | 711.7 | 717.0 | 733.3 | 729.8 | 636.9 | 705.8 | 704.5 | 726.2 | 151% |
| Buses | 13.1 | 19.4 | 18.9 | 19.3 | 21.0 | 21.9 | 22.1 | 23.4 | 24.5 | 24.8 | 20.2 | 22.3 | 24.3 | 24.4 | 86% |
| Motorcycles | 3.3 | 4.2 | 6.9 | 6.7 | 6.8 | 6.6 | 6.9 | 6.9 | 7.0 | 6.8 | 6.2 | 7.0 | 8.3 | 8.7 | 162% |
| **Aircraft** | **133.6** | **151.5** | **118.1** | **122.6** | **120.4** | **130.0** | **139.3** | **143.6** | **144.4** | **151.8** | **83.4** | **118.6** | **134.0** | **152.1** | **14%** |
| General Aviation | 42.0 | 35.3 | 19.6 | 23.3 | 20.5 | 26.5 | 34.8 | 32.9 | 32.4 | 33.3 | 19.2 | 22.8 | 24.5 | 39.5 | -6% |
| Commercial Aircraft | 91.6 | 116.1 | 98.5 | 99.4 | 99.9 | 103.5 | 104.6 | 110.6 | 112.0 | 118.5 | 64.2 | 95.8 | 109.5 | 112.6 | 23% |
| **Recreational Boats** | **17.2** | **17.3** | **13.7** | **13.4** | **13.2** | **13.3** | **13.4** | **13.6** | **13.7** | **13.8** | **12.7** | **13.6** | **13.9** | **13.9** | **-19%** |
| **Passenger Rail** | **4.4** | **5.2** | **5.5** | **5.8** | **5.7** | **5.4** | **5.2** | **5.1** | **4.5** | **4.2** | **3.6** | **3.6** | **3.7** | **3.4** | **-23%** |
| **Total** | **1,119.9** | **1,379.5** | **1,252.1** | **1,245.0** | **1,277.2** | **1,276.5** | **1,304.8** | **1,300.8** | **1,311.3** | **1,304.0** | **1,072.6** | **1,196.3** | **1,196.1** | **1,232.0** | **10%** |

Note: Totals may not sum due to independent rounding.

## Table A-94: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT $CO_2$ Eq.)

| By Mode | 1990 | 2000 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | % Change 90-23 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Trucking[a,b] | 236.6 | 344.0 | 350.9 | 356.6 | 370.6 | 377.3 | 381.7 | 396.2 | 408.5 | 411.4 | 397.9 | 432.2 | 427.8 | 425.3 | 80% |
| Freight Rail | 34.5 | 41.3 | 38.3 | 38.6 | 40.5 | 38.5 | 34.9 | 36.2 | 37.9 | 35.4 | 30.5 | 31.8 | 31.8 | 30.5 | -12% |
| Ships and Non-Recreational Boats | 29.8 | 48.5 | 26.6 | 26.3 | 15.9 | 20.5 | 27.3 | 30.3 | 27.4 | 26.3 | 19.5 | 37.0 | 36.0 | 29.9 | 0% |
| Pipelines[c] | 36.0 | 35.5 | 41.1 | 46.8 | 39.9 | 39.1 | 39.7 | 41.9 | 50.5 | 58.5 | 58.5 | 64.9 | 72.0 | 71.3 | 98% |
| Commercial Aircraft | 19.2 | 24.3 | 15.7 | 15.9 | 16.2 | 16.5 | 16.8 | 18.4 | 18.7 | 19.3 | 27.8 | 24.2 | 21.2 | 18.2 | -5% |
| **Total** | **356.0** | **493.7** | **472.6** | **484.1** | **483.1** | **491.9** | **500.4** | **522.9** | **543.0** | **551.0** | **534.2** | **590.1** | **588.9** | **575.1** | **62%** |

[a] The current *Inventory* includes updated vehicle population data based on the MOVES5 Model.

[b] Gasoline and diesel highway vehicle fuel consumption estimates used to develop $CO_2$ estimates in this *Inventory* are based on data from FHWA Highway Statistics Table MF-21, MF-27 and ratios developed from MOVES5 to apportion FHWA fuel consumption data to vehicle type and fuel type. For mobile $CH_4$ and $N_2O$ emissions estimates, gasoline and diesel highway vehicle mileage estimates are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2024) and

MOVES5 model ratios of VMT per vehicle class to total VMT.

[c] Pipelines reflect $CO_2$ emissions from natural gas-powered pipelines transporting natural gas.

Notes: Data from DOE (1993 through 2022) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. This year's *Inventory* uses the Nonroad component of MOVES5 for years 1999 through 2023. In 2017, estimates of alternative fuel vehicle mileage for the last ten years were revised to reflect updates made to EIA data on alternative fuel use and vehicle counts. These changes apply to the 2003 to 2017 time period. For 2017 and later, estimates were made using available data (Browning 2022b).

In 2016, historical confidential vehicle sales data were re-evaluated to determine the engine technology assignments. First, several light-duty trucks were re-characterized as heavy-duty vehicles based upon gross vehicle weight rating (GVWR) and confidential sales data. Second, the emission standards each vehicle type was assumed to have met were re-examined using confidential sales data. Also, in previous *Inventories*, non-plug-in hybrid electric vehicles (HEVs) were considered alternative fueled vehicles and therefore not included in the engine technology breakouts. For this *Inventory*, HEVs are classified as gasoline vehicles across the entire time series. Totals may not sum due to independent rounding.

## Motor Vehicle Emission Simulator (MOVES)

As noted in the preceding methodology discussion, EPA's MOtor Vehicle Emission Simulator (MOVES) is used to derive some of the activity data that are used as inputs to the calculation of greenhouse gas emissions in this *Inventory*. The model is not used to directly estimate greenhouse gas emissions. With respect to estimating $CO_2$ emissions from the transportation sector, MOVES is used to estimate fuel use by recreational boats and ratios developed from MOVES output are used to apportion FHWA fuel consumption data to vehicle type and fuel type. For non-$CO_2$ greenhouse gas emissions, MOVES is used to generate the age distribution and age-specific vehicle mileage accumulations for the U.S. vehicle fleet. Additionally, the Nonroad component of MOVES is used to estimate fuel consumption for gasoline- and diesel-powered equipment, and $CH_4$ and $N_2O$ emission factors for nonroad mobile sources are calculated from engine certification data and weighted by activity estimates calculated by MOVES. Finally, the Supplemental Information on Greenhouse Gas Emissions from Transportation and Other Mobile Sources section of this Annex provides estimates of $CO_2$ from non-transportation mobile sources, developed from the Nonroad component of MOVES.

The MOtor Vehicle Emission Simulator (EPA 2024) is EPA's state-of-the-science emission modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics. It is a bottom-up emissions model that is designed to estimate emissions from separate physical emission processes depending on the source. MOVES models “fleet average” emissions, rather than emissions from individual vehicles or nonroad equipment types, and MOVES adjusts emission rates to represent real-world conditions. The model covers onroad vehicles such as cars, trucks and buses, and nonroad equipment such as construction and lawn and garden equipment; it does not estimate emissions from aircraft, locomotives, and commercial marine vessels. MOVES accounts for the phase-in of federal emissions standards, vehicle and equipment activity, fuels, temperatures, humidity, and emission control activities such as inspection and maintenance programs for calendar years 1990 and 1999 through 2060. Emissions from onroad and nonroad sources can be modeled at the national or county scale using either model defaults or user-supplied inputs. Emissions from onroad sources can also be modeled at a more detailed “project” scale if the user supplies detailed inputs describing project parameters. The current *Inventory* uses output from MOVES5, which is the latest official version of MOVES. Previous versions of the model include MOVES4, MOVES3, MOVES2014 and MOVES2010.

MOVES is used by EPA to estimate emission impacts of mobile source regulations and policies, and to generate mobile sector information for national inventories of air pollutants such as the National Emissions Inventory and the Air Toxics Screening Assessment. U.S. state and local agencies use MOVES to develop emissions inventories for a variety of regulatory purposes, including the development of state implementation plans, transportation conformity determinations, general conformity evaluations, and analyses required under the National Environmental Policy Act. Others, including academics and interest groups, may also use MOVES to model the effects of policy choices and various mobile source scenarios.

The way MOVES calculates emissions varies depending on the processes and pollutants being modeled, and the vehicle or equipment type. MOVES includes the following emissions processes: running exhaust, start exhaust, hoteling (extended idle exhaust and auxiliary power exhaust), crankcase (running, start, and extended idle), brake wear, evaporative permeation, evaporative fuel vapor venting, evaporative fuel leaks, and refueling displacement vapor and spillage loss.

Running emissions are the archetypal mobile source emissions—exhaust emissions from a running vehicle. Running operation is defined as operation of internal-combustion engines after the engine and emission control systems have stabilized at operating temperature, i.e., “hot-stabilized” operation. The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. Regulatory classes define vehicles with similar emission standards, such as heavy heavy-duty regulatory classes, which may occur in vehicles classified in several different source types, such as long-haul combination, short-haul single-unit and refuse trucks. For each source bin, the model uses vehicle characteristics and activity data (VMT, speed, idle fractions and driving cycles) to estimate the source hours in each running operating mode. The running operating modes are defined by the vehicle’s instantaneous vehicle speed, acceleration, and estimated vehicle power. Each source bin and operating mode is associated with an emission rate, and these are multiplied by source hours, adjusted as needed, and summed to estimate the total running emissions. Depending on the vehicle characteristics, MOVES may adjust the running emissions to account for local fuel parameters, air conditioning effects, humidity, inspection and maintenance programs, and fuel economy adjustments.

Onroad “start” emissions are the instantaneous exhaust emissions occur at the engine start (e.g., due to the fuel rich conditions in the cylinder to initiate combustion) as well as the additional running exhaust emissions that occur because the engine and emission control systems have not yet stabilized at the running operating temperature. Operationally, start emissions are defined as the difference in emissions between an exhaust emissions test with an ambient temperature start and the same test with the engine and emission control systems already at operating temperature. As such, the units for start emission rates are instantaneous grams/start. The model uses vehicle population information to sort the vehicle population into source bins defined by vehicle source type, fuel type (gas, diesel, etc.), regulatory class, model year and age. The model uses default data from instrumented vehicles (or user-provided values) to estimate the number of starts for each source bin and to allocate them among eight operating mode bins defined by the amount of time parked (“soak time”) prior to the start. Thus, the model accounts for different amounts of cooling of the engine and emission control systems. Each source bin and operating mode has an associated g/start emission rate. Start emissions are also adjusted to account for fuel characteristics, inspection and maintenance programs, and ambient temperatures.

MOVES defines "hoteling" as any long period of time (e.g., > 1 hour) that drivers spend in their long-haul combination truck vehicles during mandated rest times. Hoteling is differentiated from off-network idling because the engines are often idling under load while hoteling (e.g., to maintain cabin climate or run accessories). MOVES computes hoteling emissions only for diesel long-haul combination trucks. The default MOVES hoteling hours are computed as a fixed ratio to the miles these trucks travel on restricted access roads. Hoteling activity is allocated among four operating modes: engine idle (“extended idle”), diesel auxiliary power unit use, battery, or plug-in, and “All Engines and Accessories Off.” This allocation varies by model year. MOVES computes emissions for the first two modes based on the hours and source-bin specific emission rates.

Crankcase emissions include combustion products that pass by the piston rings of a compression ignition engine as well as oil droplets from the engine components and engine crankcase that are vented to the atmosphere. In MOVES, onroad crankcase emissions are computed as a ratio to the exhaust emissions, with separate values for running, start and hoteling (extended idle mode only). The crankcase ratio varies by pollutant, source type, fuel type, model year and exhaust process.

MOVES estimates brake wear from on road vehicles using weighted average g/hour rates that consider brake pad composition, number and type of brakes and braking intensity. Brake pads lose material during braking. A portion of this lost material becomes airborne particulate matter. This “brake wear” differs from exhaust particulate matter in its size and chemical composition. The emission rates in MOVES vary by vehicle regulatory class to account for average vehicle weight. Braking activity is modeled as a portion of running activity. In MOVES, the running operating modes for braking, idling and coasting are all modeled as including some amount of braking.

Contact between tires and the road surface causes tires to wear, and a portion of this material becomes airborne. This tire wear differs from exhaust particulate matter in its size and chemical composition. MOVES tire wear rates in g/hr are based on analysis of light-duty vehicle tire wear rates as a function of vehicle speed, extrapolated to other vehicles based on the number and size of tires. The tire wear operating mode bins differ from those used for running emissions and brake wear because they account only for speed and not for acceleration.

Permeation is the migration of hydrocarbons through materials in the fuel system. Permeation emissions are strongly influenced by the materials used for fuel tank walls, hoses and seals, and by the temperature, vapor pressure and ethanol content of the fuel. In MOVES, permeation is estimated only for vehicles using gasoline-based fuels (including E-85). Permeation is estimated for every hour of the day, regardless of activity. Permeation rates in g/hour vary by model year to account for the phase-in of tighter standards. Permeation emissions are adjusted to account for gasoline fuel properties and ambient temperatures.

When gasoline fuel tank temperatures rise due to vehicle operation or increased ambient temperatures, hydrocarbon vapors are generated within the fuel tank. The escape of these vapors is called Tank Vapor Venting or

Evaporative Fuel Vapor Venting. This vapor venting may be eliminated with a fully sealed metal fuel tank. More commonly, venting is reduced by using an activated charcoal canister to adsorb the vapors as they are generated; vapors from the canister are later consumed during vehicle operation. However, to prevent pressure build-up, canisters are open to the atmosphere, and after several days without operating, fuel vapors can diffuse through the charcoal or pass freely through a completely saturated canister. Tampering, mal-maintenance, vapor leaks, and system failure can also result in excess vapor venting.

MOVES calculates vapor venting only for vehicles using gasoline-based fuels (including E-85). The tank vapor generated depends on the rise in fuel tank temperature, fuel vapor pressure, ethanol content and altitude. Fuel tank temperature changes are modeled as a function of 24-hour temperature patterns and default vehicle activity, with different vapor generation rates for vehicles that are operating, "hot soaking" (parked, but still warm) and "cold soaking" (parked at ambient temperature). Vapor venting is modeled as a function of vapor generated, days cold soaking, model-year specific vehicle fuel system characteristics, and age and model year related vapor leak rates.

Evaporative fuel leaks (liquid leaks) are fuels escaping the gasoline fuel system in a non-vapor form. In MOVES, they are referred to as evaporative fuel leaks because they subsequently evaporate into the atmosphere after escaping the vehicle. These leaks may occur due to failures with fuel system materials, or due to tampering or mal-maintenance. Liquid spillage during refueling is modeled separately as part of the refueling process. In MOVES, fuel leak frequency is estimated as a function of vehicle age and vehicle emission standards. Fuel leak size (g/hour) is a function of age and vehicle operating mode (cold soaking, hot soaking or operating).

Refueling emissions are the displaced fuel vapors when liquid fuel is added to the vehicle tank. Refueling spillage is the vapor emissions from any liquid fuel that is spilled during refueling and subsequently evaporates. Diesel vehicles are assumed to have negligible vapor displacement, but MOVES does compute emissions for onroad diesel fuel spillage. Refueling vapor and spillage emissions are estimated from the total volume of fuel dispensed (gallons). This volume is based on previously calculated fuel consumption. In addition, refueling emissions are a function of gasoline vapor pressure, ambient temperatures, the presence of an on-board refueling vapor recovery system on the vehicles, and the use of Stage II vapor recovery controls at the refueling pump.

The MOVES nonroad module estimates emissions as the product of an adjusted emission factor multiplied by rated power, load factor, engine population and activity. Starting with base-year equipment populations by technology type and model year, the model uses growth factors to estimate the population in the analysis year. Estimates of median life at full load, load factors, activity and age distributions are then combined to generate estimates of nonroad emissions by equipment type, fuel type and age. National equipment populations are allocated to the county level using surrogate data. The model uses estimates of annual activity for each equipment type, e.g., expressed in terms of hours of operations or gallons of fuel used per year, to calculate yearly emission inventories. MOVES will also calculate inventories on a seasonal (i.e., summer, fall, winter, spring), monthly, or daily (i.e., weekday or weekend day) basis by allocating annual activity to these smaller time periods. The MOVES nonroad module includes the following emissions processes: running exhaust, crankcase exhaust, refueling displacement vapor and spillage loss (gasoline only), fuel vapor venting (diurnal, hot soak, and running loss), and fuel system permeation (gasoline only).

The MOVES database contains the required emission factors, adjustment factors, fuel data, and default vehicle population and activity data for all U.S. counties to support model runs for calendar years 1990 and 1999–2060. User databases may contain any of the tables that are in the default input database and are used to add or replace records as input by the user. These databases typically contain region-specific fuels, vehicle populations, age distributions, activity, and where applicable, I/M program characteristics. Vehicle and equipment emissions vary by location and time. However, for the most accurate results for a given time and location, MOVES is run for a specific case using accurate local inputs. In contrast, the national results generated with model defaults are calculated based on average inputs that do not fully capture the variation in emissions from time to time and place to place. MOVES allows user input of many parameters, and therefore, the quality of model output will depend on the quality of these inputs, as well as the appropriateness of the model defaults relied on.

The MOVES model is subject to review and evaluation in several different ways, including: peer review, a stakeholder work group, beta testing, evaluation by an industry-funded research group, and comparisons to independent data.

Updates to MOVES model data and algorithms are regularly peer reviewed, following EPA's peer review policies and procedures. The peer review process encompasses the over two dozen technical reports (https://www.epa.gov/moves/moves-onroad-technical-reports and https://www.epa.gov/moves/nonroad-technical-reports) that document the model's default inputs and algorithms. Reviewer comments and EPA's responses to comments are available at https://cfpub.epa.gov/si/index.cfm.

The MOVES Review Work Group provides MOVES-related recommendations to EPA via the Mobile Sources Technical Review Subcommittee of the Clean Air Act Advisory Committee. Members of the work group represent a variety of stakeholders and mobile source emissions modeling experts, including vehicle and engine manufacturers, fuel producers, state and local emission modelers, academic researchers, environmental advocates, and affected federal agencies. Throughout the development of MOVES, the EPA presents ongoing analyses, model evaluation, and MOVES updates to the work group. Notes and presentations from past work group meetings are available at https://www.epa.gov/moves/moves-model-review-work-group.

Prior to public release, draft versions of the model are tested by a small group of experienced users who alert EPA to potential errors in the code and provide comments on new model features (e.g., updates to the graphical user interface, installer).

Although not conducted regularly, MOVES has been subject to review by the Coordinating Research Council (CRC), a non-profit corporation supported by the energy and mobility industries. The CRC's most recent review in 2014 included three distinct elements: (1) a critical evaluation of modeling methods, (2) inventory analyses applied to three locations, and (3) a validation of the fuel methodology using independent data sources. The resulting report provided detailed recommendations in 10 key areas. These recommendations helped to prioritize efforts for model development and EPA published a detailed response to the review (EPA 2016).

Evaluating the performance of the MOVES model in comparison to independent data is useful for assessing the model's performance in accurately estimating current emission inventories and forecasting emission trends. It also helps identify areas in need of improvement, guiding future work and research. However, it is not appropriate to evaluate MOVES with comparisons against measurements based only on a few vehicles, or without sufficiently customizing MOVES inputs to account for the measurement conditions (e.g., fleet composition, vehicle activity, meteorology).

One approach to assess the MOVES model's fidelity to real-world vehicle activity is to compare macro-scale/top-down gasoline and diesel fuel sales estimates with bottom-up fuel consumption modeled by MOVES. A study conducted by EPA (Han, 2021) compared fuel consumption estimated from MOVES3 output with national fuel sales data published by FHWA (FHWA Highway Statistics Table MF-27), for calendar years 2005, 2007, 2009, and 2011-2019. The study notes several limitations of the comparison, including: potential inaccuracies in state-level fuel tax data collected by FHWA, inconsistencies between MOVES and FHWA's methodology for allocating highway and off-road fuel use, uncertainties in MOVES activity estimates and fleet characterization (e.g., FHWA excludes "public" vehicles while MOVES includes these sources), and uncertainties in the average fuel energy content values used to convert MOVES total energy output to fuel consumption volumes. Given these limitations, the study found that overall, MOVES3 fuel consumption is higher than FHWA reported data. For calendar years 2016 and later, MOVES3 gasoline and diesel fuel consumption estimates are within 4 percent and 10 percent, respectively, of FHWA estimates. For earlier years, MOVES3 gasoline consumption estimates are within 9 percent of FHWA data while MOVES3 diesel fuel consumption is within 20 percent of FHWA reported values. Note that greater uncertainties exist in the diesel fuel volume data and methodology (e.g., many of the "public" vehicles that are excluded from FHWA fuel sales data but are included in MOVES are diesel-fueled vehicles such as refuse trucks and buses).

Past efforts to evaluate MOVES have prioritized comparisons for the major sources of emissions (e.g., light-duty gasoline, heavy-duty diesel) and local geographic areas where significant independent data are available. In assessing the results, systematic bias observed across multiple data sources was considered indicative of model underperformance. On the other hand, if the model predictions are within the variability of independent measurements, it gives confidence that the model is predicting real-world emissions reasonably well.

Evaluating MOVES emission rates may include comparisons to data from sources such as dynamometer tests, remote sensing devices and portable emission monitoring systems. To capture rare (but influential) high emitters, it is important that the data samples are large and diverse, and it is useful when the comparison data represent known operating conditions. Such controlled comparisons are particularly valuable because the emission rates from the study can be compared with MOVES emission rates using the same activity and fleet variables such as vehicle mix, vehicle age, and vehicle operating mode. EPA has undertaken several studies comparing MOVES emission rates with real-world measurements (e.g., Choi et al. (2017), U.S. EPA (2022)) and found that MOVES is generally within the variability of the measured data.

Other studies compare "localized composite" emissions, using composite emission measurements from many vehicles by tunnel or roadside emission monitors where vehicle emissions are predominant and vehicle activity and fleet mix can be accounted for to some degree. A strength of tunnel and roadside measurements is that they can capture the large sample sizes of vehicles operating in real-world conditions needed to measure "fleet-average" emission rates. However, such comparisons only assess the narrow operating conditions represented at the specific location.

At a more general level, some MOVES evaluations compare regional air quality model results from models such as the Community Multiscale Air Quality Modeling System with air quality monitor and deposition data and satellite data. These "top-down studies" are useful to assess the overall emissions contribution from all relevant emission sources to air quality measurements. Discrepancies between air quality modeling predictions and measurements can point to deficiencies in the emissions inventory but may be confounded with deficiencies in the air quality model (e.g., modeling transport, boundary layer, deposition, transformation, and other physical and chemical processes). In addition, top-down studies on their own cannot identify the individual sources in the emissions inventory that are responsible for the modeling discrepancy.

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## 3.3. Methodology for Estimating Emissions from Commercial Aircraft Jet Fuel Consumption

Activity data on civilian domestic and international aircraft fuel consumption for 2023 was not available at the time of this report. Therefore, data for 2023 was proxied based on 2022 data. The methodology used for estimating emissions from civilian international bunker fuels is consistent with previous Inventories. The 2023 data will be updated in future reports as needed.

## 3.4. Methodology for Estimating $CH_4$ Emissions from Coal Mining

EPA uses an IPCC Tier 3 method for estimating $CH_4$ emissions from underground mining and an IPCC Tier 2 method for estimating $CH_4$ emissions from surface mining and post-mining activities (for both coal production from underground mines and surface mines). The methodology for estimating $CH_4$ emissions from coal mining consists of two steps:

- **Estimate emissions from underground mines.** These emissions have two sources: ventilation systems and degasification systems. They are estimated using mine-specific data, then summed to determine total $CH_4$ liberated. The $CH_4$ recovered and used is then subtracted from this total, resulting in an estimate of net emissions to the atmosphere.
- **Estimate emissions from surface mines and post-mining activities.** This step does not use mine-specific data; rather, it consists of multiplying coal-basin-specific coal production by coal-basin-specific gas content and an emission factor.

### Step 1: Estimate $CH_4$ Liberated and $CH_4$ Emitted from Underground Mines

Underground mines generate $CH_4$ from ventilation systems and degasification systems. Some mines recover and use the generated $CH_4$, thereby reducing emissions to the atmosphere. Total $CH_4$ emitted from underground mines equals the $CH_4$ liberated from ventilation systems, plus the $CH_4$ liberated from degasification systems, minus $CH_4$ recovered and used.

#### Step 1.1: Estimate $CH_4$ Liberated from Ventilation Systems

All coal mines with detectable $CH_4$ emissions use ventilation systems to ensure that $CH_4$ levels remain within safe concentrations. Many coal mines do not have detectable levels of $CH_4$; others emit several million cubic feet per day (MMCFD) from their ventilation systems. On a quarterly basis, the U.S. Mine Safety and Health Administration (MSHA) measures $CH_4$ concentration levels at underground mines. MSHA maintains a database of measurement data from all underground mines with detectable levels of $CH_4$ in their ventilation air (MSHA 2024).[60] Based on quarterly measurements, MSHA estimates average daily $CH_4$ liberated at each of these underground mines.

For 1990 through 1999, average daily $CH_4$ emissions from MSHA were multiplied by the number of days in the year (i.e., coal mine assumed in operation for all four quarters) to determine the annual emissions for each mine. For 2000 through 2023, the average daily $CH_4$ emission rate for each mine is determined using the $CH_4$ total for all data measurement events conducted during the calendar year and total duration of all data measurement events (in days). The calculated average daily $CH_4$ emissions were then multiplied by 365 days to estimate annual ventilation emissions (or 366 in the case of a leap year).

Total ventilation emissions for a particular year are estimated by summing emissions from individual mines.

Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 cubic feet of $CH_4$ per year (about 17,525 MT $CO_2$ Eq.)—have been required to report to EPA's GHGRP (EPA 2024).[61] Mines that report to EPA's GHGRP must report quarterly measurements of $CH_4$ emissions from ventilation systems; they have the option of recording their own measurements, or using the measurements taken by MSHA as part of that agency's quarterly safety inspections of all mines in the U.S. with detectable $CH_4$ concentrations.

[60] MSHA records coal mine methane readings with concentrations of greater than 50 ppm (parts per million) methane. Readings below this threshold are considered non-detectable.
[61] Underground coal mines report to EPA under subpart FF of EPA's GHGRP (40 CFR Part 98). In 2023, 58 underground coal mines reported to the program.

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP[62] data submitted by underground mines, and on mine-specific $CH_4$ measurement data obtained directly from MSHA for the remaining mines. The $CH_4$ liberated from ventilation systems is estimated by summing the emissions from the mines reporting to EPA's GHGRP and emissions based on MSHA measurements for the remaining mines not reporting to EPA's GHGRP.

## Table A-95: Mine-Specific Data Used to Estimate Ventilation Emissions

| Year | Individual Mine Data Used |
|---|---|
| 1990 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 1991 | 1990 Emission Factors Used Instead of Mine-Specific Data |
| 1992 | 1990 Emission Factors Used Instead of Mine-Specific Data |
| 1993 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 1994 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 1995 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)[a] |
| 1996 | All Mines Emitting at Least 0.5 MMCFD (Assumed to Account for 94.1% of Total)[a] |
| 1997 | All Mines with Detectable Emissions (Assumed to Account for 100% of Total) |
| 1998 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 1999 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2000 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2001 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2002 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2003 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2004 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2005 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2006 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 97.8% of Total)[a] |
| 2007 | All Mines with Detectable Emissions (Assumed to Account for 100% of Total) |
| 2008 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)[b] |
| 2009 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)[b] |
| 2010 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)[b] |
| 2011 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)[b] |
| 2012 | All Mines Emitting at Least 0.1 MMCFD (Assumed to Account for 98.96% of Total)[b] |
| 2013 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2014 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2015 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2016 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2017 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2018 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2019 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2020 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2021 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2022 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |
| 2023 | All Mines with Detectable Emissions and GHGRP reported data (Assumed to account for 100% of Total) |

[a] Factor derived from a complete set of individual mine data collected for 1997.
[b] Factor derived from a complete set of individual mine data collected for 2007.

[62] In implementing improvements and integrating data from EPA's GHGRP, the EPA followed the latest guidance from the IPCC on the use of facility-level data in national inventories (IPCC 2011).

**Step 1.2: Estimate $CH_4$ Liberated from Degasification Systems**

Coal mines use several types of degasification systems to remove $CH_4$, including pre-mining vertical and horizontal wells (to recover $CH_4$ before mining) and post-mining vertical wells and horizontal boreholes (to recover $CH_4$ during mining of the coal seam). Post-mining gob wells and cross-measure boreholes recover $CH_4$ from the overburden (i.e., gob area) after mining of the seam (primarily in longwall mines).

Nineteen mines employed degasification systems in 2023, and all of these mines reported the $CH_4$ liberated through these systems to the EPA's GHGRP (EPA 2024). Eleven of the 19 mines with degasification systems had operational $CH_4$ recovery and use projects, including one mine with two recovery and use projects, and the other eight mines reported emitting $CH_4$ from degasification systems to the atmosphere. Several of the mines venting $CH_4$ from degasification systems use a small portion of the gas to fuel gob well blowers or compressors in remote locations where electricity is not available. However, this $CH_4$ use is not considered to be a formal recovery and use project.

Degasification information reported to EPA's GHGRP by underground coal mines is the primary source of data used to develop estimates of $CH_4$ liberated from degasification systems. Data reported to EPA's GHGRP were used exclusively to estimate $CH_4$ liberated from degasification systems at 14 of the 19 mines that used degasification systems in 2023.

Degasification volumes for the life of mined-through, pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.[63] EPA's GHGRP does not require gas production from virgin coal seams (coalbed methane) to be reported by coal mines under Subpart FF. Most pre-mining wells drilled from the surface are considered coalbed methane wells and are reported under another subpart of the program (Subpart W, "Petroleum and Natural Gas Systems"). As a result, for the five mines with degasification systems that include pre-mining wells that were mined through in 2023, EPA's GHGRP information was supplemented with historical data from state gas well production databases and mine-specific information regarding the dates on which pre-mining wells were mined through (GSA 2024; JWR 2010; El Paso 2009; ERG 2024). For pre-mining wells, the cumulative $CH_4$ production from the well is totaled using gas sales data and is considered liberated from the mine's degasification system the year in which the well is mined through.

Reports to EPA's GHGRP with $CH_4$ liberated from degasification systems are reviewed for errors in reporting. For some mines, GHGRP data are corrected for the *Inventory* based on expert judgment. Common errors include reporting $CH_4$ liberated as $CH_4$ destroyed and vice versa. Other errors include reporting $CH_4$ destroyed without reporting any $CH_4$ liberated by degasification systems. In the rare cases where GHGRP data are inaccurate and gas sales data are unavailable, estimates of $CH_4$ liberated are based on historical $CH_4$ liberation rates. No QA/QC issues or errors were identified in the 2023 subpart FF data.

**Step 1.3: Estimate $CH_4$ Recovered from Ventilation and Degasification Systems, and Utilized or Destroyed (Emissions Avoided)**

There were 11 active coal mines with operational $CH_4$ recovery and use projects in 2023, including one mine that had two recovery and use projects (for a total of 12 recovery and use projects overall, located at these 11 mines). All of these projects involved degasification systems. Ten of these 11 mines sold the recovered $CH_4$ to a pipeline, including one mine that used $CH_4$ to fuel a thermal coal dryer. One mine destroyed the recovered $CH_4$ using enclosed flares.

The $CH_4$ recovered and used (or destroyed) at the eleven coal mines described above were estimated using the following methods:

- EPA's GHGRP data was exclusively used to estimate the $CH_4$ recovered and used from six mines that deployed degasification systems in 2023. Based on quarterly measurements of gas flow and $CH_4$

[63] A well is "mined through" when coal mining development or the working face intersects the borehole or well.

concentrations, the GHGRP summary data for degasification destruction at each mine were added together to estimate the $CH_4$ recovered and used from degasification systems.

- State sales data were used to supplement the GHGRP data to estimate $CH_4$ recovered and used from five mines that deployed degasification systems in 2023 (DMME 2024; GSA 2024; ERG 2024; WVGES 2024). All of these mines intersected pre-mining wells in 2023. Supplemental information was used for these mines because estimating $CH_4$ recovery and use from pre-mining wells requires additional data (data not reported under Subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided prior to the well being mined through. The 2023 data came from state gas production databases (GSA 2024; ERG 2024), as well as mine-specific information on the timing of mined-through, pre-mining wells (JWR 2010; El Paso 2009, ERG 2019-2024). For pre-mining wells, the cumulative $CH_4$ production from the wells was totaled using gas sales data and was considered to be $CH_4$ recovered and used from the mine's degasification system in the year in which the well was mined through.

## Step 2: Estimate $CH_4$ Emitted from Surface Mines and Post-Mining Activities

Mine-specific data are not available for estimating $CH_4$ emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production data obtained from the Energy Information Administration's *Annual Coal Report* are multiplied by basin-specific gas contents and a 150 percent emission factor (to account for $CH_4$ from over- and under-burden) to estimate $CH_4$ emissions (King 1994; Saghafi 2013). For post-mining activities, basin-specific coal production data are multiplied by basin-specific gas contents and a mid-range 32.5 percent emission factor accounting for $CH_4$ desorption during coal transportation and storage (Creedy 1993). Basin-specific *in situ* gas content data were compiled from AAPG (1984) and USBM (1986). Beginning in 2006, revised data on *in situ* $CH_4$ content and emission factors have been used (EPA 1996, 2005).

### Step 2.1: Define the Geographic Resolution of the Analysis and Collect Coal Production Data

The first step in estimating $CH_4$ emissions from surface mining and post-mining activities is to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis is conducted by coal basin as defined in Table A-96, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2024) includes state- and county-specific underground and surface coal production by year. To calculate production by basin, the state-level data are grouped into coal basins using the basin definitions listed in Table A-96. For two states—West Virginia and Kentucky—county-level production data are used for the basin assignments because coal production occurred in geologically distinct coal basins within these states. Table A-97 presents the coal production data aggregated by basin.

### Step 2.2: Estimate Emission Factors for Each Emissions Type

Emission factors for surface-mined coal were developed from the *in situ* $CH_4$ content of the surface coal in each basin. Based on analyses conducted in Canada and Australia on coals similar to those present in the United States (King 1994; Saghafi 2013), the surface mining emission factor used was conservatively estimated to be 150 percent of the *in situ* $CH_4$ content of the basin. Furthermore, the post-mining emission factors used were estimated to be 25 to 40 percent of the average *in situ* $CH_4$ content in the basin. For this analysis, the post-mining emission factor was determined to be 32.5 percent of the *in situ* $CH_4$ content in the basin. Table A-98 presents the average *in situ* content for each basin, along with the resulting emission factor estimates.

### Step 2.3: Estimate $CH_4$ Emitted

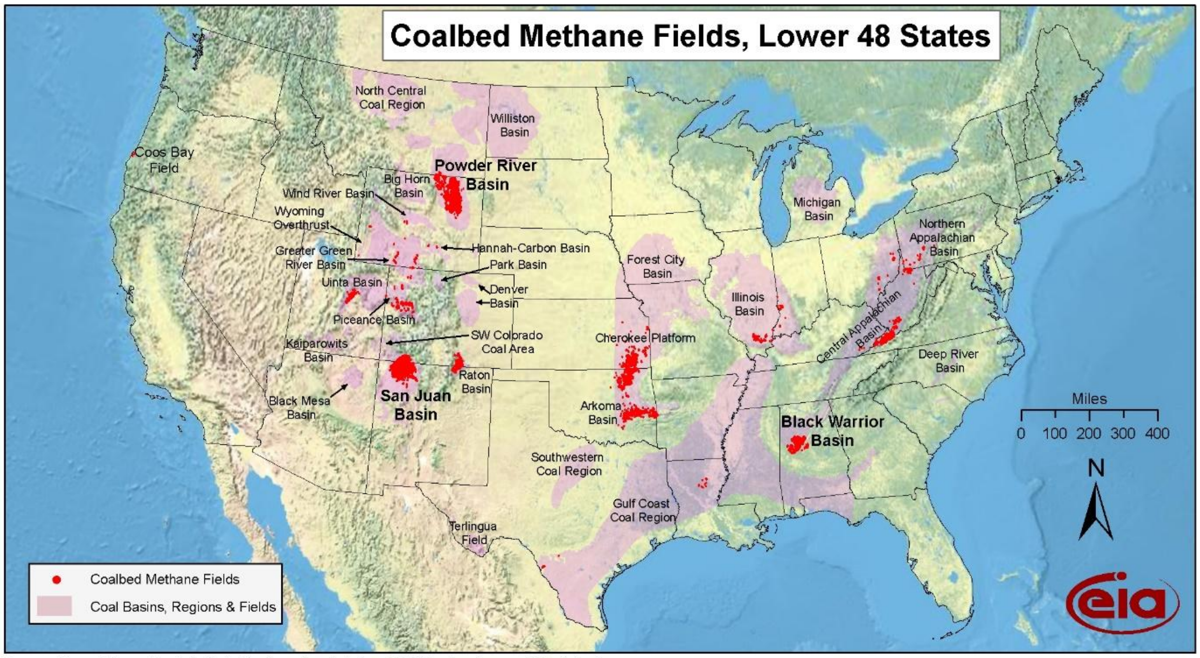
The total amount of $CH_4$ emitted from surface mines and post-mining activities is calculated by multiplying the coal production in each basin by the appropriate emission factors.

Table A-96 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-5, several coal basins span several states. Table A-97 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-98 shows the surface, post-surface, and post-underground emission factors used for estimating $CH_4$ emissions for each of the categories. For underground mines, Table A-99 presents annual estimates of $CH_4$ emissions for ventilation and degasification systems, and $CH_4$ recovered and used. Table A-100 presents annual estimates of total $CH_4$ emissions from underground, post-underground, surface, and post-surface activities.

### Table A-96: Coal Basin Definitions by Basin and by State

| Basin | States |
|---|---|
| Northern Appalachian Basin | Maryland, Ohio, Pennsylvania, West Virginia North |
| Central Appalachian Basin | Kentucky East, Tennessee, Virginia, West Virginia South |
| Warrior Basin | Alabama, Mississippi |
| Illinois Basin | Illinois, Indiana, Kentucky West |
| Southwest and Rockies Basin | Arizona, California, Colorado, New Mexico, Utah |
| North Great Plains Basin | Montana, North Dakota, Wyoming |
| West Interior Basin | Arkansas, Iowa, Kansas, Louisiana, Missouri, Oklahoma, Texas |
| Northwest Basin | Alaska, Washington |
| **State** | **Basin** |
| Alabama | Warrior Basin |
| Alaska | Northwest Basin |
| Arizona | Southwest and Rockies Basin |
| Arkansas | West Interior Basin |
| California | Southwest and Rockies Basin |
| Colorado | Southwest and Rockies Basin |
| Illinois | Illinois Basin |
| Indiana | Illinois Basin |
| Iowa | West Interior Basin |
| Kansas | West Interior Basin |
| Kentucky (east) | Central Appalachian Basin |
| Kentucky (west) | Illinois Basin |
| Louisiana | West Interior Basin |
| Maryland | Northern Appalachian Basin |
| Mississippi | Warrior Basin |
| Missouri | West Interior Basin |
| Montana | North Great Plains Basin |
| New Mexico | Southwest and Rockies Basin |
| North Dakota | North Great Plains Basin |
| Ohio | Northern Appalachian Basin |
| Oklahoma | West Interior Basin |
| Pennsylvania | Northern Appalachian Basin |
| Tennessee | Central Appalachian Basin |
| Texas | West Interior Basin |
| Utah | Southwest and Rockies Basin |
| Virginia | Central Appalachian Basin |
| Washington | Northwest Basin |
| West Virginia South | Central Appalachian Basin |
| West Virginia North | Northern Appalachian Basin |
| Wyoming | North Great Plains Basin |

## Figure A-5: Locations of U.S. Coal Basins




Source: Energy Information Administration based on data from USGS and various published studies
Updated: April 8, 2009

## Table A-97: Annual Coal Production (Thousand Short Tons)

| Basin | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| **Underground Coal Production** | **423,556** | **368,612** | **267,373** | **195,528** | **220,597** | **222,143** | **217,928** |
| N. Appalachia | 103,865 | 111,151 | 97,905 | 71,998 | 84,265 | 83,269 | 82,757 |
| Cent. Appalachia | 198,412 | 123,082 | 39,957 | 30,249 | 34,562 | 35,571 | 36,410 |
| Warrior | 17,531 | 13,295 | 11,980 | 10,451 | 7,959 | 9,121 | 11,130 |
| Illinois | 69,167 | 59,180 | 81,061 | 54,334 | 62,667 | 66,407 | 65,753 |
| S. West/Rockies | 32,754 | 60,866 | 27,257 | 20,049 | 20,702 | 20,344 | 14,297 |
| N. Great Plains | 1,722 | 572 | 9,213 | 8,447 | 10,442 | 7,431 | 7,581 |
| West Interior | 105 | 465 | 0 | 0 | 0 | 0 | 0 |
| Northwest | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Surface Coal Production** | **602,753** | **762,190** | **438,445** | **339,450** | **356,203** | **371,468** | **359,728** |
| N. Appalachia | 60,761 | 28,873 | 8,476 | 6,215 | 6,677 | 7,416 | 7,729 |
| Cent. Appalachia | 94,343 | 112,222 | 32,742 | 17,921 | 20,299 | 23,846 | 26,498 |
| Warrior | 11,413 | 11,599 | 4,841 | 4,288 | 4,581 | 4,656 | 3,598 |
| Illinois | 72,000 | 33,703 | 18,591 | 13,098 | 9,713 | 11,084 | 10,827 |
| S. West/Rockies | 43,863 | 42,756 | 18,394 | 13,420 | 12,872 | 13,722 | 12,982 |
| N. Great Plains | 249,356 | 474,056 | 329,164 | 262,968 | 283,424 | 292,263 | 282,839 |
| West Interior | 64,310 | 52,262 | 25,261 | 20,519 | 17,595 | 17,467 | 14,246 |
| Northwest | 6,707 | 6,720 | 975 | 1,021 | 1,042 | 1,014 | 1,009 |
| **Total Coal Production** | **1,026,309** | **1,130,802** | **705,818** | **534,978** | **576,800** | **593,611** | **577,656** |
| N. Appalachia | 164,626 | 140,023 | 106,381 | 78,213 | 90,942 | 90,685 | 90,486 |
| Cent. Appalachia | 292,755 | 235,305 | 72,700 | 48,170 | 54,861 | 59,417 | 62,908 |
| Warrior | 28,944 | 24,894 | 16,822 | 14,739 | 12,540 | 13,777 | 14,728 |
| Illinois | 141,167 | 92,883 | 99,652 | 67,432 | 72,380 | 77,491 | 76,580 |
| S. West/Rockies | 76,617 | 103,622 | 45,652 | 33,469 | 33,574 | 34,066 | 27,279 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| N. Great Plains | 251,078 | 474,629 | 338,376 | 271,415 | 293,866 | 299,694 | 290,420 |
| West Interior | 64,415 | 52,727 | 25,261 | 20,519 | 17,595 | 17,467 | 14,246 |
| Northwest | 6,707 | 6,720 | 975 | 1,021 | 1,042 | 1,014 | 1,009 |

Note: Totals may not sum due to independent rounding.

## Table A-98: Coal Underground, Surface, and Post-Mining $CH_4$ Emission Factors ($ft^3$ per Short Ton)

| Basin | Surface Average *In Situ* Content | Underground Average *In Situ* Content | Surface Mine Factors | Post-Mining Surface Factors | Post-Mining Underground Factors |
|---|---|---|---|---|---|
| Northern Appalachia | 59.5 | 138.4 | 89.3 | 19.3 | 45.0 |
| Central Appalachia (WV) | 24.9 | 136.8 | 37.4 | 8.1 | 44.5 |
| Central Appalachia (VA) | 24.9 | 399.1 | 37.4 | 8.1 | 129.7 |
| Central Appalachia (E KY) | 24.9 | 61.4 | 37.4 | 8.1 | 20.0 |
| Warrior | 30.7 | 266.7 | 46.1 | 10.0 | 86.7 |
| Illinois | 34.3 | 64.3 | 51.5 | 11.1 | 20.9 |
| Rockies (Piceance Basin) | 33.1 | 196.4 | 49.7 | 10.8 | 63.8 |
| Rockies (Uinta Basin) | 16.0 | 99.4 | 24.0 | 5.2 | 32.3 |
| Rockies (San Juan Basin) | 7.3 | 104.8 | 11.0 | 2.4 | 34.1 |
| Rockies (Green River Basin) | 33.1 | 247.2 | 49.7 | 10.8 | 80.3 |
| Rockies (Raton Basin) | 33.1 | 127.9 | 49.7 | 10.8 | 41.6 |
| N. Great Plains (WY, MT) | 20.0 | 15.8 | 30.0 | 6.5 | 5.1 |
| N. Great Plains (ND) | 5.6 | 15.8 | 8.4 | 1.8 | 5.1 |
| West Interior (Forest City, Cherokee Basins) | 34.3 | 64.3 | 51.5 | 11.1 | 20.9 |
| West Interior (Arkoma Basin) | 74.5 | 331.2 | 111.8 | 24.2 | 107.6 |
| West Interior (Gulf Coast Basin) | 11.0 | 127.9 | 16.5 | 3.6 | 41.6 |
| Northwest (AK) | 16.0 | 160.0 | 24.0 | 5.2 | 52.0 |
| Northwest (WA) | 16.0 | 47.3 | 24.0 | 5.2 | 15.4 |

Sources: 1986 USBM Circular 9067, *Results of the Direct Method Determination of the Gas Contents of U.S. Coal Basins*; U.S. DOE Report DOE/METC/83-76, *Methane Recovery from Coalbeds: A Potential Energy Source;* 1986–1988 Gas Research Institute Topical Report, *A Geologic Assessment of Natural Gas from Coal Seams;* 2005 U.S. EPA Draft Report, *Surface Mines Emissions Assessment*.

## Table A-99: Underground Coal Mining $CH_4$ Emissions (Billion Cubic Feet)

| Activity | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| Ventilation Output | 112 | 75 | 62 | 60 | 57 | 52 | 53 |
| Adjustment Factor for Mine Data | 98% | 98% | 100% | 100% | 100% | 100% | 100% |
| Adjusted Ventilation Output | 114 | 77 | 62 | 60 | 57 | 52 | 53 |
| Degasification System Liberated | 54 | 47 | 43 | 40 | 40 | 52 | 57 |
| Total Underground Liberated | 168 | 124 | 105 | 100 | 97 | 104 | 110 |
| Recovered & Used | (14) | (37) | (34) | (34) | (36) | (46) | (48) |
| **Total** | **154** | **87** | **71** | **65** | **61** | **58** | **62** |

Note: Totals may not sum due to independent rounding.

## Table A-100: Total Coal Mining $CH_4$ Emissions (Billion Cubic Feet)

| Activity | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| Underground Mining | 154 | 87 | 71 | 65 | 61 | 58 | 62 |
| Surface Mining | 22 | 25 | 13 | 10 | 11 | 11 | 11 |
| Post-Mining (Underground) | 19 | 16 | 11 | 8 | 9 | 9 | 9 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Post-Mining (Surface) | 5 | 5 | 3 | 2 | 2 | 2 | 2 |
| **Total** | **200** | **133** | **98** | **86** | **83** | **81** | **84** |

Note: Totals may not sum due to independent rounding.

### Table A-101: Total Coal Mining $CH_4$ Emissions by State (Million Cubic Feet)

| State | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| Alabama | 32,097 | 15,831 | 9,494 | 9,767 | 8,220 | 7,059 | 6,562 |
| Alaska | 50 | 42 | 28 | 30 | 30 | 30 | 29 |
| Arizona | 151 | 161 | 51 | 0 | 0 | 0 | 0 |
| Arkansas | 5 | + | 0 | 0 | 0 | 0 | 0 |
| California | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Colorado | 10,187 | 13,441 | 1,730 | 1,380 | 1,392 | 1,139 | 1,418 |
| Illinois | 10,180 | 6,488 | 5,661 | 4,100 | 4,267 | 5,008 | 5,419 |
| Indiana | 2,232 | 3,303 | 6,807 | 6,067 | 6,388 | 5,531 | 5,607 |
| Iowa | 24 | 0 | 0 | 0 | 0 | 0 | 0 |
| Kansas | 45 | 11 | 0 | 0 | 0 | 0 | 0 |
| Kentucky | 10,018 | 6,898 | 2,264 | 1,765 | 2,164 | 2,734 | 2,387 |
| Louisiana | 64 | 84 | 36 | 14 | 6 | 6 | 6 |
| Maryland | 474 | 361 | 119 | 92 | 113 | 145 | 114 |
| Mississippi | 0 | 199 | 151 | 145 | 179 | 189 | 150 |
| Missouri | 166 | 37 | 12 | 10 | 3 | 5 | 9 |
| Montana | 1,373 | 1,468 | 1,038 | 775 | 816 | 797 | 823 |
| New Mexico | 363 | 2,926 | 1,446 | 723 | 1,661 | 948 | 106 |
| North Dakota | 299 | 306 | 276 | 270 | 271 | 273 | 246 |
| Ohio | 4,406 | 3,120 | 1,283 | 793 | 852 | 494 | 398 |
| Oklahoma | 226 | 825 | 116 | 367 | + | + | + |
| Pennsylvania | 21,864 | 17,904 | 23,513 | 18,931 | 19,100 | 17,864 | 20,177 |
| Tennessee | 276 | 115 | 17 | 7 | 0 | 0 | 0 |
| Texas | 1,119 | 922 | 468 | 395 | 346 | 343 | 277 |
| Utah | 3,587 | 4,787 | 811 | 845 | 770 | 769 | 636 |
| Virginia | 46,041 | 8,649 | 6,959 | 6,726 | 6,198 | 5,579 | 5,856 |
| Washington | 146 | 154 | 0 | 0 | 0 | 0 | 0 |
| West Virginia | 48,335 | 29,745 | 25,556 | 24,277 | 21,416 | 23,052 | 25,361 |
| Wyoming | 6,671 | 14,745 | 10,409 | 8,099 | 8,621 | 8,933 | 8,660 |
| **Total** | **200,399** | **132,523** | **98,247** | **85,579** | **82,813** | **80,898** | **84,242** |

+ Does not exceed 0.5 million cubic feet.

Note: The emission estimates provided above are inclusive of emissions from underground mines, surface mines and post-mining activities. The totals include $CH_4$ liberated, minus $CH_4$ recovered and used (i.e., representing total "net" emissions). The following states have neither underground nor surface mining and thus report no emissions as a result of coal mining: Connecticut, Delaware, Florida, Georgia, Hawaii, Idaho, Maine, Massachusetts, Michigan, Minnesota, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Rhode Island, South Carolina, South Dakota, Vermont, and Wisconsin. Totals may not sum due to independent rounding.

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## 3.5. Methodology for Estimating $CH_4$, $CO_2$, and $N_2O$ Emissions from Petroleum Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2023 please see the spreadsheet file annexes for the current (i.e., 1990 to 2023) *Inventory*, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2023-inventory.

As described in the main body text on Petroleum Systems, the *Inventory* methodology involves the calculation of $CH_4$, $CO_2$, and $N_2O$ emissions for approximately 100 emissions sources, and then the summation of emissions for each petroleum systems segment. The approach for calculating emissions for petroleum systems generally involves the application of emission factors to activity data.

**Emission Factors**

Table 3.5-2, Table 3.5-7, and Table 3.5-10 show $CH_4$, $CO_2$, and $N_2O$ emissions, respectively, for all sources in Petroleum Systems, for all time series years. Table 3.5-3, Table 3.5-8, and Table 3.5-11 show the $CH_4$, $CO_2$, and $N_2O$ average emission factors, respectively, for all sources in Petroleum Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population.

Additional detail on the basis for emission factors used across the time series is provided in Table 3.5-4, Table 3.5-9, Table 3.5-12, and below.

In addition to the Greenhouse Gas Reporting Program (GHGRP), key references for emission factors for $CH_4$ and non-combustion-related $CO_2$ emissions from the U.S. petroleum industry include a 1999 EPA/Radian report *Methane Emissions from the U.S. Petroleum Industry* (EPA/Radian 1999), which contained the most recent and comprehensive determination of $CH_4$ emission factors for $CH_4$-emitting activities in the oil industry at that time, a 1999 EPA/ICF draft report *Estimates of Methane Emissions from the U.S. Oil Industry* (EPA/ICF 1999) which is largely based on the 1999 EPA/Radian report, and a detailed study by the Gas Research Institute and EPA *Methane Emissions from the Natural Gas Industry* (EPA/GRI 1996). These studies still represent best available data in many cases—in particular, for the early years of the time series.

Data from studies and EPA's GHGRP (EPA 2024b) allows for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For several sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time). For oil well completions with hydraulic fracturing, controlled and uncontrolled emission factors were developed using GHGRP data. For associated gas, separate emission estimates are developed from GHGRP data for venting and flaring. For oil tanks, emissions estimates were developed for large and small tanks with flaring or VRU control, without control devices, and with upstream malfunctioning separator dump valves. For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers. Some sources in Petroleum Systems that use methodologies based on GHGRP data use a basin-level aggregation approach, wherein EPA calculates basin-specific emissions and/or activity factors for basins that contribute at least 10 percent of total annual emissions (on a $CO_2$ Eq. basis) from the source in any year—and combines all other basins into one grouping. This methodology is applied for associated gas venting and flaring and miscellaneous production flaring. Other sources in the onshore production segment use basin-specific emissions and/or activity factors for all basins that reported data to subpart W and use subpart W averages for all basins that did not report data to the GHGRP. This methodology is applied to pneumatic controllers, chemical injection pumps, wellpad equipment leaks, production storage tanks, and completions and workovers (EPA 2023a; EPA 2024a). Produced Water $CH_4$ estimates are calculated using annual produced water quantities (Enverus 2023 and EPA 2023b and an emission factor from EPA's *Nonpoint Oil and Gas Emission Estimation Tool* (EPA 2017b).

For the refining segment, EPA has directly used the GHGRP data for all emission sources for recent years (2010 forward) (EPA 2024b) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990 to 2009). For some sources within refineries, EPA continues to apply the historical emission factors for all time series years. All refineries have been required to report $CH_4$, $CO_2$, and $N_2O$ emissions to GHGRP for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2023 emissions. The national emission totals for each activity were divided by refinery feed rates for four *Inventory* years (2010 to 2013) to develop average activity-specific emission factors, which were used to estimate national emissions for each refinery activity from 1990 to 2009 based on national refinery feed rates for each year (EPA 2015b).

Offshore emissions are taken from analysis of the *Gulfwide Emission Inventory Studies* and GHGRP data (BOEM 2024a-d; EPA 2024b; EPA 2024c; EPA 2020). Emission factors are calculated for offshore facilities located in the Gulf of America, Pacific, and Alaska regions.

When a $CO_2$-specific emission factor is not available for a source, the $CO_2$ emission factors were derived from the corresponding source $CH_4$ emission factors. The amount of $CO_2$ in the crude oil stream changes as it passes through various equipment in petroleum production operations. As a result, four distinct stages/streams with varying $CO_2$ contents exist. The four streams that are used to estimate the emissions factors are the associated gas stream separated from crude oil, hydrocarbons flashed out from crude oil (such as in storage tanks), whole crude oil itself when it leaks downstream, and gas emissions from offshore oil platforms. For this approach, $CO_2$ emission factors are estimated by multiplying the existing $CH_4$ emissions factors by a conversion factor, which is the ratio of $CO_2$ content to methane content for the particular stream. Ratios of $CO_2$ to $CH_4$ volume in emissions are presented in Table 3.5-1.

$N_2O$ emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the existing source-specific methodology was applied to calculate $N_2O$ emission factors.

**Activity Data**

Table 3.5-5 shows the activity data for all sources in Petroleum Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.5-6, and below.

For many sources, complete activity data were not available for all years of the time series. In such cases, one of three approaches was employed. Where appropriate, the activity data were calculated from related statistics using ratios developed based on EPA 1996, and/or GHGRP data. For major equipment (equipment leak categories), pneumatic controllers, chemical injection pumps, oil tanks, and completions and workovers, GHGRP Subpart W data were used to develop activity factors (e.g.,, count per well) that are applied to calculated activity in recent years; to populate earlier years of the time series, linear interpolation is used to connect GHGRP-based estimates with existing estimates in earlier years of the time series (e.g., 1990 to 1992). In other cases, the activity data were held constant from 1990 through 2014 based on EPA (1999). Lastly, the previous year's data were used when data for the current year were unavailable.

For offshore production in the GOA, the number of active major and minor complexes are used as activity data. For offshore production in the Pacific and Alaska region, the activity data are region-specific production. The activity data for the total crude transported in the transportation segment are not available, therefore the activity data for the refining sector (i.e., refinery feed in 1000 bbl/year) was also used for the transportation sector, applying an assumption that all crude transported is received at refineries. In the few cases where no data were located, oil industry data based on expert judgment were used. In the case of non-combustion $CO_2$ and $N_2O$ emission sources, the activity factors are the same as for $CH_4$ emission sources. In some instances, where recent time series data (e.g., year 2023) are not yet available, year 2022 data were used as proxy.

<u>Methodology for well counts and events</u>

EPA used DrillingInfo and Prism, production databases maintained by Enverus Inc. (Enverus 2023), covering U.S. oil and natural gas wells to populate time series activity data for active oil wells, oil wells drilled, and oil well completions and workovers with hydraulic fracturing. Revised data for 2023 were not available from Enverus for public review estimates, therefore EPA used 2022 data as proxy for 2023. For more information on Enverus data processing, please see Annex 3.6 Methodology for Estimating $CH_4$, $CO_2$, and $N_2O$ from Natural Gas Systems.

**Reductions data: Federal regulations**

Regulatory actions reducing emissions in the current *Inventory* include the New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents in the production segment.

The *Inventory* reflects the NSPS for oil and gas through the use of a net factor approach that captures shifts to lower emitting technologies required by the regulation. Examples include separating oil well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors and year-specific activity data for each category; establishing control category-specific emission factors and associated year-specific activity data for oil tanks; and calculating year-specific activity data for pneumatic controller bleed categories.

In regard to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production sectors and the natural gas transmission and storage sectors of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

NESHAP driven reductions from storage tanks are estimated with net emission methodologies that take into account controls implemented due to regulations.

**Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year**

Annual $CH_4$, $CO_2$, and $N_2O$ emissions for each source were calculated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual $CH_4$, $CO_2$, and $N_2O$ emissions, respectively. Emissions at a segment level are shown in Table 3.5-2, Table 3.5-7, and Table 3.5-10.

Refer to the 1990-2023 *Inventory* section at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems for the following data tables, in spreadsheet format:

- Table 3.5-1: Ratios of $CO_2$ to $CH_4$ Volume in Emissions from Petroleum Production Field Operations
- Table 3.5-2: $CH_4$ Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-3: Average $CH_4$ Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-4: $CH_4$ Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-5: Activity Data for Petroleum Systems Sources, for All Years
- Table 3.5-6: Activity Data for Petroleum Systems, Data Sources/Methodology
- Table 3.5-7: $CO_2$ Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-8: Average $CO_2$ Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-9: $CO_2$ Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-10: $N_2O$ Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years
- Table 3.5-11: Average $N_2O$ Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-12: $N_2O$ Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-13: Annex 3.5 Electronic Tables – References
- Table 3.5-14: Basin-Level $CH_4$ Emissions (kt) for Select Petroleum Systems Onshore Production Sources
- Table 3.5-15: Basin-Level $CO_2$ Emissions (kt) for Select Petroleum Systems Onshore Production Sources
- Table 3.5-16: Basin-Level Activity Factors for Select Petroleum Systems Onshore Production Sources
- Table 3.5-17: Basin-Level Activity Data for Select Petroleum Systems Onshore Production Sources
- Table 3.5-18: Average Basin-Level $CH_4$ Emission Factors (kg/unit activity) for Select Petroleum Systems Onshore Production Sources, for All Years

- Table 3.5-19: Average Basin-Level $CO_2$ Emission Factors (kg/unit activity) for Select Petroleum Systems Onshore Production Sources, for All Years
- Table 3.5-20: Basin-Level Activity Data for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-21: Basin-Level $CH_4$ Emission Factors for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-22: Basin-Level $CO_2$ Emission Factors for Select Petroleum Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.5-23: Basin-Level References

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## 3.6. Methodology for Estimating $CH_4$, $CO_2$, and $N_2O$ Emissions from Natural Gas Systems

For details on the emissions, emission factors, activity data, data sources, and methodologies for each year from 1990 to 2023 please see the spreadsheet file annexes for the current (i.e., 1990 to 2023) *Inventory*, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2023-inventory.

As described in the main body text on Natural Gas Systems, the *Inventory* methodology involves the calculation of $CH_4$, $CO_2$, and $N_2O$ emissions for over 100 emissions sources, and the summation of emissions for each natural gas segment. The approach for calculating emissions for natural gas systems generally involves the application of emission factors to activity data. For many sources, the approach uses technology-specific emission factors or emission factors that vary over time and take into account changes to technologies and practices, which are used to calculate net emissions directly. For others, the approach uses what are considered "potential methane factors" and reduction data to calculate net emissions.

**Emission Factors**

Table 3.6-1, Table 3.6-10, and Table 3.6-14 show $CH_4$, $CO_2$, and $N_2O$ emissions, respectively, for all sources in Natural Gas Systems, for all time series years. Table 3.6-2, Table 3.6-12, and Table 3.6-15 show the $CH_4$, $CO_2$, and $N_2O$ average emission factors, respectively, for all sources in Natural Gas Systems, for all time series years. These emission factors are calculated by dividing net emissions by activity. Therefore, in a given year, these emission factors reflect the estimated contribution from controlled and uncontrolled fractions of the source population and any source-specific reductions (see below section "Reductions Data"); additionally, for sources based on the GRI/EPA study, the values take into account methane compositions from GTI 2001 adjusted year to year using gross production for National Energy Modeling System (NEMS) oil and gas supply module regions from the EIA. These adjusted region-specific annual $CH_4$ compositions are presented in Table 3.6-3 (for general sources), Table 3.6-4 (for gas wells without hydraulic fracturing), and Table 3.6-5 (for gas wells with hydraulic fracturing).

Additional detail on the basis for the $CH_4$, $CO_2$, and $N_2O$ emission factors used across the time series is provided in Table 3.6-6, Table 3.6-13, Table 3.6-16, and below.

Key references for emission factors for $CH_4$ and non-combustion-related $CO_2$ emissions from the U.S. natural gas industry include the 1996 Gas Research Institute (GRI) and EPA study (GRI/EPA 1996), the Greenhouse Gas Reporting Program (GHGRP) (EPA 2024d), and others.

The GRI/EPAGRI/EPA study developed over 80 $CH_4$ emission factors to characterize emissions from the various components within the operating stages of the U.S. natural gas system for base year 1992. Since the time of this study, practices and technologies have changed. This study still represents best available data in many cases—in particular, for early years of the time series.

Data from studies and EPA's GHGRP (EPA 2024d) allow for emission factors to be calculated that account for adoption of control technologies and emission reduction practices. For some sources, EPA has developed control category-specific emission factors from recent data that are used over the time series (paired with control category-specific activity data that fluctuates to reflect control adoption over time). In other cases, EPA retains emission factors from the GRI/EPA study for early time series years (1990 to 1992), applies updated emission factors in recent years (e.g., 2011 forward), and uses interpolation to calculate emission factors for intermediate years. For some sources, EPA continues to apply the GRI/EPA emission factors for all time series years, and accounts for emission reductions through data reported to Gas STAR or estimated based on regulations (see below section "Reductions Data"). For the following sources in the exploration and production segments, EPA has used GHGRP data to calculate net emission factors and establish source type and/or control type subcategories:

- For gas well completions and workovers with hydraulic fracturing, separate emissions estimates were developed for hydraulically fractured completions and workovers that vent, flared hydraulic fracturing completions and workovers, hydraulic fracturing completions and workovers with reduced emissions completions (RECs), and hydraulic fracturing completions and workovers with RECs that flare. The estimates were developed for each basin that reported to subpart W.

- For gas well completions without hydraulic fracturing, separate emissions estimates were developed for completions that vent and completions that flare. The estimates were developed for each basin that reported to subpart W.
- For liquids unloading, separate emissions estimates were developed for each basin that reported to Subpart W for wells with plunger lifts and wells without plunger lifts.
- For condensate tanks, emissions estimates were developed for each basin that reported to subpart W for large and small tanks with flaring or vapor recovery unit (VRU) control, without control devices, and with upstream malfunctioning separator dump valves.
- For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers for each basin that reported to subpart W.
- Chemical injection pumps estimates are calculated with a basin-specific emission factor developed with GHGRP data for each basin that reported to subpart W.

For most sources in the processing, transmission and storage, and distribution segments, net emission factors have been developed for application in recent years of the time series, while the existing emission factors are applied in early time series years.

When a $CO_2$-specific emission factor is not available for a source, the $CO_2$ emission factors were derived from the corresponding source $CH_4$ emission factors using default gas composition data. $CO_2$ emission factors are estimated by multiplying the $CH_4$ emission factors by the ratio of the $CO_2$-to-$CH_4$ gas content. This approach is applied for certain sources in the natural gas production, gas processing (only for early time series years), transmission and storage, and distribution segments. The default gas composition data are specific to segment and are provided in Table 3.6-11. The default values were derived from GRI/EPA (1996), EIA (1994), and GTI (2001).

$N_2O$ emission factors were calculated using GHGRP data. For each flaring emission source calculation methodology that uses GHGRP data, the source-specific methodology used to estimate $CO_2$ was applied to calculate $N_2O$ emission factors.

<u>1990-2023 *Inventory* updates to emission factors</u>

EPA incorporated new emissions data available for year 2021 from the Bureau of Ocean Energy Management (BOEM) to update the methodology for offshore production in the Gulf of America region. The details are presented in a memorandum,[64] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2023: Updates Under Consideration to Use New Offshore Data* (EPA 2024a), as well as the "Recalculations Discussion" section of the main body text.

**Activity Data**

Table 3.6-7 shows the activity data for all sources in Natural Gas Systems, for all time series years. Additional detail on the basis for activity data used across the time series is provided in Table 3.6-8, and below.

For a few sources, recent direct activity data were not available. For these , either 2022 data were used as proxy for 2023 data or a set of industry activity data drivers was developed and was used to update activity data. Key drivers include statistics on gas production, number of wells, system throughput, miles of various kinds of pipe, and other statistics that characterize the changes in the U.S. natural gas system infrastructure and operations.

[64] Stakeholder materials including EPA memoranda for the *Inventory* are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems.

Methodology for well counts and events

EPA used datasets from Enverus (Enverus 2025), covering U.S. oil and natural gas wells to populate time series activity data for active gas wells, gas wells drilled, and gas well completions and workovers with hydraulic fracturing (for 1990 to 2010). EPA queried the Enverus datasets for relevant data on an individual well basis—including location, natural gas and liquids (i.e., oil and condensate) production by year, drill type (e.g., horizontal or vertical), and date of completion or first production. Non-associated gas wells were classified as any well that had non-zero gas production in a given year, and with a gas-to-oil ratio (GOR) of greater than 100 mcf/bbl in that year. Oil wells were classified as any well that had non-zero liquids production in a given year, and with a GOR of less than or equal to 100 mcf/bbl in that year. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that had fracking fluid data within Enverus or were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in the Enverus datasets referenced against a formation type crosswalk developed by EIA (EIA 2012).

For 1990 through 2010, gas well completions with hydraulic fracturing were identified as a subset of the gas wells with hydraulic fracturing that had a date of completion or first production in the specified year. To calculate workovers for all time series years, EPA developed year- and basin-specific subpart W AFs for 2015 forward that represent the number of HF workovers per gas well; year 2015 subpart W AFs were applied to all prior years for each basin. For 2011 forward, EPA used GHGRP data for the total number of well completions. The GHGRP data represents a subset of the national completions, due to the reporting threshold, and therefore using this data without scaling it up to national level results in an underestimate. However, because EPA's GHGRP counts of completions were higher than national counts of completions (estimated using the Enverus datasets), EPA directly used the GHGRP data to estimate national activity for years 2011 forward.

EPA calculated the percentage of gas well completions and workovers with hydraulic fracturing in each of the four control categories using year- and basin-specific GHGRP data. EPA assumed no REC use from 1990 through 2000, used a REC use percentage calculated from basin-specific GHGRP data for 2011 forward, and then used linear interpolation between the 2000 and 2011 percentages for each basin. For flaring, EPA averaged the percent of completions and workovers that were flared in 2011 and 2012 GHGRP data. EPA used this average as a basin-specific percent flaring from 1990 through 2010 to recognize that some flaring has occurred over that time period. For 2011 forward, EPA used a flaring percentage calculated from GHGRP data. For basins without subpart W data available, EPA applied national average activity factors (unweighted average of all subpart W reported data).

**Reductions Data**

As described under "Emission Factors" above, some sources in Natural Gas Systems rely on $CH_4$ emission factors developed from the 1996 GRI/EPA study. Application of these emission factors across the time series represents potential emissions and does not take into account any use of technologies or practices that reduce emissions. To take into account use of such technologies for emission sources that use potential factors, data were collected on relevant voluntary and regulatory reductions.

Voluntary and regulatory emission reductions by segment, for all time series years, are included in Table 3.6-1. Reductions by emission source, for all time series years, are shown in Table 3.6-9.

Voluntary reductions

Voluntary reductions included in the *Inventory* were those reported to Gas STAR and Methane Challenge for activities such as replacing gas engines with electric compressor drivers and installing automated air-to-fuel ratio controls for engines.

The latest reported data for each program were paired with sources in the *Inventory* that use potential emissions approaches and incorporated into the estimates (e.g., gas engines). Reductions data are only included in the *Inventory* if the emission source uses "potential" emission factors, and for Natural Gas STAR reductions, short-term emission reductions are assigned to the reported year only, while long-term emission reductions are assigned to the reported year and every subsequent year in the time series. See Recalculations Discussion for more information.

Federal regulations

Regulatory actions reducing emissions in the current *Inventory* include the New Source Performance Standards (NSPS) and National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations for dehydrator vents in the production segment.

The *Inventory* reflects the NSPS for oil and gas through the use of a net factor approach that captures shifts to lower emitting technologies required by the regulation. Examples include separating gas well completions and workovers with hydraulic fracturing into four categories and developing control technology-specific methane emission factors and year-specific activity data for each category; establishing control category-specific emission factors and associated year-specific activity data for condensate tanks; calculating year-specific activity data for pneumatic controller bleed categories; and estimating year-specific activity data for wet versus dry seal centrifugal compressors.

With regards to the oil and natural gas industry, the NESHAP regulation addresses HAPs from the oil and natural gas production segments and the natural gas transmission and storage segments of the industry. Though the regulation deals specifically with HAPs reductions, methane emissions are also incidentally reduced.

The NESHAP regulation requires that glycol dehydration unit vents that have HAP emissions and exceed a gas throughput threshold be connected to a closed loop emission control system that reduces emissions by 95 percent. The emissions reductions achieved as a result of NESHAP regulations for glycol dehydrators in the production segment were calculated using data provided in the Federal Register Background Information Document (BID) for this regulation. The BID provides the levels of control measures in place before the enactment of regulation. The emissions reductions were estimated by analyzing the portion of the industry without control measures already in place that would be impacted by the regulation.

NESHAP-driven reductions from storage tanks and from dehydrators in the processing segment are estimated with net emission methodologies that take into account controls implemented due to regulations.

**Methane, Carbon Dioxide, and Nitrous Oxide Emissions by Emission Source for Each Year**

Annual $CH_4$, $CO_2$, and $N_2O$ emissions for each source were estimated by multiplying the activity data for each year by the corresponding emission factor. These annual emissions for each activity were then summed to estimate the total annual $CH_4$, $CO_2$, and $N_2O$ emissions, respectively. As a final step for $CH_4$ emissions, any relevant reductions data from each segment is summed for each year and deducted from the total calculated emissions in that segment to estimate net $CH_4$ emissions for the *Inventory*. $CH_4$ potential emissions, reductions, and net emissions at a segment level are shown in Table 3.6-1. $CO_2$ emissions by segment and source are summarized in Table 3.6-10. $N_2O$ emissions by segment and source are summarized in Table 3.6-14.

Refer to the 1990-2023 *Inventory* section at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems for the following data tables, in spreadsheet format:

- Table 3.6-1: $CH_4$ Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years. Emissions presented are net and include GasSTAR or Methane Challenge reductions.
- Table 3.6-2: Average $CH_4$ Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-3: U.S. Production Sector $CH_4$ Content in Natural Gas by NEMS Region (General Sources)
- Table 3.6-4: U.S. Production Sector $CH_4$ Content in Natural Gas by NEMS Region (Gas Wells Without Hydraulic Fracturing)
- Table 3.6-5: U.S. Production Sector $CH_4$ Content in Natural Gas by NEMS Region (Gas Wells With Hydraulic Fracturing)
- Table 3.6-6: $CH_4$ Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-7: Activity Data for Natural Gas Systems Sources, for All Years

- Table 3.6-8: Activity Data for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-9: Voluntary and Regulatory $CH_4$ Reductions for Natural Gas Systems (kt)
- Table 3.6-10: $CO_2$ Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-11: Default Gas Content by Segment, for All Years
- Table 3.6-12: Average $CO_2$ Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-13: $CO_2$ Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-14: $N_2O$ Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- Table 3.6-15: Average $N_2O$ Emission Factors (kg/unit activity) for Natural Gas Systems Sources, for All Years
- Table 3.6-16: $N_2O$ Emission Factors for Natural Gas Systems, Data Sources/Methodology
- Table 3.6-17: Electronic Tables – References
- Table 3.6-18: Basin-Level $CH_4$ Emissions (kt) for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-19: Basin-Level $CO_2$ Emissions (kt) for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-20: Basin-Level Activity Factors for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-21: Basin-Level Activity Data for Select Natural Gas Systems Onshore Production Sources
- Table 3.6-22: Average Basin-Level $CH_4$ Emission Factors (kg/unit activity) for Select Natural Gas Systems Onshore Production Sources, for All Years
- Table 3.6-23: Average Basin-Level $CO_2$ Emission Factors (kg/unit activity) for Select Natural Gas Systems Onshore Production Sources, for All Years
- Table 3.6-24: Basin-Level Activity Data for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-25: Basin-Level $CH_4$ Emission Factors for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-26: Basin-Level $CO_2$ Emission Factors for Select Natural Gas Systems Onshore Production Sources, Data Sources/Methodology
- Table 3.6-27: Basin-Level References

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## 3.7. Methodology for Estimating $CO_2$, $CH_4$, and $N_2O$ Emissions from the Incineration of Waste

Emissions of $CO_2$ from the combustion of waste include $CO_2$ generated by the combustion of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), which, in the United States, tends to occur at waste-to-energy facilities or industrial facilities, and the combustion of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Waste combustion also results in emissions of $CH_4$ and $N_2O$. The emission estimates are calculated for all MSW sources on a mass-basis based on the data available, with the emissions from the combustion of tires calculated separately. The methodology for calculating emissions from waste combustion sources is described in this Annex.

### Municipal Solid Waste Combustion

To determine both $CO_2$ and non-$CO_2$ emissions from the combustion of waste, the tonnage of waste combusted and an estimated emissions factor are needed. Emission estimates from the combustion of tires are discussed separately. Data for total waste combusted, excluding tires, was derived from *BioCycle* (van Haaren et al. 2010), EPA Facts and Figures Report, Energy Recovery Council (ERC 2018), EPA's Greenhouse Gas Reporting Program (GHGRP) (EPA 2024), and the U.S. Energy Information Administration (EIA 2019). Multiple sources were used to ensure a complete, quality dataset, as each source encompasses a different timeframe.

EPA's Greenhouse Gas Reporting Program (GHGRP) collects data from facilities on methane ($CH_4$) and nitrous oxide ($N_2O$) emissions by fuel type under Subpart C. From these reported emissions for MSW fuel, EPA back-calculated the tonnage of waste combusted using GHGRP default emission factors for $CH_4$ and $N_2O$ for 2011 through 2023. Reporters can report $CO_2$ emissions using a number of different tiers under the GHGRP. For some tiers, input fuel values could be determined, but not for all facilities. However, the methods for reporting $CH_4$ and $N_2O$ emissions from MSW combustion under GHGRP generally rely on applying default emission factors to fuel input values. Therefore, back calculating fuel input based on the default $CH_4$ and $N_2O$ emissions factors was determined to be the best method for consistently estimating fuel input values for all MSW fuel combustion across all facilities and over time. Where values for fuel input were directly available from MSW combustion through GHGRP it was determined to be consistent with the back calculated values.

EPA Facts and Figures Reports detail materials combusted with energy recovery in the municipal waste stream. This tonnage is estimated as a percentage of total MSW after recycling and composting. These data exclude major appliances, tires and lead-acid batteries, and food. Waste-to-energy data is reported to EIA and available at the plant level. Biogenic and non-biogenic combusted waste tonnage are both reported on a monthly and annual basis starting in 2006 (EIA 2019). The sum total is used in the following calculations. Similarly, ERC's *2018 Directory of Waste and Energy Facilities* reports throughput data in tons of MSW for waste-to-energy facilities operating in the United States. Both *Biocycle* and ERC data include the tons of tires combusted in their raw data reporting. To determine total MSW combusted using these data, combusted tire tonnage is subtracted.

EPA determined the MSW combusted tonnages based on data availability and accuracy throughout the time series, and the two estimates were averaged together and converted to MSW tonnage.

- 1990-2006: MSW combustion tonnages are from BioCycle combustion data. Tire combustion data from the U.S. Tire Manufacturers Association (USTMA) are removed to arrive at MSW combusted without tires.
- 2006-2010: MSW combusted tonnages are an average of BioCycle (with USTMA tire data tonnage removed), U.S. EPA Facts and Figures, EIA, and Energy Recovery Council data (with USTMA tire data tonnage removed).
- 2011-2023: MSW combustion tonnages are from EPA's GHGRP data.

Table A-102 provides the estimated tons of MSW combusted including and excluding tires.

## Table A-102: Municipal Solid Waste Combusted (Short Tons)

| Year | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| Waste Combusted - excluding tires | 33,344,839 | 26,486,414 | 28,174,311 | 27,586,271 | 27,867,446 | 26,338,130 | 25,676,432 |
| Waste Combusted - including tires | 33,766,239 | 28,631,054 | 29,821,141 | 29,106,686 | 29,261,446 | 27,808,130 | 27,222,432 |

Sources: *BioCycle*, EPA Facts and Figures, ERC, GHGRP, EIA, USTMA.

## $CO_2$ Emissions from MSW Excluding Scrap Tires

Fossil $CO_2$ emission factors were calculated from EPA's GHGRP data for non-biogenic sources. MSW tonnage using GHGRP data, excluding tires, was calculated following the method outlined previously. Dividing fossil $CO_2$ emissions from GHGRP FLIGHT data for facilities classified as MSW combustors by the estimated tonnage from those facilities yielded an annual $CO_2$ emission factor. Note the MSW tonnage calculated for facilities characterized as MSW combustors is smaller than the total MSW tonnage back calculated from emissions by fuel type data. This indicates MSW could be co-fired at facilities whose main purpose is not waste combustion alone. As this data was only available following 2011, the $CO_2$ emission factor was proxied using an average of the $CO_2$ emission factors from years 2011 through 2015.

Finally, $CO_2$ emissions were calculated by multiplying the annual tonnage estimates, excluding tires, by the calculated emissions factor. Calculated fossil $CO_2$ emission factors are shown in Table A-103.

## Table A-103: Calculated Fossil $CO_2$ Content per Ton Waste Combusted (kg $CO_2$/Short Ton Combusted)

| Year | 1990 | 2005 | 2019 | 2020 | 2021 | 2022 | 2023 |
|---|---|---|---|---|---|---|---|
| $CO_2$ Emission Factors | 366 | 366 | 363 | 377 | 365 | 382 | 384 |

## $CO_2$ from Combustion of Synthetic Rubber and Carbon Black in Tires

Calculating emissions from tire combustion requires two pieces of information: the amount of tires combusted and the C content of the tires. "2023 End-of-Life Tire Management Report" (USTMA 2024) reports that 1,546 thousand of the 3,512 thousand tons of scrap tires generated in 2023 (approximately 44 percent of generation) were used for fuel purposes. Using USTMA's estimates of average tire composition and weight, the mass of synthetic rubber and C black in scrap tires was determined:

- Synthetic rubber in tires was estimated to be 90 percent C by weight, based on the weighted average C contents of the major elastomers used in new tire consumption.[65] Table A-104 shows consumption and C content of elastomers used for tires and other products in 2002, the most recent year for which data are available.
- C black is 100 percent C (Aslett Rubber Inc. n.d.).

Multiplying the mass of scrap tires combusted by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yields $CO_2$ emissions, as shown in Table A-105. The disposal rate of rubber in tires (0.3 MMT C/year) is smaller than the consumption rate for tires based on summing the elastomers listed in Table A-104 (1.3 MMT/year); this is due to the fact that much of the rubber is lost through tire wear during the product's lifetime and may also reflect the lag time between consumption and disposal of tires.

[65] The carbon content of tires (1,174 kt C) divided by the mass of rubber in tires (1,307 kt) equals 90 percent.

Tire production and fuel use for 1990 through 2023 were taken from USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022; USTMA 2024. For years where data were not reported, data were linearly interpolated or, for the ends of time series, set equal to the closest year with reported data.

In 2009, USTMA changed the reporting of scrap tire data from millions of tires to thousands of short tons of scrap tire. As a result, the average weight and percent of the market of light duty and commercial scrap tires was used to convert the previous years from millions of tires to thousands of short tons (STMC 1990 through 1997; USTMA 2002 through USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022; USTMA 2024).

## Table A-104: Elastomers Consumed in 2002 (kt)

| Elastomer | Consumed | Carbon Content | Carbon Equivalent |
|---|---|---|---|
| **Styrene butadiene rubber solid** | **768** | **91%** | **700** |
| For Tires | 660 | 91% | 602 |
| For Other Products[a] | 108 | 91% | 98 |
| **Polybutadiene** | **583** | **89%** | **518** |
| For Tires | 408 | 89% | 363 |
| For Other Products | 175 | 89% | 155 |
| **Ethylene Propylene** | **301** | **86%** | **258** |
| For Tires | 6 | 86% | 5 |
| For Other Products | 295 | 86% | 253 |
| **Polychloroprene** | **54** | **59%** | **32** |
| For Tires | 0 | 59% | 0 |
| For Other Products | 54 | 59% | 32 |
| **Nitrile butadiene rubber solid** | **84** | **77%** | **65** |
| For Tires | 1 | 77% | 1 |
| For Other Products | 83 | 77% | 64 |
| **Polyisoprene** | **58** | **88%** | **51** |
| For Tires | 48 | 88% | 42 |
| For Other Products | 10 | 88% | 9 |
| **Others** | **367** | **88%** | **323** |
| For Tires | 184 | 88% | 161 |
| For Other Products | 184 | 88% | 161 |
| **Total** | **2,215** | **NA** | **1,950** |
| **For Tires** | **1,307** | **NA** | **1,174** |

NA (Not Applicable)
[a] Used to calculate C content of non-tire rubber products in municipal solid waste.
Note: Totals may not sum due to independent rounding.

## Table A-105: Scrap Tire Constituents and $CO_2$ Emissions from Scrap Tire Combustion in 2023

| Material | Weight of Material (MMT) | Fraction Oxidized | Carbon Content | Emissions (MMT $CO_2$ Eq.) |
|---|---|---|---|---|
| Synthetic Rubber | 0.3 | 98% | 90% | 1.2 |
| Carbon Black | 0.4 | 98% | 100% | 1.4 |
| **Total** | **0.7** | **NA** | **NA** | **2.6** |

NA (Not Applicable)
Note: Totals may not sum due to independent rounding.

## $CH_4$ and $N_2O$ from the Combustion of Waste

Estimates of $N_2O$ emissions from the combustion of waste in the United States are based on the methodology outlined in the EPA's Compilation of Air Pollutant Emission Factors (EPA 1995) and presented in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2014), *Advancing Sustainable Materials Management: Facts and Figures: Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015; EPA 2016; EPA 2018; EPA 2019; EPA 2020) and unpublished backup data (Schneider 2007). According to this methodology, emissions of $N_2O$ from waste combustion are the product of the mass of waste combusted, an emission factor of $N_2O$ emitted per unit mass of waste combusted, and an $N_2O$ emissions control removal efficiency. The tonnage of MSW waste derived as described previously, including tires, is used in this calculation. An emission factor of 50 g $N_2O$/metric ton MSW based on the *2006 IPCC Guidelines* and an estimated emissions control removal efficiency of zero percent were used (IPCC 2006). It was assumed that all MSW combustors in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009).

Estimates of $CH_4$ emissions from the combustion of waste in the United States are based on the methodology outlined in IPCC's *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006). According to this methodology, emissions of $CH_4$ from waste combustion are the product of the mass of waste combusted and an emission factor of $CH_4$ emitted per unit mass of waste combusted. Similar to the $N_2O$ emissions methodology, the mass of waste combusted including tires was derived following the methods previously outlined. An emission factor of 0.20 kg $CH_4$/kt MSW was used based on the *2006 IPCC Guidelines* and assuming that all MSW combustors in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009).

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## 3.8. Methodology for Estimating Emissions from International Bunker Fuels used by the U.S. Military

Bunker fuel emissions estimates for the Department of Defense (DoD) were developed using data generated by the Defense Logistics Agency Energy (DLA Energy, 2025) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2023 fuel sales in the Continental United States (CONUS).[66] The methodology used for estimating emissions from international bunker fuels used by the U.S. Military is consistent with previous *Inventories*. This methodology is currently under review and will be updated in future as needed.

### References

DLA Energy (2025) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

[66] FAS contains data for 1995 through 2021, but the dataset was not complete for years prior to 1995. Using DLA aviation and marine fuel procurement data, fuel quantities from 1990 to 1994 were estimated based on a back-calculation of the 1995 data in the legacy database, the Defense Fuels Automated Management System (DFAMS). The back-calculation was refined in 1999 to better account for the jet fuel conversion from JP4 to JP8 that occurred within DoD between 1992 and 1995.

## 3.9. Methodology for Estimating Emissions from Other Fluorochemical Production

The *2006 IPCC Guidelines* as elaborated by the 2019 Refinement include Tier 1, Tier 2, and Tier 3 methods for estimating fluorinated GHG emissions from production of fluorinated compounds. The Tier 1 method calculates emissions by multiplying a default emission factor by total production. Specific default emission factors exist for production of $SF_6$ and $NF_3$; a more general default emission factor covers production of all other fluorinated GHGs. (The more general default emission factor was developed based on data from U.S. facilities collected under the GHGRP between 2011 and 2016.) The Tier 2 method calculates emissions using a mass-balance approach. The Tier 3 method is based on the collection of plant-specific data on the types and quantities of fluorinated GHGs emitted from process vents, leaks, container venting, and other sources, considering any abatement technology. The Tier 3 method is often implemented by developing and applying facility-specific emission factors indexed to production.

Based on available data on emissions and activity, EPA used a form of the IPCC Tier 3 method to estimate fluorinated GHG emissions from most U.S. production of fluorinated compounds. Emissions from U.S. production for which there are fewer data are based on the Tier 1 method.

### Overview of GHGRP Data for this Source Category

As discussed further below, much of the data used to develop the estimates presented here come from the GHGRP. The data were collected under two sections of the GHGRP regulation—Subpart L, Fluorinated Gas Production; and Subpart OO, Suppliers of Industrial Greenhouse Gases. Under Subpart L, certain fluorinated gas production facilities must report their emissions from a range of processes and sources, detailed further below. Data collected under Subpart L include emissions data for calendar years 2011 through 2023. Under Subpart OO, fluorinated GHG suppliers (including fluorinated GHG producers) must report the quantities of each fluorinated GHG that they produce, transform, destroy, import, or export. Data collected under Subpart OO include production and transformation data for calendar years 2010 through 2023. Facilities' production and transformation data are not shown here because they are considered confidential business information under the GHGRP.

***Emissions Reported Under Subpart L of the GHGRP***

Under Subpart L, facilities that produce a fluorinated gas must report their greenhouse gas emissions if the facility emits 25,000 MT $CO_2$ Eq. or more per year in combined emissions from fluorinated gas production, stationary fuel combustion units, miscellaneous uses of carbonate, and all other applicable source categories listed in the rule. (For purposes of calculating emissions from fluorinated gas production for inclusion in the total that is compared to the threshold, emissions are assumed to be uncontrolled.) Facilities must report their fluorinated GHG emissions from the production and transformation of fluorinated gases, from venting of residual fluorinated GHGs from containers, and from destruction of previously produced fluorinated GHGs. The emissions reported from production and transformation include both emissions from process vents and emissions from equipment leaks.

Under the GHGRP, "fluorinated GHGs," whose emissions must be reported, include $SF_6$, $NF_3$, and any fluorocarbon except for substances with vapor pressures below 1 Torr at 25 degrees C and substances that are regulated as "controlled substances" under EPA's ozone-protection regulations at 40 CFR Part 82, Subpart A (e.g., chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], and halons). In addition to $SF_6$ and $NF_3$, this definition includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), hydrofluoroethers (HFEs), fully fluorinated tertiary amines, perfluoropolyethers (including PFPMIE), and hydrofluoropolyethers, and others.

"Fluorinated gases," from whose production or transformation emissions must be reported, include the fluorinated GHGs detailed above as well as CFCs and HCFCs.[67]

Facilities calculate emissions from process vents using one of two methods. For vents that emit 10,000 MT $CO_2$ Eq. or more (considering controls) of fluorinated GHGs from continuous processes, facilities must use emissions testing to establish an emission factor at least every ten years, or sooner if the process changes in a way that will significantly affect emissions from the vent. For other process vents, facilities may use measurements, engineering calculations, or engineering assessments to establish the emission factor. Facilities then calculate their annual emissions based on the measured or calculated emission factor and related activity data, considering the extent to which the process is controlled and any destruction device or process malfunctions.

To calculate emissions from equipment leaks, facilities that report under Subpart L are required to collect information on the number and type of pieces of equipment; service of each piece of equipment; concentration of each fluorinated GHG in the stream; and the time period each piece of equipment was in service. Facilities use one or more of the following methods to calculate emissions from equipment leaks (EPA 1995):

- Average Emission Factor Approach in EPA Protocol for Equipment Leak Estimates.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with EPA Method 21.
- Other Approaches in EPA Protocol for Equipment Leak Estimates in conjunction with site-specific leak detection methods.
- Site-specific leak detection methods.

Most emissions are reported by chemical; the exceptions are (1) fluorinated GHGs that are emitted in quantities of 1,000 MT $CO_2$ Eq. or less across all production and transformation processes at a facility and (2) fluorinated GHGs that are emitted from facilities that produce only one fluorinated GHG, where the emitted fluorinated GHG is not the fluorinated gas produced. In these cases, the emissions are reported in $CO_2$ Eq. by fluorinated GHG group. There are 12 fluorinated GHG groups, each of which encompasses a set of GHGs with roughly similar atmospheric behavior, including similar GWPs and atmospheric lifetimes. These include, e.g., fully fluorinated GHGs such as PFCs and $SF_6$, saturated HFCs with two or fewer carbon-hydrogen bonds, saturated HFCs with more than two carbon-hydrogen bonds, unsaturated HFCs and PFCs, and others (see Table A-106 for a full list).

### Table A-106: Fluorinated GHG Groups Under Which Certain Emissions Are Reported Under Subpart L of the GHGRP and Associated GWPs

| Fluorinated GHG Group | GHGRP Default Global Warming Potential (100-yr.) |
|---|---|
| Fully fluorinated GHGs | 10,000 |
| Saturated hydrofluorocarbons (HFCs) with 2 or fewer carbon-hydrogen bonds | 3,700 |
| Saturated HFCs with 3 or more carbon-hydrogen bonds | 930 |
| Saturated hydrofluoroethers (HFEs) and hydrochlorofluoroethers (HCFEs) with 1 carbon-hydrogen bond | 5,700 |
| Saturated HFEs and HCFEs with 2 carbon-hydrogen bonds | 2,600 |
| Saturated HFEs and HCFEs with 3 or more carbon-hydrogen bonds | 270 |
| Fluorinated formates | 350 |
| Fluorinated acetates, carbonofluoridates, and fluorinated alcohols other than fluorotelomer alcohols | 30 |

[67] HCFC-22 is considered a fluorinated gas under the GHGRP, but emissions from HCFC-22 production are reported separately from emissions from production of other fluorinated gases.

| | |
|---|---|
| Unsaturated PFCs, unsaturated HFCs, unsaturated HCFCs, unsaturated halogenated ethers, unsaturated halogenated esters, fluorinated aldehydes, and fluorinated ketones | 1 |
| Fluorotelomer alcohols | 1 |
| Fluorinated GHGs with carbon-iodine bond(s) | 1 |
| Other fluorinated GHGs | 2,000 |

Two other datasets reported under Subpart L are relevant to estimating uncontrolled emission factors. (As discussed further below, such uncontrolled emission factors are applied to years before Subpart L reporting began (for CY 2011) and before emission controls were put into place.) First, in addition to reporting emissions by chemical at the facility level, facilities report emissions from each production and transformation process at the facility in tons of $CO_2$ Eq. by fluorinated GHG group. To calculate $CO_2$ Eq. emissions, facilities use a chemical-specific 100-year GWP where one is available for the compound of interest. If no chemical-specific 100-year GWP is available for the compound of interest, facilities use the GHGRP default GWP for the fluorinated GHG group of which the compound is a member. These default GWPs are shown in Table A-106.

Second, for each process, facilities also report the extent to which emissions are abated (the effective destruction efficiency or EDE) as a range. The EDE is calculated as follows:

$$EDE = 1 - \frac{CE_{PV}}{UE_{PV}}$$

where:

| | | |
|---|---|---|
| EDE | = | Effective destruction efficiency of the process |
| $CE_{PV}$ | = | Actual GWP-weighted controlled emissions from all vents for the process, MT $CO_2$ Eq. |
| $UE_{PV}$ | = | Hypothetical GWP-weighted uncontrolled emissions from all vents for the process, MT $CO_2$ Eq. ($CE_{PV}$ will equal $UE_{PV}$ if the process is not controlled, resulting in a calculated EDE of 0). |

Note that the EDE is based on the extent to which emissions from process vents are controlled. Emissions from equipment leaks are not included in the EDE calculation. Table A-107 provides the EDE ranges available for facilities to report and the arithmetic means of each range. The use of these datasets to calculate uncontrolled emission factors is discussed in more detail in the "1990-2010 Emissions Estimates" section below.

***Verification of GHGRP Reports***

Data reported under the GHGRP, including emissions and production, are electronically verified using range checks, internal consistency checks, and time-series consistency checks. Where the data fail a preliminary check, EPA contacts the facility to see whether there is an explanation for the issue or whether the data are indeed erroneous. In the latter case, facilities are required to correct the data. Where one or more of the anomalous data elements is not explained or corrected, the report for that facility for that year is considered unverified.

## 1990-2010 Emissions Estimates

For 14 of the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions are estimated using (1) facility- and chemical-specific emission factors based on the emissions data discussed under "2011-2023 Emissions" below, (2) reported or estimated production and transformation of fluorinated GHGs at each facility in each year, i.e., activity data, and (3) reported and estimated levels of emissions control at each facility in each year. (For the other 3 fluorinated gas production facilities that have reported their emissions under the GHGRP, 1990 through 2010 emissions were estimated using data submitted by the company, as explained further below.)

***Facility- and Chemical-Specific Emission Factors Reflecting Emissions Controls***

Facility- and chemical-specific emission factors were developed based on the 2011 to 2015 emissions reported under the GHGRP (discussed above) and the 2011 to 2015 production and transformation of fluorinated GHGs reported under the GHGRP. (Production and transformation of CFCs and HCFCs are not reported under the GHGRP.) For each emitted fluorinated GHG at each facility, emissions of the fluorinated GHG were summed over the five-year period. This sum was then divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility over the five-year period.[68] As discussed further below in the Uncertainty section, emissions of any particular fluorinated GHG are likely to occur only from a subset of the production or transformation processes at each facility, but in the absence of information on chemical-specific emissions at the process level, it was assumed that all fluorinated GHG production and transformation processes at the facility emit all fluorinated GHGs at the facility. This yielded the emission factors for each fluorinated GHG at each facility. Both emissions and activity (production + transformation) totals were summed over the five-year period to account for the intermittent and variable nature of some emissions and production/transformation processes. Compounds that were not emitted or produced/transformed between 2011 and 2015 but that were emitted or produced/transformed later were assumed not to have been emitted or produced/transformed (as applicable) before 2011.

***Facility- and Chemical-Specific Emission Factors Reflecting No Emissions Controls***

The 2011 to 2015 emissions reported under the GHGRP reflect emissions controls to the extent those are implemented at each facility. Because facilities have not always controlled their fluorinated GHG emissions since 1990, uncontrolled emission factors were developed for each facility to apply to years when the facility's emissions were not believed to be controlled. To estimate uncontrolled emissions, GHGRP data were first used to assess the 2011 to 2015 levels of control for each production or transformation process at each facility.

To calculate uncontrolled emissions from each process and fluorinated GHG group, a point estimate of the effective destruction efficiency (EDE, described above) was required and was estimated using the arithmetic mean of the lower and upper bounds of the EDE range reported for the process.[69] This was consistent with the approach taken in the *2019 Refinement* to develop the Tier 1 factor for fluorinated gas production facilities. The reported vented emissions for each process and fluorinated GHG group were divided by (1 - arithmetic mean EDE) to obtain the estimated uncontrolled emissions from process vents for that process and fluorinated GHG group. For each fluorinated GHG group at a facility, the controlled emissions across processes (including emissions from both vents and leaks) and the uncontrolled emissions across processes (including emissions from both vents and leaks) were then summed, and the first was divided by the second. This yielded an average level of control for each fluorinated GHG group at each facility. All fluorinated GHGs within each fluorinated GHG group at each facility were assumed to be controlled to the same level. To estimate the uncontrolled emissions of each fluorinated GHG within each group at each facility, the emissions of each fluorinated GHG were divided by the level of control estimated for its fluorinated GHG group at the facility. The same procedure was used to estimate uncontrolled emission factors as had been used to estimate controlled emission factors: the estimated uncontrolled 2011 to 2015 emissions of each fluorinated GHG were summed, and this sum was divided by the sum of the quantities of all fluorinated GHGs produced or transformed at the facility from 2011 to 2015.

**Table A-107: Destruction Efficiency Range Values Used to Estimate Pre-Abatement Emissions for Production and Transformation Processes**

| DE ranges | Lower Bound | Upper Bound | Arithmetic Mean of Bounds |
|---|---|---|---|
| >=0% to <75% | 0.0 | 0.75 | 0.375 |

[68] Permit data for two facilities indicated that they began controlling emissions at some point between 2011 and 2015. However, the actual emissions reported by these facilities did not change substantially after the date when the permit indicated that controls were imposed. For this reason, the reported 2011 to 2015 emissions and emission factors are believed to be representative of emissions for these facilities before 2011.

[69] Note that facilities would report a range of 0% to 75% even if they do not abate emissions at all; thus, the assumption that emissions are 37.5 percent controlled may overestimate the hypothetical uncontrolled emissions of some facilities, e.g., those that do not abate any emissions.

| | | | |
|---|---|---|---|
| >=75% to <95% | 0.75 | 0.95 | 0.85 |
| >=95% to <99% | 0.95 | 0.99 | 0.97 |
| >=99% | 0.99 | 0.9999 | 0.995 |

***Estimated Levels of Emissions Controls***

As discussed above, both uncontrolled emission factors and controlled emission factors were developed for each facility and fluorinated GHG; these emission factors were developed for estimating emissions from production and transformation processes for years 1990 to 2010. The following information and assumptions were used to determine whether and when emissions from facilities were likely to have been controlled from 1990 to 2010. For the estimated status of emissions controls at each facility reporting under Subpart L, and, where relevant, the starting year for those controls, see Table A-108.

- Facilities with publicly available information on the presence and use of control devices were assumed to control their emissions starting in the year specified in the publicly available information. Publicly available information included operating permits, news articles on facility modifications, company press releases, etc. Where the publicly available information documents that a control device was in place beginning in a certain year, the facility was assumed to control process emissions beginning in that year, and the controlled emission factor was used in estimating emissions for that year and the following years. The uncontrolled emission factor was used to estimate emissions in earlier years.
- In the absence of other control information, facilities that never reported DRE ranges other than “>=0% to <75%” for their production and transformation processes during reporting years 2011 and 2012 were assumed to have no control devices in place during the time period 1990 to 2012.
- Facilities that reported DRE ranges other than “>=0% to <75%” for at least one production or transformation process for 2011 or 2012 but for which other control information was not available were assumed to have begun controlling their emissions in 2005.

## Table A-108: Estimated Starting Years for Emission Controls at Each Fluorinated Gas Production Facility Reporting under Subpart L of the GHGRP

| Facility Name | Estimated Start Year | Basis of Estimation |
|---|---|---|
| 3M COMPANY | No controls | Never reported a DRE range other than “>=0% to <75%” |
| 3M CORDOVA | 2003 | Climate News Article[70] |
| 3M Cottage Grove Center - Site | 2016 | Reported a DRE range other than “>=0% to <75%” for the first time in 2016 |
| Airgas Therapeutics LLC - Scott Medical Products | No controls | Never reported a DRE range other than “>=0% to <75%” |
| ANDERSON DEVELOPMENT COMPANY | No controls | Never reported a DRE range other than “>=0% to <75%” |
| ARKEMA, INC. | 2005 | Reported a DRE range other than “>=0% to <75%” in 2011 |
| Chemours - Corpus Christi Plant | No controls | Never reported a DRE range other than “>=0% to <75%” |
| CHEMOURS CHAMBERS WORKS | 2000 | Facility correspondence indicates controls were in place by 2000; also reported a DRE range other than “>=0% to <75%” in 2011 |

[70] See https://insideclimatenews.org/news/29122022/3m-cordova-illinois-pfas-cf4-pollution/.

| | | |
|---|---|---|
| CHEMOURS COMPANY - FAYETTEVILLE WORKS | 2015 | Reported a DRE range other than “>=0% to <75%” for the first time in 2015 |
| CHEMOURS EL DORADO | 2005 | Reported a DRE range other than “>=0% to <75%” in 2011 |
| CHEMOURS LOUISVILLE WORKS | No controls | Never reported a DRE range other than “>=0% to <75%” |
| CHEMOURS WASHINGTON WORKS | 2000 | Facility indicated controls were in place by 2000 in comments on GHG Inventory estimates. |
| DAIKIN AMERICA INC. | 1993 | Title V operating permit[71] |
| HONEYWELL INTERNATIONAL INC - BATON ROUGE PLANT | 2012 | Title V operating permit[72] |
| HONEYWELL INTERNATIONAL INC - GEISMAR COMPLEX | 2011 | Title V operating permit[73] |
| Honeywell Metropolis | No controls | Never reported a DRE range other than “>=0% to <75%” (did not report under Subpart L) |
| MEXICHEM FLUOR INC. | 1993 | Title V operating permit[74] |
| Versum Materials US, LLC | No controls | Never reported a DRE range other than “>=0% to <75%” |

### *Activity Data*

The activity data for production and transformation of fluorinated compounds for 1990 to 2010 are based on production and transformation data reported to EPA by certain facilities for certain years, on production capacity data, and on fluorinated GHG production and consumption trends estimated for the various fluorinated GHG-consuming industries.

#### Production and Production Capacity Data

Production data are available from reporting to the U.S. GHGRP under Subpart OO, Suppliers of Industrial Greenhouse Gases, and from an industry survey conducted by U.S. EPA in 2008 and 2009. Production and transformation data were reported under Subpart OO for 2010 and later years. The responses to the industry survey included production data for certain fluorinated gases at certain facilities for the years 2004, 2005, and 2006. 2004 to 2006 production data are available for 15 fluorinated compounds. Year 2006 production at an $SF_6$-producing facility was estimated based on production capacity data as described below (Rand 2007). Production of certain compounds at one other facility was estimated based on 2003 production capacity estimates from SRI 2004.

#### Estimated Production

Estimated production for facilities and fluorinated GHGs for which production or production capacity data were available for some years before 2010.

For facilities and fluorinated GHGs for which production or production capacity data were available for 2006 or 2003, production between 2006 or 2003 (as applicable) and 2010 (or 2011) was estimated by interpolating between the 2006 production or 2003 production capacity value and the 2010 (or 2011) production value reported under Subpart OO. To account for production occurring in some years but not others, production for 2009 was estimated to be the average production for 2010 to 2015.

[71] Daikin (2013) http://lf.adem.alabama.gov/WebLink/DocView.aspx?id=29951882&dbid=0.

[72] Honeywell (2011) https://edms.deq.louisiana.gov/app/doc/view?doc=8579001.

[73] Honeywell (2012) https://edms.deq.louisiana.gov/app/doc/view?doc=7812895.

[74] See https://edms.deq.louisiana.gov/app/doc/view?doc=1309650.

For the years before the earliest year with production or production capacity data (e.g., years 1990 to 2002 or 2003), production was estimated based on growth or consumption trends for the major industries using each fluorinated GHG.

- For fluorinated compounds that are commonly emitted in the semiconductor industry, estimates of U.S. layer-weighted semiconductor production (Total Manufactured Layer Area, or TMLA) were used to inform the fluorinated compound production estimates (EPA 2023c). Fluorinated compound production values were assumed to vary with TMLA from 1990 to 2002 or 2003. For example, 1998 production of PFC-14 at a particular facility was estimated by multiplying the 2003 production of PFC-14 at that facility by the ratio between the TMLA estimated for 1998 and the TMLA estimated for 2003. Fluorinated compounds for which TMLA was used to estimate production include PFC-14, PFC-116, PFC-218, perfluorocyclobutane ($c\text{-}C_4F_8$), and $NF_3$. (Note that the TMLA data were also extrapolated from year 1995 to 1990 based on the average change per year from 1995 to 2009.)

- $SF_6$ is commonly used in electric power systems, magnesium production, and electronics manufacturing. $SF_6$ consumption estimates across these three industries for 1990 to 2003 were used to inform the $SF_6$ production data (EPA 2023d); $SF_6$ production was assumed to vary with consumption totals from 1990 to 2003.

- For HFCs commonly used as replacements for ozone-depleting substances (ODS), such as HFCs used as substitutes for CFCs and HCFCs in air-conditioning and refrigeration equipment, HFC production data for certain fluorinated compounds from the Vintaging Model (VM) were used to inform the HFC production estimates (EPA 2023b). HFC production values were assumed to vary with the VM estimates of production. The industry trend data were applied to the list of HFCs in Table A-109.

## Table A-109: List of Saturated HFCs, Unsaturated HFCs (Hydrofluoroolefins or HFOs), and Unsaturated HCFCs (Hydrochlorofluoroolefins or HCFOs) whose 1990-2009 Production Was Estimated Using Vintaging Model, Virgin Manufacturing by Chemical

| Fluorinated Gas |
|---|
| HFC-23 |
| HFC-32 |
| HFC-125 |
| HFC-134a |
| HFC-143a |
| HFC-152a |
| HFC-236fa |
| HFC-245fa |
| HFC-365mfc |
| HCFO-1233zd(E) |
| HFO-1234yf |
| HFO-1234ze |
| HFO-1336mzz(Z) |
| HFC-4310mee |

**Estimated production for facilities and fluorinated GHGs for which production data before 2010 were not available.**

In the absence of production data for the period 1990 to 2009, the production data reported to the GHGRP under Subpart OO were extrapolated backward based on the industry trends discussed above. For compounds for which industry trend data were unavailable, production was assumed to have remained constant over the time series.

In both cases, 2009 production was estimated by conducting a trend analysis on the Subpart OO production data for years 2010 to 2015. In instances where there did not appear to be a trend, the average of the production values for years 2010 to 2015 was used as the estimated production for year 2009. In instances where there was a trend, the year 2010 (or 2011) production value was used as the estimated production for year 2009.

If the industry trend information discussed above was applicable to a fluorinated compound, it was assumed that production varied with the industry trend from 1990 to 2009. If no industry trend information was available, it was assumed that production from 1990 to 2008 remained constant at the 2009 value.

For facilities and fluorinated compounds where information was available on annual production capacity, the estimated activity data was reviewed and compared to the known production capacity. For instances where the estimated activity data exceeded known production capacity for a certain year, the production estimate was set equal to the capacity value. In addition, where information was available on the starting year for production of a fluorinated GHG at a facility, production was only estimated beginning in the process startup year through 2009.

***Estimated Emissions for 3M Facilities***

3M provided 1990, 1995, 2000, and 2002 through 2010 emissions data for three facilities: 3M Cordova, 3M Company, and 3M Cottage Grove Center - Site.[75] Therefore, speciated 1990-2010 emissions at these facilities were estimated using a different methodology than that described above.[76]

3M emissions data were provided by facility and by fluorinated GHG group in metric tons of $CO_2$ Eq., weighted by 100-year GWPs from various IPCC Assessment Reports. The fluorinated GHG groups included HFCs, PFCs, $SF_6$, HFEs, and other fluorinated GHGs. (3M noted that the "other fluorinated GHG" category included $NF_3$.) GWPs from the IPCC *Third Assessment Report* (TAR) were used to report totals for 1990, 1995, 2000, and 2003 to 2006. GWPs from the IPCC *Fifth Assessment Report* (AR5) were used to report totals for 2002, and GWPs from the IPCC *Fourth Assessment Report* (AR4) were used to report totals for 2007 to 2010. The emissions were also categorized as emissions from electrochemical fluorination (ECF) processes and downstream (DS) emissions. The DS emissions for 1990, 1995, and 2000 were reported as a total for each facility rather than by fluorinated GHG group.

To present emissions estimates by compound, EPA needed to disaggregate the data provided by 3M. The first step was to disaggregate the 1990, 1995, and 2000 DS emissions into fluorinated GHG groups. Since the 2003 to 2006 data were calculated using the same set of GWPs as the 1990, 1995, and 2000 data, the DS emissions of each group at each facility for 2003 to 2006 were divided by the total DS 2003 to 2006 emissions at that facility to obtain a set of fractions. These fractions were then multiplied by the 1990, 1995, and 2000 DS totals to sort those emissions into groups.

For 2002, ECF and DS emissions were only reported under the PFC group. (3M noted that chemical classifications were not preserved when 2002 emissions were recalculated using GWP values from AR5.) Since data for every other year showed emissions reported from multiple fluorinated GHG groups, and since 2004 was the closest year with emissions well sorted into fluorinated GHG groups, the ECF and DS emissions for 2002 were separated into multiple fluorinated GHG groups using the 2004 ECF and DS groups shares for each facility.

The next step was to disaggregate the emissions of each fluorinated GHG group into emissions of the relevant compounds in that group. To accomplish this, EPA assumed that emissions of each fluorinated GHG group before 2011 consisted of the same fluorinated GHGs, in the same proportions, as from 2011 through 2015. However, each

[75] For 1990, 1995, and 2000, 3M provided emissions data for a Pilot Development Center in addition to the other three facilities. Emissions by group from the Pilot Development Center were added to and are represented by the emissions by group for 3M Cottage Grove Center – Site.

[76] 3M's methods for estimating its emissions are described in detail in "3M Global EHS Laboratory Response to EPA Data Request on Fluorochemical Emissions," February 2024 (3M, 2024). In brief, 3M estimated emissions from its processes using emission factors that were developed using methods similar to those used for developing emission factors under the GHGRP. As under the GHGRP, emission factors were multiplied by different types of activity data (e.g., production) to estimate emissions for each facility and year. In 2003 and later years, 3M also accounted for emission reductions attributable to operation of the thermal oxidizer at the Cordova plant.

compound’s share of the GWP-weighted emissions of the group in a given year depends on the GWPs used for that compound and for the other compounds in the group in that year. To account for this, EPA multiplied the reported 2011 to 2015 emissions of each compound in metric tons by the corresponding GWPs for that compound from the TAR, AR4, and AR5 to generate three sets of emissions by compound in metric tons of $CO_2$ Eq. For each set, the sum of emissions across 2011 to 2015 for each compound were divided by the total emissions for the corresponding fluorinated GHG group for those five years to calculate shares for each group.

The 3M emissions data by group for 1990, 1995, 2000, and 2002 to 2010 were then speciated by compound using the appropriate set of share values for each year. Since 3M Company only reported emissions of one compound in 2011 to 2015 but had emissions from multiple fluorinated GHG groups in 1990, 1995, 2000, and 2002 to 2010, the share values for 3M Cordova were used to speciate the 1990, 1995, 2000, and 2002-2010 emissions by group for 3M COMPANY. The speciated emissions in metric tons of $CO_2$ Eq. by compound for each facility were then divided by the appropriate TAR, AR4, or AR5 GWP for each compound to obtain the estimated emissions in metric tons of each compound for 1990, 1995, 2000, and 2002 to 2010.

Linear interpolation was then used to estimate emissions for 1991 to 1994, 1996 to 1999, and 2001 for each compound for these three facilities.

***Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L***

There is a subset of facilities that report production and transformation of fluorinated gases under Subpart OO and that also have emission levels less than the threshold value for reporting under Subpart L (i.e., uncontrolled emissions below the 25,000-MT $CO_2$ Eq. threshold). For these facilities, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table. Emissions are assumed to have been flat at the 2010 value in the years before 2010.

***Estimated Emissions for $SF_6$ Production Facility***

For an $SF_6$ production facility that ceased production in 2010, the year before emissions from fluorinated gas production were required to be reported under the GHGRP, $SF_6$ emissions were estimated using historical production capacity, the global growth rate of $SF_6$ sales reported in RAND 2007, and the Tier 1 default emission factor for production of $SF_6$ in the 2019 Refinement. For this plant, a 1982 $SF_6$ production capacity of 1,200 short tons (Perkins 1982) was multiplied by the ratio between the RAND survey $SF_6$ sales totals for 2006 and 1982, 1.52 (RAND 2007), resulting in estimated production of 1,652 metric tons in 2006. This production was assumed to have declined linearly to zero in 2011.

## 2011-2023 Emissions Estimates

For the 17 fluorinated gas production facilities that have reported their emissions under the GHGRP, 2011 to 2023 emissions are estimated using the fluorinated GHG emissions reported under Subpart L of the GHGRP.

As discussed above, most emissions reported under Subpart L are reported by chemical, but some emissions are reported only by fluorinated GHG group in MT $CO_2$ Eq. Between 2011 and 2023, the share of total $CO_2$ Eq. emissions reported only by fluorinated GHG group has ranged between 1 and 2 percent. In this analysis, to ensure that all emissions are reported by species, emissions that are reported only by fluorinated GHG group are assumed to consist of the fluorinated GHGs in that group that are reported by chemical at the facility in that year. When no fluorinated GHGs in the group are reported by chemical by that facility in that year, the emissions are assumed to consist of fluorinated GHGs in that group reported in other years at that facility. If no fluorinated GHGs in that group were ever reported by chemical by the facility, the emissions are assumed to consist of fluorinated GHGs in that group reported across the industry for that year. Because 3M facilities emitted many more individual compounds than the rest of the industry, fluorinated GHG groups at non-3M facilities were assumed to consist of fluorinated GHGs in groups as reported at other non-3M facilities. In each of these scenarios, fractions of gases emitted in mtCO2e from each fluorinated GHG group were established and applied to the total mtCO2e emitted from a fluorinated GHG group to calculate emissions in mtCO2e of each individual fluorinated GHG. As discussed further in the Uncertainty section, this is likely to result in incorrect speciation of some emissions, but the impact of this incorrect speciation is expected to be small.

***Estimated Emissions for Facilities that Produce Fluorinated GHGs but Do Not Report Under Subpart L***

As discussed above, for facilities that produce fluorinated GHGs but that do not report their emissions under subpart L, EPA developed emission estimates based on aggregated production estimates and the Tier 1 default emission factor in the 2019 Refinement. Because the specific fluorinated GHGs emitted are not known, the emissions were assumed to consist of the fluorinated GHGs shown in Table 3.28b of chapter 3.10.2 of Volume 3 IPPU (IPCC 2019), in the proportions shown in that table.

### Uncertainty

The estimates in this memo are subject to a number of uncertainties. These uncertainties are generally greater for years before 2011, when reporting of fluorinated GHG emissions from fluorinated gas production began under the GHGRP, than for 2011 and following years. However, the emissions estimated from 2011 to 2023 are also subject to various uncertainties. The uncertainties for both the 1990 to 2010 and 2011 to 2023 periods are discussed in more detail below.

## 1990-2010 Uncertainty

The uncertainty of emissions estimated for 1990 through 2010 is considerably greater than that for emissions for 2011 through 2023 because emissions were not reported under the GHGRP. EPA has estimated emissions using estimated emission rates, fluorochemical production and transformation activity, and levels of control, and each set of estimates is subject to uncertainty.

***Uncertainty regarding activity data***

**Identity of emitting processes**

In reality, emissions of particular fluorinated GHGs are linked to production and/or transformation of particular fluorinated gases at facilities. However, GHGRP information/data does not link emissions of specific fluorinated GHGs to production or transformation of specific fluorinated gases. For the estimates presented here, therefore, all emissions are indexed to total production across all fluorinated gases. This may not capture trends in emissions that are driven by trends in production or transformation of subsets of the fluorinated gases produced at a facility.

**Produced and emitted gases change over time**

The set of gases produced at a facility, and therefore the set of fluorinated GHGs that are emitted by that facility, may change over time. It is likely that certain production and transformation processes that existed from 2011 to 2015 (the basis of the emission factors used to back-cast emissions in this analysis) did not exist throughout the entire previous time series (1990 to 2010). In such cases, emissions of the fluorinated GHGs emitted from the new processes will be overestimated by this analysis for certain years before 2011. On the other hand, it is also likely that some production and transformation processes, and their associated fluorinated GHG emissions, occurred only during the 1990 to 2010 period and not later, meaning that their emissions are not represented in the emission factors developed based on the 2011 to 2015 emissions and production data collected under the GHGRP. Such emissions will therefore not be captured by this analysis. The most prominent example of the second situation is probably production of CFCs and HCFCs other than HCFC-22 between 1990 and 2009, which has declined steadily since 1990 as the production of CFCs and HCFCs for emissive uses has been phased out in the United States and Globally. Production of CFCs and HCFCs can sometimes result in emissions of HFCs or PFCs.

**Quantity of produced gases**

Where production or production capacity data were available for certain fluorinated gases, facilities, and years before 2010, those data were incorporated into this analysis. However, even for facilities and compounds for which data were available in certain years, there were several years for which data were not available. For multiple produced compounds, data were available only in 2010. To estimate trends in production of compounds for years before production or production capacity data were available, production of certain compounds was indexed to known national production or consumption trends for those compounds. This is the case for most HFCs, several PFCs, $SF_6$, and $NF_3$. National production estimates are available for HFCs, increasing confidence in country-level production estimates, but the distribution of production among the various HFC-producing facilities is uncertain. Where estimated production was indexed to consumption (for several PFCs, $SF_6$, and $NF_3$), the uncertainty is larger than for HFCs because changes in net imports/exports (which are not known) may also affect the production trend.

For certain fluorinated gases, trend information was not available; therefore, production was back-cast by assuming that it had remained constant at the 2010 level from 1990 through 2009. This is a highly uncertain assumption.

**Some production and transformation activity is not reported under Subpart OO or modeled in back-casting**

Under Subpart OO, quantities of fluorinated GHGs that are produced and transformed at the same facility are not reported to us, although any emissions from such processes are reported under Subpart L. Such unreported production and transformation are therefore not captured in the 1990 to 2010 activity estimates used to estimate 1990 through 2010 emissions. To the extent that such unreported production and transformation drive emissions and change over time, the trends will not be captured by this analysis.

**Facilities that no longer produce fluorinated gases or that started producing them after 1990**

Some facilities may have produced fluorinated gases at some point between 1990 and 2010 that no longer produced those compounds after 2010. One $SF_6$ producer is known to fall into this category and its 1990 to 2010 emissions were estimated, but there may be other facilities that are not included in this analysis. On the other hand, some facilities for which 1990 to 2010 emissions were estimated may not have produced them over the entire time series, in which case emissions of the compounds those facilities are assumed to have emitted could be overestimated.

***Uncertainty regarding emission factors***

**Emission rates change over time**

The emission factors used to estimate 1990 to 2010 emissions are based on the emissions and production reported from 2011 to 2015, reflecting emission rates during that period. For processes that have been used throughout the timeseries, emission rates may have changed over time as the process was optimized to increase efficiency, decreasing by-product emissions, or alternatively, as the process was optimized to maximize production, which sometimes increases by-product emissions. Emission rates also depend on the extent to which emissions are controlled at the facility, the uncertainties for which are discussed further below.

**Emissions from container venting and destruction may not scale with production**

In this analysis, emissions from container venting and destruction of previously produced fluorinated GHGs were included in the emission factors used to estimate 1990 to 2010 emissions. This implicitly assumes that such emissions scale with production and transformation. While this seems likely to be broadly true, there may be exceptions. However, since emissions from container venting and destruction are generally a small share of facility emissions (2 percent, on average), the impact of such exceptions is expected to be small.

**Uncertainty regarding levels of control**

In this analysis, the arithmetic mean of the DRE range reported by each facility for each process was used to estimate the DRE for that process and the uncontrolled emissions for that process. Since the emissions implied by the bounds of each DRE range span at least a factor of four,[77] this is an uncertain assumption. The uncertainty is mitigated somewhat by the fact that there are generally several processes at each facility, meaning that departures from the assumed mean average out to some extent. There is also uncertainty in the assumptions that (1) all fluorinated GHGS within a particular fluorinated GHG group are abated to the same extent and (2) facilities for which control device start dates are unavailable began to control emissions in 2005.

**Quantitative uncertainty estimate for uncontrolled emission factors from *2019 Refinement***

As noted above, 2011 to 2016 data from the GHGRP was used to develop the Tier 1 default uncontrolled emission factor for the *2019 Refinement*, using methods similar to those described here. A Monte Carlo analysis performed to assess the uncertainty of the Tier 1 default factor indicated that the uncertainty for each facility's uncontrolled emission factor was less than 50 percent. This uncertainty estimate considered the uncertainty regarding the levels of control, but not the uncertainty of applying factors from one time period at the facility to much earlier time period (although the variability of each facility's emission factor over the 6-year span of the *2019 Refinement* analysis was found to be relatively low).

***Uncertainty regarding the identity of 3M emitted compounds***

For the three 3M facilities that submitted their 1990 through 2010 emissions by fluorinated GHG group, it is assumed that the emissions of each group consist of the compounds in that group that were reported by species by the facility from 2011 through 2014. However, 3M indicated that the mix of products made at its facilities had changed over time, which would have affected the identities of the fluorinated GHGs emitted. For example, at one facility, only one compound was reported to be emitted for 2011-2015 but 3M's historical emissions data showed multiple fluorinated GHG groups for that facility for 1990 to 2010. For that facility, it is assumed that emissions consisted of the compounds in each gas type that were reported by species by the 3M facility that was determined to be the most similar. Additionally, there were a few years of data for these three facilities where some emissions were reported as a total rather than separated by group. For these years, the group shares were assumed to be the same as in nearby years. There is uncertainty involved with each of the assumptions made while speciating emissions for these three facilities, though the uncertainty is minimal regarding total emissions in metric tons of $CO_2$ Eq. In at least one case, the speciation method appears to have resulted in an overestimate for an individual compound. In this analysis, 3M's emissions of $C_4F_8O$ are estimated to have peaked at around 410 MT in 2000, but at least one study has inferred considerably lower global emissions (around 120 MT) for that year based on atmospheric measurements of $C_4F_8O$ (Vollmer et al. 2019).

## 2011-2023 Uncertainty

Emissions from 2011 to 2023 reflect reporting by fluorinated gas production facilities under the GHGRP. As discussed above, emissions reported under the GHGRP are based on facility- and process-specific measurements or calculations and are therefore expected to be reasonably accurate for the reporting facilities. (Emissions from the largest sources, process vents emitting 10,000 MT $CO_2$ Eq. or more annually, are estimated using Tier 3 methods.)

***Unverified reports*** Ninety-four percent (184/196) of the Subpart L reports submitted by fluorinated gas production facilities from 2011 to 2023 are considered to be fully verified; seven percent (12/196) of the reports include one or more data elements that are not verified. One facility accounts for 58 percent (7/12) of the unverified reports. Many of the issues in the unverified reports for this facility relate to time-series inconsistencies that have arisen as the facility updates reports for recent years, but not previous years, to reflect refinements to estimated emission rates. This facility has accounted for between 6 percent (in 2011) and 29 percent (in 2022) of the GWP-weighted

[77] For example, the DRE range 0 to 75% implies emissions of (1-0) x uncontrolled emissions to (1-75%) x uncontrolled emissions, or, rearranging and calculating, 0.25 x uncontrolled emissions to 1 x uncontrolled emissions, a factor of four.

emissions reported for this source category. The uncertainties for this facility therefore have an appreciable impact on the uncertainty of the estimates for the source category as a whole.

***Facilities that do not produce fluorinated gases but may emit fluorinated GHGs from other fluorochemical production processes***

Under the GHGRP, EPA collects information from facilities that produce fluorinated gases. While this likely includes most, and possibly all, U.S. facilities that produce fluorochemicals of any kind, it is possible that some fluorochemical producers do not report either their production of fluorochemicals or their emissions of fluorinated GHGs to EPA under the GHGRP. In this case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

At fluorinated gas production facilities that currently report their emissions under the GHGRP, it is possible that some processes that emit fluorinated GHGs neither produce nor transform a fluorinated gas, in which case their emissions would not be reported under the GHGRP. In that case, emissions estimates based only on GHGRP reporting would underestimate actual emissions.

***Exclusion of nitrous oxide***

The GHGRP does not currently require facilities to report emissions of nitrous oxide ($N_2O$) from fluorinated gas production or transformation, but the IPCC *2019 Refinement* includes a default emission factor for $N_2O$ from production of $NF_3$, implying such emissions may occur. The GHGRP data (and this analysis) may therefore underestimate emissions of $N_2O$ from fluorinated gas production. Because the GWP of $N_2O$ is considerably lower than that of saturated HFCs, PFCs, and other fluorinated GHGs, any underestimate is expected to be relatively small.

***Identity of emitted compounds***

In this analysis, it is assumed that emissions that are reported only in MT $CO_2$ Eq. by fluorinated GHG group consist of the compounds in that group that are reported by species by the facility. However, if that were actually the case, emissions of those compounds would have been included in the speciated emissions rather than reported separately in MT $CO_2$ Eq. This analysis therefore incorrectly speciates some emissions. As noted in the Methodology section, the share of total $CO_2$ Eq. emissions reported only by fluorinated GHG group is small, ranging between 1 and 2 percent. Moreover, while the emissions are not assigned to the exact species emitted, they are assigned to a species that is closely related and likely to have similar atmospheric impacts (e.g., another saturated HFC with two or fewer carbon-hydrogen bonds). The impact of this uncertainty is therefore limited.

***Quantities of Reactants Consumed or Fluorinated Gases Produced***

The emissions reported under Subpart L are required to be calculated using process activity data, such as the quantity of reactants consumed or the quantity of the fluorinated gas product produced. In general, the uncertainties in process activity levels are expected to be small. The *2019 Refinement* places such uncertainties "in the region of 1 percent."

Because the uncertainties enumerated above are either small or difficult to quantify, EPA did not attempt to include them in the 2023 quantitative uncertainty estimate for this source category. The 2023 quantitative uncertainty estimate includes the following uncertainties:

***Process Vent Emission Factors***

Process vent emission factors that were developed based on stack testing (for continuous process vents emitting 10,000 MT $CO_2$ Eq. or more) were estimated to have an uncertainty (95-percent confidence interval) of ±35 percent based on Subpart L requirements.[78] Process vent emission factors that were developed based on calculations (for batch process vents and for continuous process vents emitting less than 10,000 MT $CO_2$ Eq.) were estimated to have a larger uncertainty of ±50 percent. Continuous processes were assumed to have two vents per process; batch processes were assumed to have five vents per process.[79]

***Equipment Leak Estimates***

The estimated equipment leaks reported by each facility for each process were estimated to have an uncertainty of ± 90 percent. The uncertainty of leak estimates depends on the method used to estimate leaks; there are multiple methods. For simplicity, this analysis uses a conservatively high uncertainty estimate that is appropriate for the Average EF Approach.

***Venting of Residual Gas in Containers***

The reported emissions of fluorinated GHGs from venting of residual gas in returned containers were estimated to have an uncertainty of ± 30 percent for each facility. This estimate is based on the Subpart L requirement to either measure the contents of each container or to measure the contents of at least 30 representative containers for each compound and container size and type.

***Facilities that produce fluorinated gases but do not report their emissions to the GHGRP***

EPA estimated emissions for fluorinated gas production facilities that do not report their emissions under Subpart L of the GHGRP. The estimates presented here for 2011 to 2024 are based on aggregated production estimates, the Tier 1 default emission factor in the *2019 Refinement*, and the default fluorinated GHG speciation from Table 3.28b (chapter 3.10.2 of *2019 Refinement*). There is considerable uncertainty in both the magnitude of the emissions and the identity of the emitted compounds. The *2019 Refinement* estimates the uncertainty of the Tier 1 emission factor as -98 percent to +470 percent. (In the quantitative uncertainty estimate below, which is based on error propagation, values of ±98 percent were used because error propagation requires the assumption of symmetric uncertainty bounds.) In 2024, estimated emissions from the six non-reporting facilities accounted for 50 percent of total estimated U.S. emissions from production of fluorinated gases other than HCFC-22. In contrast, production and transformation by these facilities accounted for less than three percent of total fluorinated GHG production and transformation (excepting HCFC-22 production) across all facilities. Because the emissions estimated for several of the six facilities exceeded the 25,000 MT $CO_2$ Eq. reporting threshold under Subpart L, but these facilities have not reported their emissions under Subpart L, it appears likely that emissions from at least some facilities are overestimated.

***Quantitative uncertainty estimate***

The uncertainties in process vent emission factors (±35% for emission factors based on emissions testing; ±50% for emission factors based on engineering calculations), equipment leak estimates (±90%), the quantities of residual gas vented from containers (±30%), and emissions from facilities that produce fluorinated gases but do not report their emissions to the GHGRP (±98%) were convolved using error propagation to arrive at an overall uncertainty estimate for 2023. The results of the Approach 1 quantitative uncertainty analysis are summarized in Table A-110. Emissions of HFCs, PFCs, $SF_6$, and $NF_3$ from production of fluorochemicals other than HCFC-22 were

[78] *Technical Support Document for Emissions from Production of Fluorinated Gases*, Office of Air and Radiation, U.S. Environmental Protection Agency, November 5, 2010. Available online at: https://www.epa.gov/sites/default/files/2015-02/documents/subpart-l_techsuppdoc.pdf.

[79] *Economic Impact Analysis for the Mandatory Reporting of Greenhouse Gas Emissions F-Gases: Subparts I, L, DD, QQ, SS*, U.S. Environmental Protection Agency, November 2010. Available online at: https://www.regulations.gov/document/EPA-HQ-OAR-2009-0927-0179.

estimated to fall between 3.40 and 5.15 MMT $CO_2$ Eq. at the 95 percent confidence level. This indicates a range of approximately 20 percent below and 20 percent above the emission estimate of 4.27 MMT $CO_2$ Eq.

### Table A-110: Approach 1 Quantitative Uncertainty Estimates for HFC, PFC, $SF_6$, and $NF_3$ from Production of Fluorochemicals other than HCFC-22 (MMT $CO_2$ Eq. and Percent)

| Source | Gas | 2023 Emission Estimate (MMT $CO_2$ Eq.) | Uncertainty Range Relative to Emission Estimate | | | |
|---|---|---|---|---|---|---|
| | | | (MMT $CO_2$ Eq.) | | (%) | |
| | | | Lower Bound[a] | Upper Bound[a] | Lower Bound | Upper Bound |
| Production of Fluorochemicals other than HCFC-22 | HFCs, PFCs, $SF_6$, and $NF_3$ | 4.27 | 3.40 | 5.15 | -20% | +20-% |

[a] Absolute lower and upper bounds were calculated using the corresponding lower and upper bounds in percentages.