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-64 through Table A-69.

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 2023a). 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 2023b) and Jacobs (2010).[46] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[47] Construction and agricultural fuel use was obtained from EPA (2022b) and the Federal Highway Administration (FHWA) (1996 through 2021). 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-64 provides annual energy consumption data for the years 1990 through 2021.

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 2023). Total fuel consumption in the electric power sector from EIA (2023a) was apportioned to each combustion technology type and fuel combination using a ratio of fuel consumption by technology type derived from EPA (2023) data. The combustion technology and fuel use data by facility obtained from EPA (2023) were only available from 1996 to 2021, so the consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type from EPA (2023) to the total EIA (2023a) consumption for each year from 1990 to 1995.

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

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[46] 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.

[47] 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.

sector in which each fuel was combusted. Table A-65 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-. 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 2022a) 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 (2022a) 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-64: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Coal	**19,637**	**20,912**	**23,088**	**22,966**	**20,731**	**15,446**	**14,268**	**13,770**	**13,161**	**11,132**	**9,121**	**10,404**
Residential	31	17	11	8	NO	NO	NO	NO	NO	NO	NO	NO
Commercial	124	117	92	97	70	31	24	21	19	17	15	15
Industrial	1,668	1,557	1,362	1,246	993	734	662	614	569	517	449	450
Electric Power	17,807	19,216	21,618	21,582	19,633	14,645	13,547	13,110	12,546	10,559	8,625	9,908
U.S. Territories[a]	5	5	5	33	35	36	35	25	28	39	33	31
Petroleum	**6,063**	**5,591**	**6,408**	**6,676**	**5,030**	**4,615**	**4,267**	**4,041**	**4,148**	**4,119**	**3,671**	**3,512**
Residential	1,376	1,259	1,425	1,366	1,103	939	799	766	946	975	842	814
Commercial	1,022	724	767	761	698	938	834	809	735	801	764	730
Industrial	2,600	2,457	2,456	2,896	2,409	2,260	2,205	2,102	2,097	2,060	1,800	1,713
Electric Power	797	860	1,269	1,003	412	173	159	71	93	42	24	22
U.S. Territories[a]	268	290	491	649	408	306	270	292	278	241	241	234
Natural Gas	**17,229**	**19,315**	**20,900**	**20,921**	**22,897**	**26,545**	**26,566**	**26,111**	**28,952**	**29,967**	**29,263**	**29,309**
Residential	4,487	4,954	5,105	4,946	4,878	4,777	4,506	4,563	5,174	5,208	4,846	4,888
Commercial	2,680	3,096	3,252	3,073	3,165	3,316	3,224	3,273	3,638	3,647	3,286	3,419
Industrial	7,687	8,701	8,637	7,315	7,670	8,688	8,770	8,847	9,325	9,482	9,187	9,444
Electric Power	2,376	2,564	3,894	5,562	7,157	9,707	10,003	9,381	10,752	11,559	11,894	11,484
U.S. Territories[a]	0	0	13	24	28	57	64	48	62	71	50	74
Wood	**2,095**	**2,252**	**2,138**	**1,963**	**2,046**	**2,127**	**2,059**	**2,018**	**2,107**	**2,105**	**1,936**	**1,981**
Residential	580	520	420	430	541	513	445	430	525	546	441	464
Commercial	66	72	71	70	72	79	84	84	84	84	83	83
Industrial	1,442	1,652	1,636	1,452	1,409	1,476	1,474	1,442	1,432	1,407	1,356	1,366
Electric Power	7	8	11	11	25	59	57	62	66	68	56	68
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

NO (Not Occurring)

[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-65: 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 = 9.486×10^{-4} Btu.

Table A-66: 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.

Table A-67: NOx Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**6,045**	**5,792**	**4,829**	**3,434**	**2,226**	**1,419**	**1,234**	**1,049**	**1,025**	**886**	**717**	**710**
Coal	5,119	5,061	4,130	2,926	1,896	1,209	1,051	894	873	755	611	605
Fuel Oil	200	87	147	114	74	47	41	35	34	30	24	24
Natural gas	513	510	376	250	162	103	90	76	75	64	52	52
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	36	29	19	12	10	9	9	7	6	6
Internal Combustion	213	134	140	115	75	48	41	35	34	30	24	24
Industrial	**2,559**	**2,650**	**2,278**	**1,515**	**1,087**	**921**	**890**	**859**	**898**	**864**	**864**	**864**
Coal	530	541	484	342	245	208	201	194	203	195	195	195
Fuel Oil	240	224	166	101	73	62	60	57	60	58	58	58
Natural gas	877	999	710	469	336	285	275	266	278	268	268	268
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	76	55	46	45	43	45	44	44	44
Internal Combustion	792	774	809	527	378	320	309	298	312	300	300	300
Commercial/Institutional	**671**	**607**	**507**	**490**	**456**	**444**	**440**	**537**	**512**	**402**	**402**	**402**
Coal	36	35	21	19	15	14	13	13	13	13	13	13
Fuel Oil	88	94	52	49	38	35	34	33	33	33	33	33
Natural gas	181	210	161	155	120	112	108	105	105	105	105	105
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	267	284	283	284	386	361	250	250	250
Residential	**749**	**813**	**439**	**418**	**324**	**301**	**292**	**283**	**283**	**284**	**284**	**284**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	20	16	15	14	14	14	14	14	14
Other Fuels[a]	707	769	417	398	308	286	278	269	269	270	270	270
Total	**10,023**	**9,862**	**8,053**	**5,858**	**4,092**	**3,084**	**2,856**	**2,728**	**2,718**	**2,436**	**2,266**	**2,259**

NA (Not Applicable)
[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022a).
[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2022a).
Note: Totals may not sum due to independent rounding.

Table A-68: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**329**	**337**	**439**	**582**	**693**	**618**	**575**	**532**	**505**	**424**	**424**	**424**
Coal	213	227	221	292	347	310	288	267	253	212	212	212
Fuel Oil	18	9	27	37	44	39	36	34	32	27	27	27
Natural gas	46	49	96	122	145	130	121	112	106	89	89	89
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	43	51	45	42	39	37	31	31	31
Internal Combustion	52	52	63	89	106	94	88	81	77	65	65	65
Industrial	**797**	**958**	**1,106**	**1,045**	**853**	**806**	**771**	**736**	**758**	**753**	**753**	**753**
Coal	95	88	118	115	94	89	85	81	83	83	83	83
Fuel Oil	67	64	48	42	34	32	31	29	30	30	30	30
Natural gas	205	313	355	336	274	259	248	237	244	242	242	242
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	295	241	228	218	208	214	213	213	213
Internal Combustion	177	222	285	257	209	198	189	181	186	185	185	185
Commercial	**205**	**211**	**151**	**166**	**140**	**124**	**128**	**133**	**133**	**133**	**133**	**133**
Coal	13	14	14	14	12	11	11	12	12	12	12	12
Fuel Oil	16	17	17	19	16	14	14	15	15	15	15	15
Natural gas	40	49	83	91	77	68	71	73	73	73	73	73
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	41	35	31	32	33	33	33	33	33
Residential	**3,668**	**3,877**	**2,644**	**2,856**	**2,416**	**2,140**	**2,215**	**2,291**	**2,286**	**2,286**	**2,286**	**2,286**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,615	2,212	1,959	2,028	2,097	2,093	2,093	2,093	2,093
Other Fuels[a]	238	248	228	241	204	181	187	193	193	193	193	193
Total	**5,000**	**5,383**	**4,340**	**4,648**	**4,103**	**3,688**	**3,690**	**3,691**	**3,682**	**3,596**	**3,596**	**3,596**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022a).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2022a).

Note: Totals may not sum due to independent rounding.

Table A-69: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Electric Power	**43**	**40**	**56**	**44**	**38**	**33**	**31**	**29**	**30**	**28**	**28**	**28**
Coal	24	26	27	21	18	16	15	14	14	13	13	13
Fuel Oil	5	2	4	3	3	3	2	2	2	2	2	2
Natural Gas	2	2	12	10	8	7	7	6	7	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	8	7	6	6	6	6	5	5	5
Industrial	**165**	**187**	**157**	**120**	**100**	**100**	**101**	**101**	**106**	**107**	**107**	**107**
Coal	7	5	9	8	7	7	7	7	7	7	7	7
Fuel Oil	11	11	9	6	5	5	5	5	6	6	6	6
Natural Gas	52	66	53	41	34	34	34	34	36	36	36	36
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	22	18	18	19	19	20	20	20	20
Internal Combustion	49	60	58	43	36	36	36	36	38	38	38	38
Commercial	**10**	**14**	**304**	**188**	**145**	**118**	**117**	**116**	**116**	**116**	**116**	**116**
Coal	1	1	1	1	+	+	+	+	+	+	+	+
Fuel Oil	3	3	4	2	2	1	1	1	1	1	1	1
Natural Gas	7	10	14	9	7	6	6	6	6	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	285	177	136	111	110	109	109	109	109	109
Residential	**686**	**725**	**837**	**518**	**399**	**324**	**322**	**319**	**319**	**319**	**319**	**319**
Coal[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fuel Oil[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	502	386	314	311	308	309	309	309	309
Other Fuels[a]	35	37	27	17	13	11	10	10	10	10	10	10
Total	**904**	**966**	**1,353**	**871**	**681**	**575**	**570**	**565**	**571**	**571**	**571**	**571**

+ Does not exceed 0.5 kt.

NA (Not Applicable)

[a] "Other Fuels" include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2022a).

[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2022a).

Note: Totals may not sum due to independent rounding.

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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 2022a and EIA 2021d) 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 2023), while CO_2 emissions from other aircraft jet fuel consumption is determined using a top-down approach.

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 2023). 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 1990-2021 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 MOVES3 model (EPA 2021a), 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. With respect to estimating CO_2 emissions from the transportation sector, EPA’s MOVES model is used only to estimate fuel use by recreational boats. 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.

Estimates of diesel fuel consumption from rail were taken from: the Association of American Railroads (AAR 2008 through 2021) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2021 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004), Whorton (2006 through 2014), and Railinc (2014 through 2021) 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 2021).

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 (2022) for domestic and international commercial aircraft, and DLA Energy (2021) for domestic and international military aircraft. 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 2022), 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 3.11 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 2022a).

Table A-70 displays estimated fuel consumption by fuel and vehicle type. Table A-71 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 UNFCCC reporting obligations, 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 2021. Biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2021, 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 2021 biodiesel and renewable diesel fuel consumption estimates from EIA (2022a) 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 2022a) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates. Total ethanol and biodiesel consumption estimates are in Table A-72.[48]

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[48] 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-72. 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-70 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-70: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	2000	2010[a]	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Motor Gasoline[b,c]	**107,651**	**125,232**	**119,829**	**117,229**	**116,810**	**116,960**	**121,472**	**120,631**	**123,482**	**123,079**	**124,886**	**123,709**	**106,666**	**117,096**
Passenger Cars	68,795	61,845	51,702	48,158	42,316	43,314	44,773	43,722	44,018	42,691	43,547	43,268	37,342	41,038
Light-Duty Trucks	31,836	57,173	63,422	64,640	69,955	69,067	71,913	72,131	74,458	75,259	76,001	74,987	64,398	70,570
Motorcycles	376	491	708	697	789	764	784	759	803	800	832	840	747	843
Buses	237	157	139	150	175	197	231	241	257	281	302	316	285	325
Medium- and Heavy-Duty Trucks	4,804	3,961	2,544	2,314	2,331	2,397	2,576	2,582	2,741	2,837	2,986	3,078	2,749	3,118
Recreational Boats[d]	1,604	1,606	1,315	1,270	1,243	1,220	1,196	1,197	1,205	1,211	1,218	1,220	1,145	1,202
Distillate Fuel Oil (Diesel Fuel)[b,c]	**25,631**	**39,241**	**41,311**	**41,588**	**41,470**	**41,785**	**43,203**	**44,377**	**44,012**	**45,337**	**46,347**	**46,096**	**43,499**	**46,724**
Passenger Cars	921	301	199	230	235	243	266	321	301	288	273	263	245	264
Light-Duty Trucks	822	1,900	2,753	2,990	3,249	3,012	2,992	3,054	3,007	3,022	3,037	3,039	2,936	3,242
Buses	1,079	1,673	1,408	1,486	1,570	1,589	1,732	1,807	1,806	1,915	1,982	2,013	1,924	2,086
Medium- and Heavy-Duty Trucks	18,423	29,619	32,096	31,643	31,503	31,989	33,208	33,802	34,063	35,233	36,126	36,277	34,379	36,971
Recreational Boats	267	270	263	254	252	246	245	256	262	269	276	279	260	273
Ships and Non-Recreational Boats	658	1,372	809	1,075	830	841	719	1,278	1,060	975	908	725	738	758
Rail[e]	3,461	4,106	3,783	3,910	3,831	3,866	4,041	3,858	3,514	3,635	3,746	3,501	3,016	3,131
Jet Fuel[f]	**19,168**	**19,992**	**15,529**	**15,030**	**14,698**	**15,082**	**15,210**	**16,155**	**17,021**	**17,609**	**17,667**	**18,489**	**12,372**	**15,656**
Commercial Aircraft	11,569	14,672	11,931	12,067	11,932	12,031	12,131	12,534	12,674	13,475	13,650	14,397	9,613	12,527
General Aviation Aircraft	3,940	3,107	2,287	1,865	1,629	2,005	1,751	2,327	3,152	2,952	2,880	2,950	1,659	1,966
Military Aircraft	3,660	2,213	1,311	1,097	1,137	1,046	1,327	1,294	1,194	1,181	1,138	1,141	1,100	1,163
Aviation Gasoline[f]	**374**	**302**	**225**	**225**	**209**	**186**	**181**	**176**	**170**	**174**	**186**	**195**	**168**	**179**
General Aviation Aircraft	374	302	225	225	209	186	181	176	170	174	186	195	168	179
Residual Fuel Oil[f, g]	**2,006**	**2,963**	**1,818**	**1,723**	**1,410**	**1,345**	**517**	**378**	**1,152**	**1,465**	**1,246**	**1,289**	**651**	**2,125**
Ships and Non-Recreational Boats	2,006	2,963	1,818	1,723	1,410	1,345	517	378	1,152	1,465	1,246	1,289	651	2,125
Natural Gas[f] (trillion cubic feet)	**0.7**	**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**
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	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
LPG[f]	**251**	**130**	**49**	**49**	**48**	**57**	**65**	**84**	**97**	**100**	**98**	**95**	**50**	**50**
Passenger Cars	1	0.6	0	0	0	0	+	0	0	0	0	0	+	+
Light-Duty Trucks	37	18	8	7	3	4	9	8	7	9	10	11	8	9
Medium- and Heavy-Duty Trucks	184	93	30	38	41	46	48	64	69	72	72	71	38	39
Buses	28	19	11	4	4	7	8	12	21	19	16	13	5	2
Electricity[h,i]	**4,751**	**4,771**	**6,839**	**7,317**	**7,716**	**7,811**	**8,930**	**8,756**	**9,333**	**9,821**	**10,886**	**11,556**	**12,077**	**12,856**
Passenger Cars	+	+	23	86	202	441	737	1,076	1,426	1,845	2,721	3,537	3,505	4,541
Light-Duty Trucks	+	+	3	2	4	9	15	21	125	245	405	579	802	1,789

Buses	+	+	4	5	4	4	5	5	15	18	88	120	144	191
Rail	4,751	4,771	6,810	7,224	7,506	7,358	8,173	7,653	7,768	7,712	7,672	7,320	7,625	6,334

+ 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 MOVES3 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 MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type.

[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 2014-2021 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 (2021a). 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).

Table A-71: Energy Consumption by Fuel and Vehicle Type (TBtu)

Fuel/Vehicle Type	1990	2000	2010[a]	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Motor Gasoline[a,b]	**13,464**	**15,663**	**14,899**	**14,576**	**14,523**	**14,542**	**15,103**	**14,999**	**15,353**	**15,303**	**15,528**	**15,381**	**13,262**	**14,559**
Passenger Cars	8,604	7,735	6,428	5,988	5,261	5,385	5,567	5,436	5,473	5,308	5,414	5,380	4,643	5,102
Light-Duty Trucks	3,982	7,151	7,885	8,037	8,698	8,587	8,941	8,968	9,258	9,357	9,450	9,323	8,007	8,774
Motorcycles	47	61	88	87	98	95	97	94	100	99	103	104	93	105
Buses	30	20	17	19	22	25	29	30	32	35	38	39	35	40
Medium- and Heavy-Duty Trucks	601	495	316	288	290	298	320	321	341	353	371	383	342	388
Recreational Boats[c]	201	201	163	158	155	152	149	149	150	151	151	152	142	149
Distillate Fuel Oil (Diesel Fuel)[a,b]	**3,555**	**5,442**	**5,729**	**5,768**	**5,751**	**5,795**	**5,992**	**6,155**	**6,104**	**6,288**	**6,428**	**6,393**	**6,033**	**6,480**
Passenger Cars	128	42	28	32	33	34	37	44	42	40	38	36	34	37
Light-Duty Trucks	114	263	382	415	451	418	415	424	417	419	421	421	407	450
Buses	150	232	195	206	218	220	240	251	250	266	275	279	267	289
Medium- and Heavy-Duty Trucks	2,555	4,108	4,451	4,389	4,369	4,437	4,606	4,688	4,724	4,886	5,010	5,031	4,768	5,127
Recreational Boats	37	37	36	35	35	34	34	36	36	37	38	39	36	38
Ships and Non-Recreational Boats	91	190	112	149	115	117	100	177	147	135	126	101	102	105
Rail[d]	480	569	525	542	531	536	560	535	487	504	520	486	418	434
Jet Fuel[e]	**2,588**	**2,699**	**2,096**	**2,029**	**1,984**	**2,036**	**2,053**	**2,181**	**2,298**	**2,377**	**2,385**	**2,496**	**1,670**	**2,114**
Commercial Aircraft	1,562	1,981	1,611	1,629	1,611	1,624	1,638	1,692	1,711	1,819	1,843	1,944	1,298	1,691
General Aviation Aircraft	532	419	309	252	220	271	236	314	426	399	389	398	224	265

Military Aircraft	494	299	177	148	154	141	179	175	161	159	154	154	149	157
Aviation Gasoline	**45**	**36**	**27**	**27**	**25**	**22**	**22**	**21**	**20**	**21**	**22**	**23**	**20**	**22**
General Aviation Aircraft	45	36	27	27	25	22	22	21	20	21	22	23	20	22
Residual Fuel Oil[e,f,]	**300**	**443**	**272**	**258**	**211**	**201**	**77**	**57**	**172**	**219**	**186**	**193**	**97**	**318**
Ships and Non-Recreational Boats	300	443	272	258	211	201	77	57	172	219	186	193	97	318
Natural Gas[e]	**679**	**672**	**719**	**734**	**780**	**887**	**760**	**745**	**757**	**799**	**962**	**1,114**	**1,109**	**1,230**
Passenger Cars	+	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	+	+
Light-Duty Trucks	+	0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks	+	1.0	1.0	1.0	1.1	1.3	1.5	1.5	1.8	1.8	1.9	1.9	1.9	2.2
Buses	0	4	6	6	7	7	8	8	9	10	10	11	11	14
Pipelines	679	666	712	726	772	879	750	735	746	787	950	1,101	1,095	1,214
LPG[e]	**23**	**12**	**4**	**5**	**4**	**5**	**6**	**8**	**9**	**9**	**9**	**9**	**5**	**5**
Passenger Cars	0.1	0.1	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	3	2	1	1	0	0	1	1	1	1	1	1	1	1
Medium- and Heavy-Duty Trucks	17	8	3	3	4	4	4	6	6	7	7	6	3	4
Buses	3	1.7	1	0	0	1	1	1	2	2	1	1	0	0
Electricity[g]	**16**	**18**	**26**	**26**	**26**	**28**	**29**	**30**	**31**	**33**	**37**	**40**	**38**	**44**
Passenger Cars	+	+	0.1	0.3	0.7	1.5	2.5	3.7	4.9	6.3	9.3	12.1	12.0	15.5
Light-Duty Trucks	+	+	+	+	+	+	0.1	0.1	0.4	0.8	1.4	2.0	2.7	6.1
Buses	+	+	+	+	+	+	+	+	0.1	0.1	0.3	0.4	0.5	0.7
Rail	16	18	26	26	25	26	26	26	26	26	26	26	22	22
Total	**20,670**	**24,986**	**23,774**	**23,422**	**23,305**	**23,517**	**24,042**	**24,194**	**24,745**	**25,049**	**25,558**	**25,650**	**22,234**	**24,771**

+ Does not exceed 0.5 TBtu

[a] 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.

[b] 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 MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type.

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

[d] Class II and Class III diesel consumption data for 2014 through 2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

[e] Estimated based on EIA transportation sector energy estimates, with bottom-up data used for apportionment to modes. Transportation sector natural gas and LPG consumption are based on data from EIA (2022a). 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. These changes were first incorporated in the 2016 Inventory and apply to the 1990–2021 time period.

[f] Fluctuations in reported fuel consumption may reflect data collection problems. Residual fuel oil for ships and boats data is based on EIA (2022a).

[g] 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). In Inventory years prior to 2017, CO_2 emissions from electric vehicle charging were allocated to the residential and commercial sectors. They are now allocated to the transportation sector. These changes were first incorporated in the 2017 Inventory and apply to the 2010 through 2021 time period.

Table A-72: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990		2000		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ethanol	699		1,556		11,833	11,972	11,997	12,154	12,758	12,793	13,261	13,401	13,573	13,589	11,744	13,016
Biodiesel	NA		NA		260	886	899	1,429	1,417	1,494	2,085	1,985	1,904	1,813	1,873	1,709

NA (Not Applicable)

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 2023). 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 2023) was allocated to fuel types (gasoline, diesel, other) using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT. This corrects historical inconsistencies in vehicle type definitions in FHWA data[49] (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.[50] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-73 and Table A-74, 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 2021 in Table A-75.

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 MOVES3 model for years 1999 forward (EPA 2021a).[51] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES3 model (EPA 2021a).[52]

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 in Table A-81 through Table A-84. 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 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

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[49] VMT is now allocated to vehicle classes using MOVES3 ratios of VMT in each vehicle class to total VMT

[50] 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.

[51] 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.

[52] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES3 model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

1998).[53] 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 1999b). 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 2021 were determined using confidential engine family sales data submitted to EPA (EPA 2022c). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2021d). 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 run on either the alternative fuel or gasoline (or diesel), or some combination.[54] 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. The EIA data provides vehicle counts and fuel use for fleet vehicles used by electricity providers, federal agencies, natural gas

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53 For further description, see "Definitions of Emission Control Technologies and Standards" section of this annex below.

54 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.

providers, propane providers, state agencies and transit agencies, for calendar years 2003 through 2021. 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. For 2018-2021, 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 “More electric buses join transit fleets as costs and technology improve” (SmartCitiesDive 2022). A regression analysis of vehicle counts was used for other fuels for the 2018-2021 period. VMT for those vehicles were assumed to be the same as the baseline conventional fueled vehicle of the same class.

For the current Inventory, 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, 2020, and 2021, EV and PHEV sales were taken from Wards Intelligence U.S. Light Vehicle Sales Report (Wards Intelligence, 2021). EVs were divided into cars and trucks using vehicle type information from fueleconomy.gov publications (EPA 2010-2021). 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 MOVES3. 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 GREET2021 model (ANL 2021). 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). Note that there was an impact of COVID-19 pandemic related declines in travel in 2020. Gasoline VMT was down 11.1 percent and diesel VMT was down 9.8 percent from 2019. For 2021, AFV VMT was adjusted based on the EIA trend in gasoline and diesel consumption for transportation between 2020 and 2021. The EIA data show that gasoline use increased by 9.6 percent between 2020 and 2021 while diesel use increased by 5.1 percent. VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-75, while more detailed estimates of VMT by control technology are shown in Table A-76.

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 2022) and are reported in Browning (2018). These emission factors are shown in Table A-86 and Table A-87.

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-80. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2021) for distillate fuel, and DHS (2008) and EIA (2022a) 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.[55] 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 MOVES3 model (EPA 2022a). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2021), diesel consumption from commuter rail was obtained from APTA (2007 through 2021) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2014).[56] 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 2021) and fuel consumption data provided by Whorton, D. (2006 through 2014). Class II and Class III diesel consumption for 2014-2021 is estimated by multiplying this average historical fuel usage per carload factor by the number of shortline carloads originated each year (RailInc 2014 through 2021). Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2021). Data for 2020 and 2021 was estimated by applying a scaling factor to 2019 and 2020 fuel consumption, to account for the COVID-19 pandemic and associated restrictions. The scaling factors were derived from trends in the "fuel, power, and utilities" expenses from 2019 through 2021 for National Railroad Passenger Corporation and Subsidiaries (Amtrak 2022). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2022a) and FAA (2022), 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 2022 and FAA 2023). Pipeline fuel consumption was obtained from EIA (2007 through 2022) (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 MOVES3 model (EPA 2022a) for gasoline and diesel powered equipment, and from FHWA (1996 through 2023) for gasoline consumption by off-road trucks used in the agriculture, industrial, commercial, and construction sectors.[57] 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 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 MOVES3 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 2021a). 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 MOVES3 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 MOVES3 to determine overall emission factors in grams per kg of fuel consumed by fuel type (Browning 2020).

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55 See International Bunker Fuels section of the Energy chapter.

56 Diesel consumption from Class II and Class III railroad were unavailable for 2014-2021. Diesel consumption data for 2014-2021 is estimated by applying the historical average fuel usage per carload factor to the annual number of carloads.

57 "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.

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 2022). 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-73: 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	1,455.0	427.7	44.3	11.4
1991	1,441.0	464.8	43.9	11.5
1992	1,456.9	513.5	44.5	11.8
1993	1,454.2	558.2	44.5	12.0
1994	1,457.3	607.3	44.7	12.3
1995	1,461.0	659.4	44.9	12.5
1996	1,461.5	712.7	45.1	12.8
1997	1,467.4	771.7	45.4	13.1
1998	1,467.7	831.0	45.5	13.4
1999	1,460.2	888.9	45.4	13.6
2000	1,467.2	939.7	42.2	12.2
2001	1,470.3	978.0	41.1	11.1
2002	1,481.3	1,021.7	40.7	11.2
2003	1,473.4	1,053.2	40.7	11.4
2004	1,478.1	1,118.6	38.4	15.0
2005	1,464.9	1,156.1	35.8	13.8
2006	1,436.5	1,185.5	38.2	19.2
2007	1,430.3	1,203.3	35.4	21.4
2008	1,403.8	1,171.4	36.3	20.8
2009	1,397.6	1,181.1	34.0	20.8
2010	1,391.1	1,202.7	30.8	18.5
2011	1,320.1	1,272.9	28.2	18.6
2012	1,191.3	1,408.8	28.2	21.4
2013	1,213.9	1,402.1	28.1	20.4
2014	1,213.4	1,435.0	28.2	20.0
2015	1,219.1	1,494.9	27.8	19.6
2016	1,225.3	1,556.4	28.4	20.5
2017	1,200.1	1,606.5	28.9	20.2
2018	1,210.9	1,613.5	29.0	20.4
2019	1,216.7	1,616.4	29.3	20.5
2020	1,082.9	1,432.5	26.1	18.2
2021	1,168.6	1,541.8	28.3	19.7

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.

[b] VMT is now allocated to vehicle classes using MOVES3 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 2021 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 2023). VMT estimates were then allocated using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT.

Source: Derived from FHWA (1996 through 2021), DOE (1990 through 2022), Browning (2022a), Browning (2018a), and Browning (2017).

Table A-74: 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	40.8	19.8	136.4	8.3
1991	38.1	21.2	142.3	8.7
1992	36.0	23.2	151.4	9.2
1993	33.3	25.0	158.9	9.7
1994	30.6	26.9	167.6	10.2
1995	27.7	29.0	176.7	10.7
1996	24.7	31.1	186.0	11.3
1997	21.6	33.5	196.4	11.9
1998	18.1	35.8	206.7	12.5
1999	14.5	38.1	216.4	13.1
2000	12.5	39.4	219.7	13.0
2001	11.3	41.5	231.5	11.4
2002	9.8	43.1	234.8	11.7
2003	8.7	44.7	245.4	11.6
2004	7.9	48.1	245.6	11.8
2005	7.5	49.6	248.5	11.5
2006	7.1	51.7	260.9	12.3
2007	6.3	51.4	266.8	12.7
2008	5.8	49.5	272.5	12.9
2009	6.1	48.7	252.4	12.5
2010	6.8	47.9	254.5	11.9
2011	7.3	49.2	234.4	11.9
2012	7.8	54.6	236.0	12.7
2013	8.2	50.6	238.6	12.9
2014	8.7	50.0	242.7	13.6
2015	10.6	50.8	243.4	13.8
2016	9.7	51.9	247.0	13.9
2017	9.2	53.8	256.7	14.6
2018	8.7	55.6	262.3	14.9
2019	8.5	58.5	268.5	15.2
2020	7.5	55.1	240.5	13.0
2021	8.2	63.1	261.8	14.2

[a] Heavy-Duty Trucks includes Medium-Duty Trucks and Heavy-Duty Trucks.
[b] VMT is now allocated to vehicle classes using MOVES3 ratios.
Notes: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2023). VMT estimates were then allocated using EPA's MOVES3 model ratios of VMT per vehicle class to total VMT.
Sources: Derived from FHWA (1996 through 2023), DOE (1993 through 2022), and Browning (2017), Browning (2018a), Browning (2022a).

Table A-75: 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	0.1
1992	0.0	0.1	0.4	0.1
1993	0.0	0.1	0.5	0.1
1994	0.0	0.1	0.5	0.1
1995	0.0	0.1	0.5	0.1
1996	0.0	0.1	0.5	0.1
1997	0.0	0.1	0.5	0.2
1998	0.0	0.1	0.5	0.2
1999	0.0	0.1	0.5	0.2
2000	0.1	0.1	0.5	0.2
2001	0.1	0.2	0.5	0.2
2002	0.2	0.2	0.6	0.2
2003	0.1	0.3	0.7	0.3
2004	0.2	0.2	0.6	0.3
2005	0.2	0.3	0.9	0.3
2006	0.2	0.5	1.9	0.4
2007	0.2	0.6	2.5	0.4
2008	0.2	0.5	2.3	0.4
2009	0.2	0.6	2.4	0.4
2010	0.2	0.5	1.9	0.4
2011	0.6	1.3	5.5	0.5
2012	0.9	1.5	5.6	0.5
2013	1.8	2.1	8.8	0.6
2014	2.7	2.0	8.6	0.7
2015	3.8	2.1	8.8	0.7
2016	5.0	3.2	12.4	0.8
2017	6.2	3.5	11.9	0.8
2018	9.1	3.9	11.3	0.9
2019	12.0	4.3	11.0	0.9
2020	12.0	5.0	10.0	0.8
2021	15.5	8.1	9.8	0.9

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

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

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 2021 time period.

Table A-76: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars	**3.7**	**86.7**	**237.4**	**552.1**	**937.7**	**1,825.3**	**2,722.6**	**3,811.3**	**4,991.4**	**6,234.3**	**9,086.7**	**12,049.6**	**12,013.8**	**15,512.6**
Methanol-Flex Fuel ICE	-	+	+	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	-	18.2	109.1	107.3	137.5	157.9	117.9	106.4	117.4	81.0	79.2	76.0	72.4	67.9
CNG ICE	+	4.8	9.6	10.2	10.6	11.1	10.1	10.4	11.8	10.9	9.3	8.0	6.6	5.4
CNG Bi-fuel	+	15.7	7.1	6.4	4.1	3.1	2.2	1.6	1.3	1.4	1.3	1.3	1.3	1.2
LPG ICE	1.1	1.0	+	+	+	+	0.1	0.1	0.2	0.2	0.3	0.1	0.1	+
LPG Bi-fuel	2.6	2.6	1.1	0.3	0.2	0.2	0.1	0.1	0.1	+	+	+	+	+
Biodiesel (BD100)	-	1.6	45.5	168.1	181.4	297.7	302.6	379.3	481.4	423.0	372.1	345.8	313.9	309.6
NEVs	-	41.5	61.7	102.9	98.9	103.8	113.2	124.3	83.8	89.9	86.5	83.5	76.9	68.7
Electric Vehicle	-	1.2	1.3	108.1	265.7	772.5	1,441.6	2,238.3	2,984.5	3,878.5	6,208.5	8,846.0	9,056.3	12,134.2
SI PHEV - Electricity	-	-	2.0	48.5	238.9	478.4	734.2	949.8	1,304.0	1,722.0	2,290.2	2,633.1	2,434.9	2,847.6
Fuel Cell Hydrogen	-	-	+	0.3	0.5	0.6	0.8	0.8	7.0	27.4	39.3	55.8	51.5	77.9
Light-Duty Trucks	**71.3**	**148.9**	**495.5**	**1,308.5**	**1,474.3**	**2,091.7**	**2,008.2**	**2,106.7**	**3,194.3**	**3,524.6**	**3,896.2**	**4,339.7**	**4,985.1**	**8,060.0**
Ethanol-Flex Fuel ICE	-	18.9	114.0	129.9	173.6	203.0	190.8	206.7	258.7	384.3	411.4	438.2	462.1	480.7
CNG ICE	+	4.5	7.5	8.1	8.3	7.8	6.5	4.3	3.6	5.0	4.4	3.7	3.1	2.7
CNG Bi-fuel	+	38.2	17.8	17.5	14.2	15.3	17.6	19.3	24.4	22.3	26.8	25.1	23.2	21.1
LPG ICE	20.6	22.3	8.7	9.0	4.4	5.1	5.5	5.2	5.1	5.2	5.1	5.2	5.1	4.9
LPG Bi-fuel	50.7	54.8	22.3	12.0	4.8	5.7	20.4	8.5	6.3	7.6	8.5	9.6	10.6	11.3
LNG	+	0.1	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	0.1
Biodiesel (BD100)	-	6.0	321.7	1,128.6	1,263.6	1,837.7	1,736.4	1,820.9	2,581.6	2,464.2	2,377.0	2,368.0	2,282.7	2,359.8
Electric Vehicle	-	4.1	3.5	3.2	5.2	16.9	30.5	33.3	268.6	527.4	845.4	1,171.5	1,791.2	4,083.3
SI PHEV - Electricity	-	-	+	+	+	+	0.4	8.1	45.4	103.5	212.0	311.3	399.6	1,070.0
Fuel Cell Hydrogen	-	-	+	0.2	0.2	0.2	0.2	0.4	0.6	5.0	5.6	7.0	7.3	26.1
Medium-Duty Trucks	**220.9**	**257.1**	**613.9**	**1,751.2**	**1,816.0**	**2,809.1**	**2,800.6**	**2,895.6**	**4,072.3**	**3,869.1**	**3,695.4**	**3,579.8**	**3,287.7**	**3,265.2**
CNG ICE	+	3.3	8.1	9.0	9.8	11.2	12.8	12.7	15.2	15.4	16.2	17.1	15.4	17.7
CNG Bi-fuel	+	38.1	28.4	26.5	28.4	30.2	39.3	42.3	40.7	41.6	44.4	47.2	43.1	49.7
LPG ICE	178.9	167.8	37.2	34.2	29.9	27.8	29.4	21.5	18.6	16.4	14.8	13.3	9.9	9.0
LPG Bi-fuel	42.0	39.4	18.0	15.5	25.2	26.7	29.6	23.3	28.7	26.4	25.1	23.6	18.8	18.6
LNG	-	-	+	+	+	0.1	+	0.2	0.2	0.5	0.6	0.7	0.7	0.9
Biodiesel (BD100)	-	8.4	522.2	1,666.1	1,722.8	2,713.1	2,689.6	2,795.5	3,968.9	3,768.8	3,594.3	3,478.0	3,199.7	3,169.4
Heavy-Duty Trucks	**217.4**	**274.6**	**1,277.3**	**3,782.8**	**3,779.4**	**5,989.1**	**5,768.6**	**5,947.4**	**8,322.0**	**8,001.7**	**7,633.3**	**7,388.2**	**6,725.1**	**6,563.8**
Neat Methanol ICE	-	-	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	-	-	+	+	+	+	1.0	1.2	4.3	10.4	8.8	7.4	3.7	1.9
CNG ICE	0.5	9.4	16.3	16.3	17.7	23.9	24.9	21.9	31.8	32.0	33.1	34.0	29.7	32.5
LPG ICE	201.9	224.7	73.1	74.6	48.1	48.7	37.9	33.3	31.0	26.8	22.6	17.9	10.9	6.3

LPG Bi-fuel	15.0	16.7	12.6	18.0	13.9	15.7	6.6	5.8	5.9	5.7	5.6	5.4	4.4	4.3
LNG	-	0.6	4.5	4.7	4.7	4.4	4.1	4.0	3.4	3.2	3.0	2.5	1.7	1.1
Biodiesel (BD100)	-	23.2	1,170.8	3,669.2	3,695.0	5,896.4	5,694.0	5,881.2	8,245.6	7,923.5	7,560.2	7,320.9	6,674.7	6,517.8
Buses	**36.9**	**206.9**	**356.2**	**464.8**	**497.2**	**619.1**	**658.2**	**663.7**	**819.7**	**835.7**	**872.3**	**900.3**	**831.8**	**907.1**
Neat Methanol ICE	6.4	-	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	-	0.1	+	2.1	4.9	5.0	5.5	5.7	5.1	3.7	1.9	0.9	0.4	+
CNG ICE	7.4	153.1	271.9	262.3	277.0	289.6	327.8	319.6	339.3	367.2	392.5	421.1	385.6	443.2
LPG ICE	23.1	27.8	13.9	3.9	3.8	5.9	6.5	5.6	9.3	7.1	5.6	4.1	2.1	0.8
LNG	-	22.9	13.8	13.1	14.3	10.4	10.2	8.1	7.4	5.5	3.5	1.8	0.8	0.3
Biodiesel (BD100)	-	1.1	54.0	180.4	194.6	305.5	304.9	321.1	450.0	441.5	420.5	406.7	371.6	364.6
Electric	-	2.0	2.7	2.8	2.2	2.3	2.7	3.0	8.1	9.9	47.3	64.4	69.7	95.8
Fuel Cell Hydrogen	-	-	+	0.4	0.4	0.4	0.5	0.5	0.6	0.7	1.1	1.4	1.6	2.4
Total VMT	**550.1**	**974.3**	**2,980.3**	**7,859.4**	**8,504.6**	**13,334.3**	**13,958.3**	**15,424.7**	**21,399.7**	**22,465.5**	**25,184.0**	**28,257.7**	**27,843.5**	**34,308.8**

+ Does not exceed 0.05 million vehicle miles traveled.

Sources: Derived from Browning (2017), Browning (2018a), Browning (2022b), and EIA (2021).

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 2021 time period.

Table A-77: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2021

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	HDDB
0	5.9%	5.8%	5.1%	5.6%	9.6%	5.7%	5.9%	5.5%
1	5.9%	5.7%	5.1%	4.9%	9.4%	5.8%	6.0%	5.6%
2	5.9%	5.8%	5.2%	2.8%	8.2%	6.0%	5.9%	5.9%
3	6.0%	5.8%	4.9%	0.9%	6.8%	5.7%	5.6%	5.5%
4	5.2%	7.2%	5.3%	0.2%	7.1%	6.1%	4.1%	8.1%
5	5.7%	6.8%	4.9%	1.0%	6.0%	5.8%	3.9%	7.4%
6	6.1%	6.2%	4.7%	21.5%	4.7%	6.0%	3.6%	6.8%
7	6.2%	5.4%	4.3%	13.4%	3.2%	5.4%	3.4%	6.4%
8	5.7%	4.2%	2.7%	11.1%	2.4%	3.4%	2.9%	3.5%
9	5.0%	3.6%	3.4%	9.2%	2.8%	4.0%	3.0%	3.4%
10	3.8%	3.5%	2.5%	6.4%	2.5%	2.7%	2.1%	3.1%
11	3.8%	2.7%	1.3%	5.8%	1.1%	1.5%	1.6%	3.3%
12	3.4%	2.0%	1.9%	3.8%	1.0%	1.9%	3.5%	3.8%
13	4.1%	3.3%	3.5%	0.4%	3.0%	3.1%	4.4%	3.6%
14	4.1%	3.4%	2.6%	0.3%	2.7%	4.7%	5.4%	3.3%
15	3.5%	3.3%	3.8%	3.5%	4.1%	4.4%	5.2%	3.3%
16	3.1%	3.3%	3.0%	2.2%	3.3%	3.8%	4.7%	2.4%
17	2.5%	3.2%	2.6%	1.2%	3.6%	2.5%	3.8%	2.5%
18	2.2%	2.8%	2.2%	1.3%	2.9%	2.2%	4.1%	2.2%
19	1.8%	2.5%	2.2%	1.2%	2.4%	1.9%	3.3%	2.2%
20	1.5%	2.1%	2.4%	0.7%	2.4%	2.4%	2.7%	2.5%
21	1.4%	2.0%	2.5%	0.6%	1.6%	2.7%	2.2%	2.4%
22	1.0%	1.7%	3.9%	0.3%	1.8%	2.0%	1.6%	1.4%
23	0.8%	1.3%	1.9%	0.3%	0.5%	1.2%	1.2%	1.1%
24	0.7%	1.1%	2.1%	0.1%	1.4%	1.2%	1.0%	0.9%
25	0.5%	0.8%	1.5%	0.1%	0.9%	1.0%	0.9%	0.8%
26	0.5%	0.8%	2.0%	0.1%	0.8%	1.2%	0.7%	0.7%
27	0.3%	0.6%	1.2%	0.0%	0.6%	0.9%	0.6%	0.4%
28	0.3%	0.4%	1.0%	0.0%	0.5%	0.6%	0.5%	0.4%
29	0.2%	0.3%	0.9%	0.0%	0.3%	0.4%	0.4%	0.3%
30	3.0%	2.3%	9.5%	1.2%	2.3%	4.0%	5.9%	1.3%
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 MOVES3 Model.
Source: EPA (2022a)

Table A-78: Annual Average Vehicle Mileage Accumulation per Vehicles[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]	HDDB
0	14,398	16,274	20,089	14,398	16,274	44,230	9,377	24,870
1	14,125	15,968	20,033	14,125	15,968	44,991	5,007	24,061
2	13,829	15,623	19,961	13,829	15,623	45,969	3,788	23,289
3	13,514	15,245	19,857	13,514	15,245	45,850	3,132	22,540
4	13,181	14,838	21,308	13,181	14,838	45,028	2,710	21,668
5	12,832	14,405	19,952	12,832	14,405	43,386	2,410	21,301
6	12,470	13,951	18,578	12,470	13,951	44,814	2,185	20,061
7	12,096	13,479	17,311	12,096	13,479	41,017	2,007	19,479
8	11,714	12,995	15,198	11,714	12,995	41,753	1,857	19,341
9	11,324	12,501	14,819	11,324	12,501	34,633	1,735	18,436
10	10,931	12,002	12,839	10,931	12,002	27,505	1,632	16,870
11	10,535	11,502	13,396	10,535	11,502	30,391	1,538	17,978

12	10,140	11,006	11,189	10,140	11,006	27,159	1,463	16,604
13	9,746	10,518	9,569	9,746	10,518	14,875	1,388	15,568
14	9,357	10,041	7,941	9,357	10,041	19,673	1,322	15,703
15	8,975	9,579	6,767	8,975	9,579	14,356	1,266	15,805
16	8,602	9,138	5,622	8,602	9,138	12,029	1,219	13,943
17	8,240	8,719	5,219	8,240	8,719	10,030	1,172	13,265
18	7,890	8,330	5,062	7,890	8,331	9,473	1,125	14,662
19	7,557	7,974	4,710	7,557	7,974	7,792	1,088	13,308
20	7,241	7,654	4,354	7,241	7,654	8,177	1,050	12,968
21	6,947	7,374	4,055	6,947	7,374	8,696	1,022	13,465
22	6,673	7,138	3,698	6,673	7,138	8,404	994	13,538
23	6,424	6,952	3,393	6,424	6,952	8,312	938	12,507
24	6,203	6,819	3,332	6,203	6,819	6,298	881	12,126
25	6,010	6,741	2,971	6,010	6,741	6,274	825	11,698
26	5,848	6,726	2,714	5,848	6,726	4,951	760	11,015
27	5,720	6,726	2,693	5,720	6,726	4,487	703	12,131
28	5,627	6,726	2,216	5,627	6,726	3,781	666	10,818
29	5,573	6,726	1,999	5,573	6,726	2,973	619	9,383
30	5,573	6,726	888	5,573	6,726	1,199	572	10,804

[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 (2022a).

Table A-79: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2021

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC	HDDB
0	7.67%	7.69%	8.90%	6.96%	12.50%	8.62%	23.73%	20.59%
1	7.53%	7.52%	8.93%	5.94%	11.90%	8.93%	12.74%	11.29%
2	7.37%	7.42%	9.02%	3.39%	10.22%	9.42%	9.47%	8.89%
3	7.23%	7.19%	8.50%	1.07%	8.28%	8.88%	7.44%	6.95%
4	6.10%	8.77%	9.81%	0.22%	8.39%	9.35%	4.74%	8.74%
5	6.62%	8.05%	8.56%	1.10%	6.84%	8.55%	3.97%	7.17%
6	6.78%	7.12%	7.70%	23.12%	5.26%	9.22%	3.39%	5.92%
7	6.69%	5.95%	6.50%	14.00%	3.46%	7.54%	2.92%	5.10%
8	5.96%	4.50%	3.54%	11.26%	2.46%	4.83%	2.28%	2.61%
9	5.10%	3.66%	4.38%	8.96%	2.83%	4.77%	2.23%	2.34%
10	3.69%	3.46%	2.81%	6.06%	2.40%	2.52%	1.44%	2.05%
11	3.60%	2.58%	1.55%	5.31%	0.97%	1.56%	1.05%	2.04%
12	3.07%	1.81%	1.85%	3.32%	0.89%	1.75%	2.20%	2.22%
13	3.60%	2.88%	2.94%	0.34%	2.52%	1.56%	2.58%	2.00%
14	3.47%	2.81%	1.83%	0.22%	2.18%	3.18%	3.03%	1.73%
15	2.81%	2.57%	2.22%	2.70%	3.16%	2.16%	2.81%	1.66%
16	2.37%	2.46%	1.47%	1.61%	2.42%	1.55%	2.44%	1.17%
17	1.84%	2.26%	1.18%	0.86%	2.47%	0.87%	1.91%	1.18%
18	1.56%	1.88%	0.98%	0.90%	1.94%	0.73%	1.97%	1.00%
19	1.24%	1.66%	0.89%	0.79%	1.55%	0.51%	1.53%	0.97%
20	0.97%	1.34%	0.92%	0.45%	1.46%	0.67%	1.23%	1.04%
21	0.85%	1.19%	0.90%	0.36%	0.96%	0.82%	0.95%	0.97%
22	0.62%	0.98%	1.26%	0.16%	1.03%	0.57%	0.69%	0.54%
23	0.47%	0.75%	0.56%	0.14%	0.26%	0.35%	0.48%	0.42%
24	0.38%	0.63%	0.61%	0.05%	0.75%	0.25%	0.37%	0.33%
25	0.27%	0.44%	0.38%	0.05%	0.49%	0.22%	0.31%	0.25%
26	0.24%	0.42%	0.47%	0.03%	0.44%	0.20%	0.23%	0.21%

27	0.17%	0.35%	0.27%	0.00%	0.31%	0.13%	0.18%	0.12%
28	0.13%	0.24%	0.19%	0.01%	0.27%	0.08%	0.15%	0.11%
29	0.10%	0.18%	0.15%	0.02%	0.18%	0.05%	0.10%	0.08%
30	1.50%	1.25%	0.74%	0.58%	1.21%	0.16%	1.44%	0.29%
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).

Note: Estimated by weighting data in Table A-78. This year's Inventory includes updated vehicle population data based on the MOVES3 model that affects this distribution.

Table A-80: Fuel Consumption for Non-Road Sources by Fuel Type (million gallons unless otherwise noted)

Vehicle Type/Year	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Aircraft[a]	**19,542**	**20,294**	**15,754**	**15,255**	**14,907**	**15,268**	**15,390**	**16,331**	**17,191**	**17,783**	**17,854**	**18,683**	**12,540**	**15,835**
Aviation Gasoline	374	302	225	225	209	186	181	176	170	174	186	195	168	179
Jet Fuel	19,168	19,992	15,529	15,030	14,698	15,082	15,210	16,155	17,021	17,609	17,667	18,489	12,372	15,656
Commercial Aviation[b]	*11,569*	*14,672*	*11,931*	*12,067*	*11,932*	*12,031*	*12,131*	*12,534*	*12,674*	*13,475*	*13,650*	*14,397*	*9,613*	*12,527*
Ships and Boats	**4,826**	**6,544**	**4,693**	**4,833**	**4,239**	**4,175**	**3,191**	**3,652**	**4,235**	**4,469**	**4,190**	**4,053**	**3,333**	**4,906**
Diesel	1,156	1,882	1,361	1,641	1,389	1,414	1,284	1,881	1,680	1,593	1,525	1,342	1,342	1,377
Gasoline	1,611	1,636	1,446	1,401	1,372	1,349	1,323	1,325	1,335	1,344	1,352	1,355	1,272	1,337
Residual	2,060	3,027	1,886	1,791	1,477	1,413	584	445	1,219	1,532	1,313	1,356	719	2,192
Construction/Mining Equipment[c]														
Diesel	4,317	5,181	5,727	5,650	5,533	5,447	5,313	5,200	5,483	5,978	6,262	6,464	6,068	6,374
Gasoline	472	357	678	634	651	1,100	710	367	375	375	385	387	389	389
CNG (million cubic feet)	5,082	6,032	6,219	6,121	5,957	5,802	5,598	5,430	5,629	6,018	6,204	6,321	5,933	6,233
LPG	22	27	26	25	24	24	23	22	23	25	26	27	25	27
Agricultural Equipment[d]														
Diesel	3,514	3,278	3,942	3,876	3,932	3,900	3,925	3,862	3,760	3,728	3,732	3,742	3,638	3,429
Gasoline	813	652	692	799	875	655	644	159	168	168	160	129	135	135
CNG (million cubic feet)	1,758	1,678	1,647	1,600	1,611	1,588	1,590	1,561	1,517	1,503	1,502	1,507	1,465	1,380
LPG	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail	**3,461**	**4,106**	**3,807**	**3,999**	**3,921**	**4,025**	**4,201**	**4,020**	**3,715**	**3,832**	**3,936**	**3,696**	**3,203**	**3,327**
Diesel	3,461	4,106	3,807	3,999	3,921	4,025	4,201	4,020	3,715	3,832	3,936	3,696	3,203	3,327
Other[e]														
Diesel	2,095	2,047	2,450	2,523	2,639	2,725	2,811	2,832	2,851	2,919	3,027	3,110	2,896	3,053
Gasoline	4,371	4,673	5,525	5,344	5,189	5,201	5,281	5,083	5,137	5,178	5,238	5,287	5,096	5,265
CNG (million cubic feet)	20,894	25,035	29,891	32,035	35,085	37,436	39,705	38,069	37,709	38,674	40,390	41,474	38,930	40,898
LPG	1,412	2,191	2,165	2,168	2,181	2,213	2,248	2,279	2,316	2,408	2,526	2,616	2,456	2,580
Total (gallons)	**44,845**	**49,351**	**45,459**	**45,106**	**44,092**	**44,734**	**43,737**	**43,808**	**45,254**	**46,864**	**47,335**	**48,195**	**39,780**	**45,320**
Total (million cubic feet)	**27,735**	**32,745**	**37,757**	**39,755**	**42,653**	**44,826**	**46,893**	**45,060**	**44,854**	**46,194**	**48,097**	**49,301**	**46,328**	**48,511**

[a] For aircraft, this is aviation gasoline. For all other categories, this is motor gasoline.
[b] Commercial aviation, as modeled in FAA's AEDT, consists of passenger aircraft, cargo, and other chartered flights.
[c] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[d] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[e] "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.

Table A-81: 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
1973-1974	100%	-	-	-	-	-	-	-	-
1975	20%	80%	-	-	-	-	-	-	-
1976-1977	15%	85%	-	-	-	-	-	-	-
1978-1979	10%	90%	-	-	-	-	-	-	-
1980	5%	88%	7%	-	-	-	-	-	-
1981	-	15%	85%	-	-	-	-	-	-
1982	-	14%	86%	-	-	-	-	-	-
1983	-	12%	88%	-	-	-	-	-	-
1984-1993	-	-	100%	-	-	-	-	-	-
1994	-	-	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%

- (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 (2022d), and EPA (2022c).

Table A-82: 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
1973-1974	100%	-	-	-	-	-	-	-	-
1975	30%	70%	-	-	-	-	-	-	-
1976	20%	80%	-	-	-	-	-	-	-
1977-1978	25%	75%	-	-	-	-	-	-	-
1979-1980	20%	80%	-	-	-	-	-	-	-
1981	-	95%	5%	-	-	-	-	-	-
1982	-	90%	10%	-	-	-	-	-	-
1983	-	80%	20%	-	-	-	-	-	-
1984	-	70%	30%	-	-	-	-	-	-
1985	-	60%	40%	-	-	-	-	-	-
1986	-	50%	50%	-	-	-	-	-	-
1987-1993	-	5%	95%	-	-	-	-	-	-
1994	-	-	60%	40%	-	-	-	-	-
1995	-	-	20%	80%	-	-	-	-	-
1996	-	-	-	100%	-	-	-	-	-
1997	-	-	-	100%	-	-	-	-	-
1998	-	-	-	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%	0%	44%	53%
2020	-	-	-	-	-	-	-	50%	50%
2021	-	-	-	-	-	-	-	50%	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 (2022d), and EPA (2022c).

Table A-83: 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%

- (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 (2022d), and EPA (2022c).

Table A-84: 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	2007-2021
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960–1989
Moderate control	1990–2003
Advanced control	2004–2006
Aftertreatment	2007–2021
Motorcycles	
Uncontrolled	1960–1995
Non-catalyst controls	1996–2005
Advanced	2006-2021

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

Table A-85: 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	0.0083	0.0070
Non-Catalyst Control	0.0000	0.0000
Uncontrolled	0.0083	0.0070

[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 (2006b and 2017a), Browning (2022a).

Table A-86: Emission Factors for N_2O for Alternative Fuel Vehicles (g/mi)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
Ethanol-Flex Fuel ICE	0.040	0.027	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
CNG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
CNG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
LPG ICE	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	0.004	0.004	0.004
LPG Bi-fuel	0.024	0.022	0.006	0.006	0.006	0.006	0.006	0.006	0.005	0.005	0.005	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	0.007	0.007	0.006	0.006	0.005	0.005	0.005
CNG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
CNG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LPG ICE	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LPG Bi-fuel	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	0.005	0.005	0.005
LNG	0.046	0.045	0.007	0.007	0.007	0.007	0.007	0.007	0.007	0.006	0.006	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	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
CNG Bi-fuel	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LPG ICE	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LPG Bi-fuel	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
LNG	0.127	0.127	0.104	0.105	0.106	0.108	0.109	0.110	0.095	0.080	0.065	0.049	0.034	0.034
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	0.114	0.117	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027
Neat Ethanol ICE	0.128	0.128	0.114	0.117	0.121	0.124	0.127	0.130	0.110	0.089	0.069	0.048	0.028	0.027
CNG ICE	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LPG ICE	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LPG Bi-fuel	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
LNG	0.077	0.077	0.110	0.109	0.109	0.108	0.108	0.108	0.090	0.071	0.053	0.035	0.017	0.017
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	0.144	0.142	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029
Neat Ethanol ICE	0.198	0.198	0.144	0.142	0.141	0.139	0.137	0.136	0.114	0.093	0.072	0.051	0.029	0.029
CNG ICE	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017
LPG ICE	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017
LNG	0.119	0.119	0.086	0.085	0.084	0.083	0.082	0.081	0.069	0.056	0.043	0.030	0.018	0.017

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
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-87: Emission Factors for CH_4 for Alternative Fuel Vehicles (g/mi)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Light-Duty Cars														
Methanol-Flex Fuel ICE	0.126	0.083	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
Ethanol-Flex Fuel ICE	0.126	0.083	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
CNG ICE	1.793	1.103	0.225	0.211	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133
CNG Bi-fuel	1.793	1.103	0.225	0.211	0.198	0.185	0.171	0.158	0.156	0.153	0.151	0.149	0.146	0.133
LPG ICE	0.179	0.110	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
LPG Bi-fuel	0.179	0.110	0.022	0.021	0.020	0.018	0.017	0.016	0.016	0.015	0.015	0.015	0.015	0.013
Biodiesel (BD100)	-	0.002	-	0.006	0.012	0.018	0.024	0.030	0.019	0.030	0.030	0.030	0.030	0.036
Light-Duty Trucks														
Ethanol-Flex Fuel ICE	0.184	0.118	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
CNG ICE	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
CNG Bi-fuel	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
LPG ICE	0.263	0.158	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
LPG Bi-fuel	0.263	0.158	0.024	0.023	0.021	0.019	0.018	0.016	0.016	0.016	0.016	0.016	0.016	0.014
LNG	2.632	1.580	0.242	0.226	0.211	0.195	0.179	0.164	0.162	0.161	0.160	0.159	0.158	0.144
Biodiesel (BD100)	-	-	-	0.026	0.052	0.078	0.104	0.130	0.131	0.132	0.133	0.134	0.135	0.127
Medium Duty Trucks														
CNG ICE	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
CNG Bi-fuel	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
LPG ICE	0.680	0.680	0.557	0.563	0.570	0.576	0.583	0.589	0.508	0.427	0.345	0.264	0.183	0.181
LPG Bi-fuel	0.680	0.680	0.557	0.563	0.570	0.576	0.583	0.589	0.508	0.427	0.345	0.264	0.183	0.181
LNG	6.800	6.800	5.566	5.632	5.697	5.762	5.827	5.893	5.080	4.267	3.454	2.641	1.829	1.807
Biodiesel (BD100)	0.000	0.000	0.052	0.050	0.047	0.044	0.042	0.039	0.039	0.039	0.040	0.040	0.040	0.040
Heavy-Duty Trucks														
Neat Methanol ICE	0.287	0.287	0.256	0.263	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073
Neat Ethanol ICE	0.287	0.287	0.256	0.263	0.271	0.278	0.285	0.292	0.249	0.205	0.162	0.118	0.075	0.073
CNG ICE	4.100	4.100	5.871	5.849	5.827	5.805	5.783	5.761	4.793	3.825	2.857	1.889	0.921	0.921
LPG ICE	0.410	0.410	0.587	0.585	0.583	0.581	0.578	0.576	0.479	0.383	0.286	0.189	0.092	0.092
LPG Bi-fuel	0.410	0.410	0.587	0.585	0.583	0.581	0.578	0.576	0.479	0.383	0.286	0.189	0.092	0.076
LNG	4.100	4.100	5.871	5.849	5.827	5.805	5.783	5.761	4.793	3.825	2.857	1.889	0.921	0.921
Biodiesel (BD100)	0.000	0.000	0.061	0.052	0.043	0.034	0.025	0.016	0.016	0.015	0.015	0.015	0.014	0.014

Buses														
Neat Methanol ICE	1.316	1.316	0.960	0.948	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193
Neat Ethanol ICE	1.316	1.316	0.960	0.948	0.937	0.926	0.915	0.904	0.762	0.620	0.478	0.337	0.195	0.193
CNG ICE	18.800	18.800	13.710	13.550	13.389	13.229	13.068	12.908	10.884	8.860	6.836	4.811	2.787	2.753
LPG ICE	1.880	1.880	1.371	1.355	1.339	1.323	1.307	1.291	1.088	0.886	0.684	0.481	0.279	0.275
LNG	18.800	18.800	13.710	13.550	13.389	13.229	13.068	12.908	10.884	8.860	6.836	4.811	2.787	2.753
Biodiesel (BD100)	0.000	0.000	0.070	0.060	0.050	0.040	0.030	0.020	0.020	0.020	0.020	0.020	0.019	0.016

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-88: Emission Factors for N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
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	0.024	0.025	0.025	0.026	0.026	0.026	0.027	0.027	0.027	0.027	0.027	0.028
4 Stroke	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	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
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	0.170
4 Stroke	0.355	0.365	0.409	0.411	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433
Gasoline-Off-road Trucks	0.355	0.365	0.409	0.411	0.415	0.417	0.420	0.422	0.423	0.425	0.427	0.429	0.431	0.433
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	0.336
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	0.174
CNG	0.061	0.061	0.074	0.074	0.075	0.075	0.076	0.076	0.076	0.076	0.076	0.076	0.076	0.076
LPG	0.389	0.389	0.437	0.440	0.444	0.446	0.449	0.451	0.452	0.454	0.456	0.458	0.460	0.462
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	0.516	0.519	0.521	0.523	0.524	0.525	0.526	0.527	0.527	0.528	0.528	0.528
Gasoline-Off-road Trucks	0.408	0.450	0.516	0.519	0.521	0.523	0.524	0.525	0.526	0.527	0.527	0.528	0.528	0.528

Diesel-Equipment	0.295	0.295	0.294	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295	0.295
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	0.174
CNG	0.367	0.367	0.391	0.395	0.398	0.402	0.405	0.409	0.416	0.424	0.431	0.437	0.442	0.445
LPG	0.197	0.197	0.223	0.226	0.229	0.231	0.233	0.235	0.237	0.239	0.240	0.242	0.243	0.243
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	0.107	0.120	0.171	0.171	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172	0.172
4 Stroke	0.519	0.578	0.684	0.688	0.690	0.692	0.693	0.694	0.695	0.695	0.695	0.696	0.696	0.696
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	0.110
4 Stroke	0.409	0.476	0.530	0.531	0.532	0.533	0.534	0.534	0.534	0.535	0.535	0.535	0.535	0.535
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	0.153
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	0.153
LPG	0.245	0.245	0.291	0.297	0.300	0.302	0.303	0.304	0.305	0.306	0.306	0.306	0.306	0.306
Airport Equipment														
Gasoline														
4 Stroke	0.299	0.316	0.372	0.376	0.378	0.380	0.381	0.382	0.382	0.383	0.383	0.383	0.383	0.383
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	0.364
LPG	0.346	0.346	0.414	0.421	0.424	0.427	0.429	0.430	0.431	0.431	0.432	0.432	0.432	0.432
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	0.107	0.123	0.177	0.177	0.177	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178
4 Stroke	0.425	0.473	0.542	0.545	0.548	0.550	0.551	0.552	0.553	0.553	0.552	0.551	0.551	0.550
Diesel	0.183	0.180	0.187	0.188	0.190	0.191	0.192	0.190	0.190	0.189	0.189	0.189	0.189	0.189
CNG	0.034	0.031	0.040	0.041	0.043	0.044	0.044	0.044	0.043	0.043	0.043	0.043	0.043	0.042
LPG	0.250	0.250	0.291	0.297	0.303	0.305	0.307	0.308	0.309	0.310	0.311	0.311	0.311	0.312
Logging Equipment														
Gasoline														
2 Stroke	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4 Stroke	0.579	0.604	0.672	0.678	0.688	0.699	0.709	0.719	0.725	0.730	0.733	0.735	0.736	0.737
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	0.398
Railroad Equipment														
Gasoline														
4 Stroke	0.498	0.555	0.643	0.645	0.646	0.647	0.648	0.649	0.649	0.650	0.650	0.650	0.650	0.650
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	0.297
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	0.035	0.035	0.036	0.036	0.037	0.037	0.037	0.038	0.038	0.039	0.039	0.039
4 Stroke	0.487	0.503	0.534	0.535	0.535	0.536	0.536	0.536	0.536	0.536	0.536	0.537	0.537	0.531
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	0.207
LPG	0.255	0.255	0.270	0.272	0.275	0.277	0.279	0.281	0.284	0.286	0.288	0.290	0.293	0.295

- 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 (2022a).

Table A-89: Emission Factors for CH_4 Emissions from Non-Road Mobile Combustion (g/kg fuel)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
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	0.309
Gasoline														
2 Stroke	1.255	1.270	1.465	1.489	1.514	1.536	1.557	1.578	1.597	1.615	1.629	1.642	1.652	1.661
4 Stroke	0.717	0.725	0.760	0.763	0.768	0.773	0.777	0.783	0.788	0.793	0.797	0.801	0.805	0.808
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	2.008	2.008	2.008
Rail														
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	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	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	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	2.480	2.480	2.480
4 Stroke	0.570	0.586	0.656	0.660	0.666	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695
Gasoline-Off-road Trucks	0.570	0.586	0.656	0.660	0.666	0.670	0.674	0.677	0.679	0.682	0.686	0.689	0.692	0.695
Diesel-Equipment	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397
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	0.286	0.286	0.286
CNG	1.391	1.391	1.676	1.698	1.710	1.719	1.726	1.731	1.734	1.736	1.736	1.736	1.736	1.736
LPG	0.135	0.135	0.152	0.153	0.154	0.155	0.156	0.157	0.157	0.158	0.158	0.159	0.160	0.160
Construction/Mining Equipment[c]														
Gasoline-Equipment														
2 Stroke	1.868	1.997	2.857	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858	2.858
4 Stroke	0.789	0.871	0.999	1.005	1.009	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022
Gasoline-Off-road Trucks	0.789	0.871	0.999	1.005	1.009	1.011	1.013	1.015	1.017	1.019	1.020	1.021	1.022	1.022
Diesel-Equipment	0.317	0.317	0.316	0.316	0.316	0.316	0.316	0.316	0.316	0.317	0.317	0.317	0.317	0.317

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	0.286	0.286	0.286
CNG	1.322	1.322	1.409	1.422	1.434	1.447	1.459	1.473	1.499	1.529	1.554	1.574	1.595	1.605
LPG	0.233	0.233	0.264	0.267	0.271	0.273	0.276	0.278	0.280	0.283	0.285	0.286	0.287	0.288
Lawn and Garden Equipment														
Gasoline-Residential														
2 Stroke	1.489	1.666	2.361	2.373	2.379	2.381	2.381	2.382	2.382	2.382	2.382	2.383	2.383	2.384
4 Stroke	0.803	0.894	1.058	1.063	1.067	1.070	1.072	1.073	1.074	1.075	1.075	1.075	1.076	1.076
Gasoline-Commercial														
2 Stroke	1.685	1.859	2.609	2.609	2.609	2.609	2.609	2.609	2.609	2.610	2.610	2.610	2.611	2.611
4 Stroke	0.821	0.956	1.064	1.067	1.069	1.071	1.072	1.072	1.073	1.073	1.073	1.073	1.073	1.074
Diesel-Residential	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208
Diesel-Commercial	0.236	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208	0.208
LPG	0.162	0.162	0.192	0.196	0.198	0.199	0.200	0.201	0.202	0.202	0.202	0.202	0.202	0.202
Airport Equipment														
Gasoline														
4 Stroke	0.287	0.303	0.356	0.360	0.362	0.364	0.365	0.366	0.366	0.366	0.367	0.367	0.367	0.367
Diesel	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593	0.593
LPG	0.137	0.137	0.164	0.167	0.168	0.169	0.170	0.171	0.171	0.171	0.171	0.171	0.171	0.171
Industrial/Commercial Equipment														
Gasoline														
2 Stroke	1.541	1.774	2.545	2.547	2.549	2.550	2.551	2.552	2.553	2.553	2.554	2.554	2.554	2.555
4 Stroke	0.758	0.837	0.965	0.972	0.979	0.984	0.987	0.987	0.987	0.987	0.986	0.985	0.984	0.983
Diesel	0.120	0.106	0.127	0.131	0.137	0.140	0.143	0.141	0.139	0.135	0.134	0.133	0.133	0.132
CNG	2.334	2.420	2.824	2.836	2.840	2.837	2.832	2.854	2.867	2.877	2.885	2.892	2.897	2.904
LPG	0.174	0.174	0.203	0.206	0.210	0.212	0.213	0.214	0.215	0.215	0.216	0.216	0.216	0.216
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	3.468	3.468	3.468
4 Stroke	0.914	0.950	1.072	1.084	1.099	1.114	1.127	1.137	1.143	1.149	1.153	1.157	1.159	1.161
Diesel	0.153	0.153	0.154	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153	0.153
Railroad Equipment														
Gasoline														
4 Stroke	0.897	0.990	1.147	1.151	1.153	1.155	1.157	1.158	1.158	1.159	1.160	1.160	1.160	1.160
Diesel	0.125	0.125	0.126	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
LPG	0.784	0.787	0.870	0.893	0.905	0.919	0.927	0.936	0.943	0.956	0.962	0.966	0.970	0.973
Recreational Equipment														
Gasoline														
2 Stroke	5.170	5.252	5.553	5.616	5.700	5.781	5.862	5.944	6.024	6.100	6.176	6.244	6.310	3.510

4 Stroke	0.935		0.965		1.026	1.028	1.028	1.029	1.030	1.030	1.030	1.031	1.031	1.031	1.032	0.975
Diesel	0.228		0.228		0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228	0.228
LPG	0.182		0.182		0.193	0.195	0.196	0.198	0.200	0.201	0.203	0.204	0.206	0.208	0.209	0.211

[a] Emissions of CH_4 from jet fuels have been zeroed out across the time series. 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 consumer methane. Over the range of engine operating modes, aircraft engines are net consumers of methane on average. Based on this data, CH_4 emissions factors for jet aircraft were changed to zero to reflect the latest emissions testing data.

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

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

Sources: IPCC (2006) and Browning, L (2018b), EPA (2022a).

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-81 through Table A-84 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 (1993, 1994a, 1994b, 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. Although the Inventory is not required to provide details beyond what is contained in the body of this report, the IPCC allows presentation of additional data and detail on emission sources. 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-90 provides estimates of CO_2 from these other mobile sources, developed from the Nonroad component of EPA's MOVES3 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-80). 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-90, Table A-92, and Table A-93 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).

Table A-90: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)[a]

Fuel Type/ Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Agricultural Equipment[a]	43.4	39.9	46.6	46.8	48.0	45.8	45.9	41.1	40.2	39.8	39.8	39.7	38.6	36.5
Construction/Mining Equipment[b]	48.9	57.4	65.3	64.0	62.9	65.9	61.1	57.0	60.0	65.1	68.2	70.3	66.2	69.3
Other Sources[c]	69.6	76.3	86.6	85.8	85.9	87.0	88.8	87.4	88.3	89.9	92.3	94.1	89.3	93.1
Total	**161.9**	**173.6**	**198.4**	**196.6**	**196.8**	**198.7**	**195.9**	**185.6**	**188.4**	**194.8**	**200.3**	**204.1**	**194.1**	**198.9**

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

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

[c] "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: The method used to estimate CO_2 emissions 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). The current Inventory uses the Nonroad component of MOVES3 for years 1999 through 2021.

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-91 below presents these HFC emissions. Table A-92 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-91: HFC Emissions from Transportation Sources (MMT CO_2 Eq.)

Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Mobile AC	**+**	**50.2**	**58.8**	**53.2**	**47.9**	**42.4**	**39.4**	**36.8**	**33.6**	**30.2**	**28.2**	**26.2**	**24.2**	**22.4**
Passenger Cars	+	25.5	25.0	21.7	18.7	15.7	14.4	13.3	12.0	10.4	9.4	8.4	7.6	7.0
Light-Duty Trucks	+	23.3	31.0	28.8	26.6	24.1	22.4	20.9	19.2	17.5	16.4	15.4	14.2	13.0
Heavy-Duty Vehicles	+	1.5	2.8	2.7	2.7	2.6	2.6	2.6	2.4	2.4	2.4	2.4	2.4	2.4
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**	**0.4**
School and Tour Buses	+	0.1	0.4	0.4	0.4	0.4	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
Rail	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	**+**	**0.8**	**2.9**	**3.4**	**3.9**	**4.4**	**4.9**	**5.4**	**5.9**	**6.4**	**6.9**	**7.4**	**7.9**	**8.4**
Medium- and Heavy-Duty Trucks	+	0.4	1.6	1.8	2.0	2.3	2.5	2.6	2.8	3.0	3.2	3.4	3.6	3.8
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	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.2	4.5
Total	**+**	**51.1**	**62.1**	**57.0**	**52.3**	**47.3**	**44.7**	**42.6**	**39.9**	**37.0**	**35.5**	**34.0**	**32.5**	**31.2**

+ 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-92 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 2,015.0 MMT CO_2 Eq. in 2021, an increase of 19 percent from 1990.[58] Transportation sources account for 1,809.5 MMT CO_2 Eq. while non-transportation mobile sources account for 205.5 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-90 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 2023 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.[59] 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 2021). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from the Nonroad component of EPA's MOVES3 model (EPA 2022a). 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 3.9 (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 1,809.5 MMT CO_2 Eq. in 2021.

On-road vehicles were responsible for about 74 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2021. 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 42 percent between 1990 and 2021. Greenhouse gas emissions from light-duty trucks increased by 122 percent between 1990 and 2021. Overall, between 1990 and 2021, greenhouse gas emissions from passenger cars and light-duty trucks increased by 10 percent. Meanwhile, greenhouse

[58] 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).

[59] VMT is allocated to vehicle classes using MOVES3 ratios of VMT in each vehicle class to total VMT.

gas emissions from medium- and heavy-duty trucks increased 78 percent between 1990 and 2021, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 18 percent between 1990 and 2021. Emissions from military aircraft decreased 65 percent between 1990 and 2021. Commercial aircraft emissions rose 27 percent between 1990 and 2007, dropped 2 percent from 2007 to 2019, and then dropped 33 percent from 2019 to 2020. Overall, commercial aircraft emissions increased by approximately 8 percent between 1990 and 2021.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 205.5MMT CO_2 Eq. in 2021. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased, growing approximately 23 percent between 1990 and 2021. 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-93 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 97 percent in 2021). Emissions of CO_2 from transportation and mobile sources increased by 319 MMT CO_2 Eq. between 1990 and 2021. In contrast, the combined emissions of CH_4 and N_2O decreased by 26.4 MMT CO_2 Eq. over the same period, due largely to the introduction of control technologies designed to reduce criteria pollutant emissions.[60] Meanwhile, HFC emissions from mobile air-conditioners and refrigerated transport increased from virtually no emissions in 1990 to 31.2 MMT CO_2 Eq. in 2021 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 UNFCCC reporting requirements.

Greenhouse Gas Emissions from Freight and Passenger Transportation

Table A-94 and Table A-95 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-94. 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-95. 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 to allocate to the passenger and freight categories was calculated using BTS data on freight shipped by commercial aircraft, and the total number of passengers enplaned. 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-92. In addition, estimates of fuel consumption from DOE (1993 through 2022) were used to allocate rail emissions between passenger and freight categories.

In 2021, passenger transportation modes emitted 1,221.8 MMT CO_2 Eq., while freight transportation modes emitted 564.6 MMT CO_2 Eq. Between 1990 and 2021, the percentage growth of greenhouse gas emissions from freight sources was 60 percent. Emissions from passenger sources decreased by 2 percent from 1990 to 2021. This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

60 The decline in CFC emissions is not captured in the official transportation estimates.

Table A-92: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
Transportation Total[a]	**1,524.6**	**1,907.3**	**1,799.8**	**1,766.7**	**1,747.5**	**1,751.0**	**1,785.3**	**1,793.5**	**1,828.4**	**1,846.0**	**1,876.2**	**1,879.2**	**1,629.2**	**1,809.5**	**19%**
On-Road Vehicles	**1,202.0**	**1,548.4**	**1,508.1**	**1,477.0**	**1,467.0**	**1,460.8**	**1,509.2**	**1,505.6**	**1,528.9**	**1,535.1**	**1,557.9**	**1,549.1**	**1,374.1**	**1,496.4**	**24%**
Passenger Cars	**648.4**	**602.3**	**493.7**	**458.2**	**401.3**	**405.2**	**415.9**	**405.5**	**406.2**	**392.7**	**398.7**	**395.5**	**341.7**	**374.2**	**-42%**
Gasoline[b]	639.0	573.7	466.6	434.0	380.0	386.7	398.3	388.2	390.4	378.5	385.3	382.8	330.3	362.7	**-43%**
Diesel[b]	9.5	3.1	2.1	2.4	2.4	2.5	2.8	3.3	3.1	3.0	2.8	2.7	2.6	2.8	**-71%**
AFVs[c]	+	+	+	0.1	0.1	0.2	0.4	0.5	0.7	0.8	1.2	1.4	1.3	1.8	**NA**
HFCs from Mobile AC	-	25.5	25.5	21.7	18.7	15.7	14.4	13.3	12.0	10.4	9.4	8.4	7.6	7.0	**NA**
Light-Duty Trucks	**302.5**	**575.3**	**632.0**	**642.5**	**688.5**	**672.1**	**693.4**	**693.2**	**710.9**	**716.2**	**720.6**	**711.8**	**615.4**	**671.8**	**122%**
Gasoline[b]	293.8	532.2	572.5	582.8	628.4	616.8	640.0	640.6	660.5	667.3	672.4	664.6	570.4	624.4	**113%**
Diesel[b]	8.4	19.7	28.4	30.9	33.6	31.2	31.0	31.6	31.1	31.3	31.5	31.5	30.5	33.7	**299%**
AFVs[c]	0.2	0.1	0.1	0.1	+	+	0.1	0.1	0.1	0.2	0.3	0.3	0.4	0.8	**262%**
HFCs from Mobile AC	-	23.3	31.0	28.8	26.6	24.1	22.4	20.9	19.2	17.5	16.4	15.4	14.2	13.0	**NA**
Medium- and Heavy-Duty Trucks	**234.3**	**347.0**	**359.4**	**352.5**	**351.5**	**357.5**	**371.9**	**378.3**	**382.5**	**395.6**	**406.7**	**409.5**	**386.7**	**417.1**	**78%**
Gasoline[b]	44.0	37.1	23.2	21.1	21.1	21.5	23.0	23.0	24.3	25.2	26.4	27.2	24.3	27.5	**-37%**
Diesel[b]	189.2	307.4	331.5	326.6	325.3	330.7	343.5	349.6	352.4	364.5	374.1	375.9	356.0	383.0	**102%**
AFVs[c]	1.1	0.6	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5	0.3	0.4	**-66%**
HFCs from Refrigerated Transport and Mobile AC[e]	-	1.9	4.4	4.5	4.7	4.9	5.1	5.2	5.3	5.4	5.6	5.8	6.1	6.3	**NA**
Buses	**13.4**	**19.4**	**16.7**	**17.6**	**18.7**	**19.1**	**21.0**	**21.9**	**22.1**	**23.4**	**24.4**	**24.8**	**23.6**	**25.7**	**91%**
Gasoline[b]	2.2	1.5	1.3	1.4	1.6	1.8	2.1	2.1	2.3	2.5	2.7	2.8	2.5	2.9	**32%**
Diesel[b]	11.1	17.4	14.5	15.3	16.2	16.4	17.9	18.7	18.7	19.8	20.5	20.9	19.9	21.6	**95%**
AFVs[c]	0.2	0.4	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.7	0.9	**376%**
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	**NA**
Motorcycles	**3.4**	**4.4**	**6.4**	**6.3**	**7.1**	**6.8**	**7.0**	**6.8**	**7.2**	**7.2**	**7.4**	**7.5**	**6.7**	**7.5**	**121%**
Gasoline[b]	3.4	4.4	6.4	6.3	7.1	6.8	7.0	6.8	7.2	7.2	7.4	7.5	6.7	7.5	**121%**
Aircraft	**188.8**	**199.1**	**154.6**	**149.7**	**146.3**	**149.8**	**151.0**	**160.3**	**168.8**	**174.6**	**175.3**	**183.4**	**123.0**	**155.4**	**-18%**
General Aviation Aircraft	**42.0**	**35.3**	**26.3**	**22.2**	**19.6**	**23.3**	**20.5**	**26.5**	**34.8**	**32.9**	**32.4**	**33.3**	**19.2**	**22.8**	**-46%**
Jet Fuel[f]	38.8	32.7	24.4	20.3	17.8	21.7	19.0	25.0	33.3	31.5	30.8	31.7	17.8	21.3	**-45%**
Aviation Gasoline	3.2	2.6	1.9	1.9	1.8	1.6	1.5	1.5	1.5	1.5	1.6	1.7	1.4	1.5	**-52%**
Commercial Aircraft	**110.8**	**140.5**	**114.2**	**115.5**	**114.2**	**115.2**	**116.1**	**120.0**	**121.4**	**129.0**	**130.7**	**137.8**	**92.0**	**120.0**	**8%**
Jet Fuel[f]	110.8	140.5	114.2	115.5	114.2	115.2	116.1	120.0	121.4	129.0	130.7	137.8	92.0	120.0	**8%**
Military Aircraft	**36.0**	**23.3**	**14.0**	**11.9**	**12.4**	**11.3**	**14.4**	**13.9**	**12.6**	**12.6**	**12.2**	**12.3**	**11.8**	**12.6**	**-65%**

Jet Fuel[f]	36.0	23.3	14.0	11.9	12.4	11.3	14.4	13.9	12.6	12.6	12.2	12.3	11.8	12.6	**-65%**
Ships and Boats[d]	**47.0**	**65.9**	**45.0**	**46.4**	**40.3**	**39.7**	**29.1**	**33.8**	**40.7**	**43.8**	**41.1**	**40.0**	**32.4**	**50.2**	**7%**
Gasoline	14.4	14.5	11.8	11.4	11.1	10.9	10.7	10.7	10.7	10.8	10.9	10.9	10.2	10.7	**-26%**
Distillate Fuel	9.8	17.4	11.3	14.0	11.4	11.5	10.2	16.2	14.0	13.1	12.5	10.6	10.6	10.9	**12%**
Residual Fuel[e]	22.8	33.6	20.7	19.6	16.0	15.3	5.9	4.3	13.1	16.6	14.2	14.6	7.4	24.1	**6%**
HFCs from Refrigerated Transport[e]	+	0.3	1.2	1.5	1.7	2.0	2.3	2.6	2.9	3.2	3.6	3.9	4.2	4.5	**NA**
Rail	**39.0**	**46.6**	**44.0**	**45.1**	**43.8**	**44.4**	**46.2**	**44.0**	**40.2**	**41.3**	**42.5**	**39.7**	**34.0**	**35.2**	**-10%**
Distillate Fuel[f]	35.8	42.9	39.3	40.6	39.7	40.1	41.9	40.0	36.5	37.7	38.9	36.3	31.3	32.5	**-9%**
Electricity	3.1	3.5	4.5	4.3	3.9	4.1	4.1	3.8	3.5	3.4	3.4	3.2	2.5	2.5	**-17%**
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	**8%**
HFCs from Comfort Cooling	-	+	+	+	+	+	+	+	+	+	+	+	+	+	**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	0.1	**NA**
Pipelines[h]	**36.0**	**35.4**	**37.8**	**38.5**	**41.0**	**46.6**	**39.7**	**38.9**	**39.5**	**41.6**	**50.2**	**58.2**	**57.9**	**64.2**	**78%**
Natural Gas	36.0	35.4	37.8	38.5	41.0	46.6	39.7	38.9	39.5	41.6	50.2	58.2	57.9	64.2	**78%**
Other Transportation	**11.8**	**12.1**	**10.4**	**10.0**	**9.1**	**9.6**	**10.0**	**11.0**	**10.4**	**9.6**	**9.2**	**8.8**	**7.8**	**8.0**	**-33%**
Lubricants	**11.8**	**12.1**	**10.4**	**10.0**	**9.1**	**9.6**	**10.0**	**11.0**	**10.4**	**9.6**	**9.2**	**8.8**	**7.8**	**8.0**	**-33%**
Non-Transportation Mobile[i] Total	**166.9**	**179.1**	**205.3**	**203.4**	**203.6**	**205.6**	**202.8**	**192.0**	**194.9**	**201.4**	**207.0**	**210.9**	**200.6**	**205.5**	**23%**
Agricultural Equipment[i,j]	**44.7**	**41.1**	**48.1**	**48.3**	**49.6**	**47.3**	**47.4**	**42.4**	**41.4**	**41.1**	**41.1**	**40.9**	**39.8**	**37.6**	**-16%**
Gasoline	7.5	6.0	6.2	7.1	7.8	5.8	5.7	1.4	1.5	1.5	1.4	1.1	1.2	1.2	**-84%**
Diesel	37.2	35.0	41.8	41.1	41.7	41.4	41.6	40.9	39.8	39.5	39.6	39.7	38.6	36.3	**-2%**
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	**-21%**
LPG	+	+	+	+	+	+	+	+	+	+	+	+	+	+	**-16%**
Construction/Mining Equipment[i,k]	**50.2**	**58.9**	**67.1**	**65.8**	**64.7**	**67.8**	**62.9**	**58.6**	**61.6**	**66.9**	**70.0**	**72.2**	**68.0**	**71.2**	**42%**
Gasoline	4.4	3.3	6.1	5.7	5.9	9.9	6.4	3.3	3.4	3.4	3.5	3.5	3.5	3.5	**-20%**
Diesel	45.4	55.1	60.5	59.6	58.4	57.5	56.1	54.8	57.8	63.0	66.0	68.2	64.0	67.2	**48%**
CNG	0.3	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.3	0.4	**25%**
LPG	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.2	**19%**
Other Equipment[i,l]	**71.9**	**79.1**	**90.1**	**89.3**	**89.3**	**90.5**	**92.4**	**90.9**	**91.8**	**93.5**	**96.0**	**97.9**	**92.8**	**96.7**	**34%**
Gasoline	40.5	43.2	50.0	48.3	46.8	46.8	47.5	45.6	46.1	46.5	47.1	47.5	45.8	47.2	**16%**
Diesel	21.9	21.6	25.7	26.4	27.6	28.5	29.4	29.6	29.8	30.5	31.7	32.5	30.3	31.9	**46%**
CNG	1.2	1.4	1.7	1.8	2.0	2.1	2.2	2.2	2.1	2.2	2.3	2.4	2.2	2.3	**98%**
LPG	8.3	12.9	12.8	12.8	12.9	13.1	13.3	13.5	13.7	14.3	15.0	15.5	14.5	15.3	**84%**

Transportation and Non-Transportation Mobile Total[l]	**1,691.4**	**2,086.4**	**2,005.1**	**1,970.2**	**1,951.1**	**1,956.6**	**1,988.1**	**1,985.5**	**2,023.3**	**2,047.4**	**2,083.2**	**2,090.2**	**1,829.8**	**2,015.0**	**19%**

+ 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 MOVES3 to apportion FHWA fuel consumption data to vehicle type and fuel type. MOVES3 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 2023). Total VMT estimates were then allocated using EPA's MOVES3 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 2021 is not available. Diesel consumption data for 2014-2021 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 (MOVES3) 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 MOVES3 for years 1999 through 2021. 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.

Table A-93: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
CO_2 [a]	1,645.7	1,981.3	1,909.9	1,881.3	1,869.3	1,881.5	1,917.7	1,919.1	1,960.7	1,988.8	2,027.2	2,034.1	1,778.5	1,964.3	19%
N_2O	38.4	48.3	29.2	28.1	26.1	24.3	22.4	20.6	19.5	18.5	17.5	19.0	16.1	16.7	-57%
CH_4	7.2	5.6	3.7	3.6	3.5	3.4	3.2	3.1	3.0	2.9	2.9	2.9	2.6	2.6	-64%
HFC	+	51.6	62.1	57	52.3	47.3	44.7	42.6	39.9	37.0	35.5	34.0	32.5	31.2	NA
Total[b]	**1,691.3**	**2,086.3**	**2,000.5**	**1,970.1**	**1,951.0**	**1,960.8**	**1,988.0**	**1,985.4**	**2,023.2**	**2,047.3**	**2,083.1**	**2,090**	**1,829.7**	**2,014.9**	**19%**

+ 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 MOVES3 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 2023). VMT estimates were then allocated to vehicle type using ratios of VMT per vehicle type to total VMT, derived from EPA's MOVES3 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.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2021

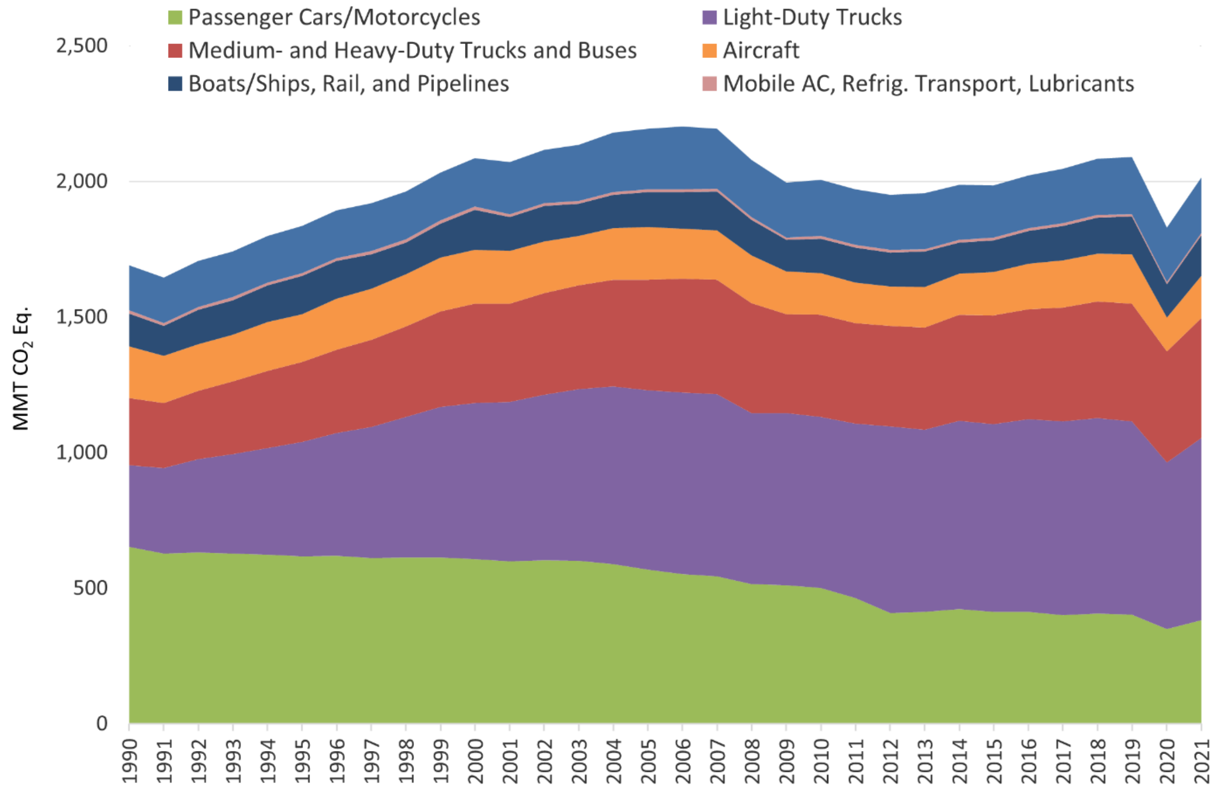

Table A-94: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
On-Road Vehicles[a,b]	**967.7**	**1,201.4**	**1,148.7**	**1,124.6**	**1,115.6**	**1,103.3**	**1,137.3**	**1,127.3**	**1,146.4**	**1,139.5**	**1,151.2**	**1,139.6**	**987.3**	**1,079.2**	**12%**
Passenger Cars	648.4	602.3	493.7	458.2	401.3	405.2	415.9	405.5	406.2	392.7	398.7	395.5	341.7	374.2	-42%
Light-Duty Trucks	302.5	575.3	632.0	642.5	688.5	672.1	693.4	693.2	710.9	716.2	720.6	711.8	615.4	671.8	122%
Buses	13.4	19.4	16.7	17.6	18.7	19.1	21.0	21.9	22.1	23.4	24.4	24.8	23.6	25.7	91%
Motorcycles	3.4	4.4	6.4	6.3	7.1	6.8	7.0	6.8	7.2	7.2	7.4	7.5	6.7	7.5	121%
Aircraft	**133.6**	**151.5**	**124.3**	**121.7**	**118.1**	**122.6**	**120.4**	**130.0**	**139.3**	**143.6**	**144.4**	**151.5**	**98.1**	**125.7**	**-6%**
General Aviation	42.0	35.3	26.3	22.2	19.6	23.3	20.5	26.5	34.8	32.9	32.4	33.3	19.2	22.8	-46%
Commercial Aircraft	91.6	116.1	97.9	99.5	98.5	99.4	99.9	103.5	104.6	110.6	112.0	118.1	78.9	102.8	12%
Recreational Boats	**17.2**	**17.3**	**14.5**	**14.0**	**13.7**	**13.4**	**13.2**	**13.3**	**13.4**	**13.6**	**13.7**	**13.8**	**12.9**	**13.5**	**-21%**
Passenger Rail	**4.4**	**5.2**	**6.2**	**5.9**	**5.5**	**5.8**	**5.7**	**5.4**	**5.2**	**5.1**	**4.5**	**4.2**	**3.4**	**3.3**	**-24%**
Total	**1,122.9**	**1,375.4**	**1,293.7**	**1,266.2**	**1,252.9**	**1,245.1**	**1,276.6**	**1,276.0**	**1,304.3**	**1,301.7**	**1,313.8**	**1,309.0**	**1,101.7**	**1,221.8**	**-2%**

[a] The current Inventory includes updated vehicle population data based on the MOVES3 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 MOVES3 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 2023). These total mileage estimates are combined with MOVES3 model ratios to apportion VMT.

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. The Inventory uses the Nonroad component of MOVES3 for years 1999 through 2021. 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).

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.

Table A-95: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	2000	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Percent Change 1990-2021
Trucking[a,b]	234.3	345.5	356.6	349.8	348.8	354.9	369.3	375.8	380.1	393.2	404.3	407.1	384.3	414.7	77%
Freight Rail	34.5	41.3	37.8	39.1	38.3	38.6	40.5	38.5	35.0	36.2	38.0	35.4	30.5	31.8	-8%
Ships and Non-Recreational Boats	29.8	48.6	30.5	32.5	26.6	26.3	15.9	20.5	27.3	30.3	27.4	26.3	19.5	36.7	23%
Pipelines[c]	36.0	35.4	37.8	38.5	41.0	46.6	39.7	38.9	39.5	41.6	50.2	58.2	57.9	64.2	78%

Commercial Aircraft	19.2	24.3	16.3	16.0	15.7	15.9	16.2	16.5	16.8	18.4	18.7	19.3	13.1	17.1	-11%
Total	**353.8**	**495.1**	**478.9**	**475.9**	**470.4**	**482.3**	**481.6**	**490.1**	**498.6**	**519.7**	**538.6**	**546.7**	**505.4**	**564.6**	**60%**

[a] The current Inventory includes updated vehicle population data based on the MOVES3 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 MOVES3 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 2023) and MOVES3 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 2021) 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 MOVES3 for years 1999 through 2021. Is 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).

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.

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. 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 2022a) 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. MOVES3 is the latest official version of MOVES; previous versions of the model include MOVES2010 and MOVES2014.

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 (2021e)) 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

IPCC Tier 3B Method: Commercial aircraft jet fuel burn and carbon dioxide (CO_2) emissions estimates were developed by the U.S. Federal Aviation Administration (FAA) using radar-informed data from the FAA Enhanced Traffic Management System (ETMS) for 2000 through 2021 as modeled with the Aviation Environmental Design Tool (AEDT). This bottom-up approach is built from modeling dynamic aircraft performance for each flight occurring within an individual calendar year. The analysis incorporates data on the aircraft type, date, flight identifier, departure time, arrival time, departure airport, arrival airport, ground delay at each airport, and real-world flight trajectories. To generate results for a given flight within AEDT, the radar-informed aircraft data is correlated with engine and aircraft performance data to calculate fuel burn and exhaust emissions. Information on exhaust emissions for in-production aircraft engines comes from the International Civil Aviation Organization (ICAO) Aircraft Engine Emissions Databank (EDB). This bottom-up approach is in accordance with the Tier 3B method from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

International Bunkers: The IPCC guidelines define international aviation (International Bunkers) as emissions from flights that depart from one country and arrive in a different country. Bunker fuel emissions estimates for commercial aircraft were developed for this report for 2000 through 2021 using the same radar-informed data modeled with AEDT. Since this process builds estimates from flight-specific information, the emissions estimates for commercial aircraft can include emissions associated with the U.S. territories (i.e., American Samoa, Guam, Puerto Rico, U.S. Virgin Islands, Wake Island, and other U.S. Pacific Islands). However, to allow for the alignment of emissions estimates for commercial aircraft with other data that is provided without the U.S. territories, this annex includes emissions estimates for commercial aircraft both with and without the U.S. territories included.

Time Series and Analysis Update: The FAA incrementally improves the consistency, robustness, and fidelity of the CO_2 emissions modeling for commercial aircraft, which is the basis of the Tier3B inventories presented in this report. While the FAA does not anticipate significant changes to the AEDT model in the future, recommended improvements are limited by budget and time constraints, as well as data availability. For instance, previous reports included reported annual CO_2 emission estimates for 2000 through 2005 that were modeled using the FAA's System for assessing Aviation's Global Emissions (SAGE). That tool and its capabilities were significantly improved after it was incorporated and evolved into AEDT. For this report, the AEDT model was used to generate annual CO_2 emission estimates for 2000, 2005, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020 and 2021 only. The reported annual CO_2 emissions values for 2001 through 2004 were estimated from the previously reported SAGE data. Likewise, CO_2 emissions values for 2006 through 2009 were estimated by interpolation to preserve trends from past reports.

Commercial aircraft radar data sets are not available for years prior to 2000. Instead, the FAA applied a Tier3B methodology by developing Official Airline Guide (OAG) schedule-informed estimates modeled with AEDT and great circle trajectories for 1990, 2000 and 2010. The ratios between the OAG schedule-informed and the radar-informed inventories for the years 2000 and 2010 were applied to the 1990 OAG scheduled-informed inventory to generate the best possible CO_2 inventory estimate for commercial aircraft in 1990. The resultant 1990 CO_2 inventory served as the reference for generating additional 1995-1999 emissions estimates, which were established using previously available trends. International consumption estimates for 1991-1999 and domestic consumption estimates for 1991-1994 are calculated using fuel consumption estimates from the Bureau of Transportation Statistics (DOT 1991 through 2013), adjusted based on the ratio of DOT to AEDT data.

Notes on the 1990 CO_2 Emissions Inventory for Commercial Aircraft: There are uncertainties associated with the modeled 1990 data that do not exist for the modeled years, 2000 to 2021 data. Radar-based data is not available for 1990. The OAG schedule information generally includes fewer carriers than radar information, and this will result in a different fleet mix, and in turn, different CO_2 emissions than would be quantified using a radar-based data set. For this reason, the FAA adjusted the OAG-informed schedule for 1990 with a ratio based on radar-informed information. In addition, radar trajectories are also generally longer than great circle trajectories. While the 1990 fuel burn data was adjusted to address these differences, it inherently adds greater uncertainty to the revised 1990 commercial aircraft CO_2 emissions as compared to data from 2000 forward. Also, the revised 1990 CO_2 emissions inventory now reflects only commercial aircraft jet fuel consumption, while previous reports may have aggregated jet fuel sales data from non-commercial aircraft into this category. Thus, it would be inappropriate to compare 1990 to future years for other than qualitative purposes.

The 1990 commercial aircraft CO_2 emissions inventory is approximately [18] % lower than the 2020 CO_2 emissions inventory. It is important to note that the distance flown increased by more than [63] % over this 29 year period and that fuel burn and aviation activity trends over the past two decades indicate significant improvements in commercial aviation's ability to provide increased service levels while using less fuel.

Additional information on the AEDT modeling process is available at: http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/

Methane Emissions: Contributions of methane (CH_4) emissions from commercial aircraft are reported as zero. Years of scientific measurement campaigns conducted at the exhaust exit plane of commercial aircraft gas turbine engines have repeatedly indicated that CH_4 emissions are consumed over the full mission flight envelope (*Aircraft Emissions of Methane and Nitrous Oxide during the Alternative Aviation Fuel Experiment*, Santoni et al., Environ. Sci. Technol., 2011, 45, 7075-7082). As a result, the U.S. Environmental Protection Agency published that "*…methane is no longer considered to be an emission from aircraft gas turbine engines burning Jet A at higher power settings and is, in fact, consumed in net at these higher powers.*" (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, http://www.epa.gov/otaq/aviation.htm) In accordance with the following statements in the 2006 IPCC Guidelines (IPCC 2006), the FAA does not calculate CH_4 emissions for either the domestic or international bunker commercial aircraft jet fuel emissions inventories. *"Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines." "Current scientific understanding does not allow other gases (e.g., N_2O and CH_4) to be included in calculation of cruise emissions." (IPCC 1999)*

Results: For each inventory calendar year the graph and table below include four jet fuel burn values. These values are comprised of domestic and international fuel burn totals for the U.S. 50 States and the U.S. 50 States + Territories. Data are presented for domestic defined as jet fuel burn from any commercial aircraft flight departing and landing in the U.S. 50 States and for the U.S. 50 States + Territories. The data presented as international is respective of the two different domestic definitions, and represents flights departing from the specified domestic area and landing anywhere in the world outside of that area.

Note that the graph and table present more fuel burn for the international U.S. 50 States + Territories than for the international U.S. 50 States. This is because the flights between the 50 states and U.S. Territories are "international" when only the 50 states are defined as domestic, but they are "domestic" for the U.S. 50 States + Territories definition.

Figure A-5: Commercial Aviation Fuel Burn for the United States and Territories

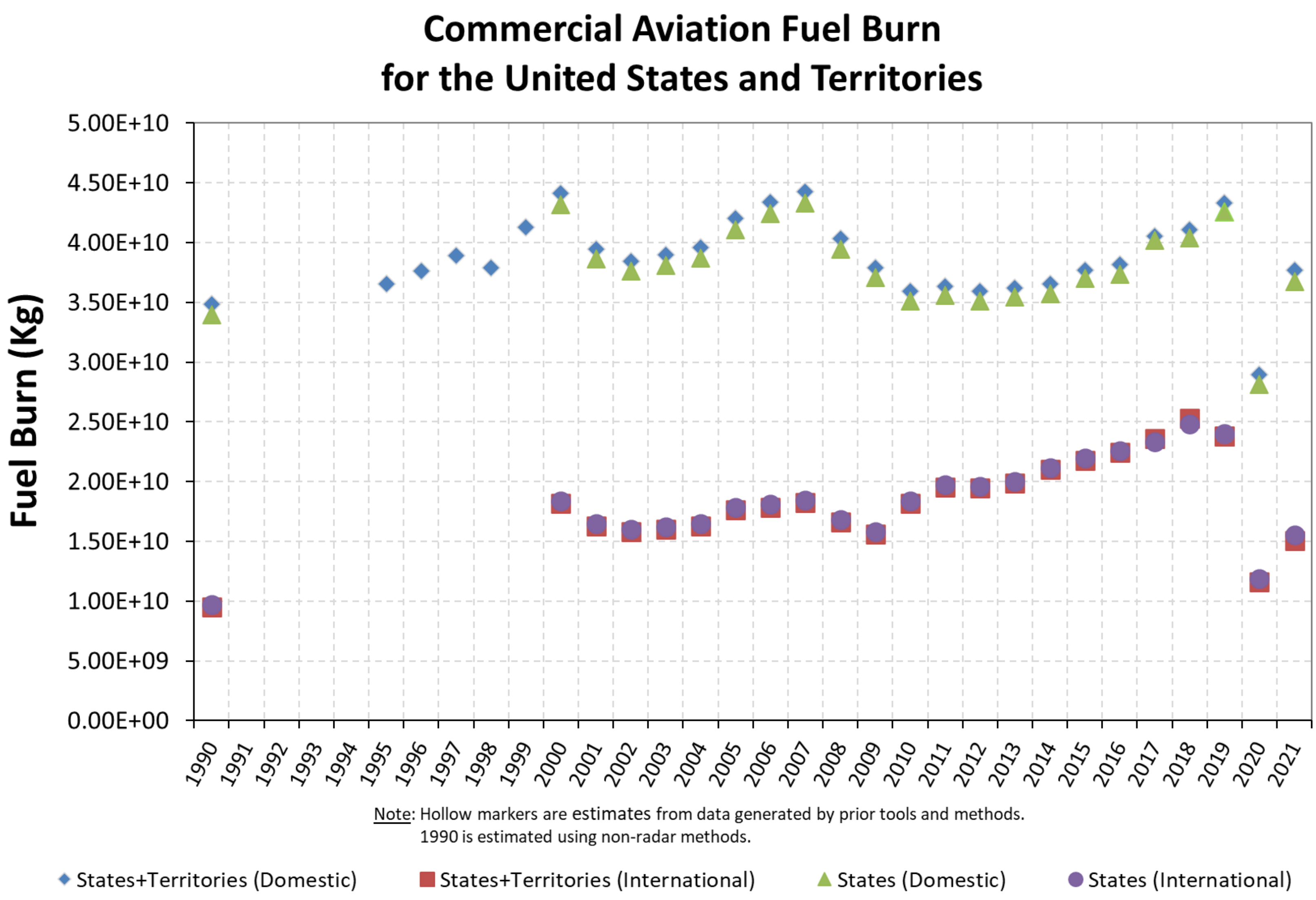

Table A-96: Commercial Aviation Fuel Burn for the United States and Territories

Year	Region	Distance Flown (nmi)	Fuel Burn (Mgal)	Fuel Burn (TBtu)	Fuel Burn (Kg)	CO_2 (Tg)
1990	Domestic U.S. 50 States and U.S. Territories	4,057,195,988	11,568	1,562	34,820,800,463	109.9
	International U.S.50 States and U.S. Territories	599,486,893	3,155	426	9,497,397,919	30.0
	Domestic U.S. 50 States	3,984,482,217	11,287	1,524	33,972,832,399	107.2
	International U.S. 50 States	617,671,849	3,228	436	9,714,974,766	30.7
1995*	Domestic U.S. 50 States and U.S. Territories	N/A	12,136	1,638	36,528,990,675	115.2
1996*	Domestic U.S. 50 States and U.S. Territories	N/A	12,492	1,686	37,600,624,534	118.6
1997*	Domestic U.S. 50 States and U.S. Territories	N/A	12,937	1,747	38,940,896,854	122.9
1998*	Domestic U.S. 50 States and U.S. Territories	N/A	12,601	1,701	37,930,582,643	119.7
1999*	Domestic U.S. 50 States and U.S. Territories	N/A	13,726	1,853	41,314,843,250	130.3
2000	Domestic U.S. 50 States and U.S. Territories	5,994,679,944	14,672	1,981	44,161,841,348	139.3
	International U.S. 50 States and U.S. Territories	1,309,565,963	6,040	815	18,181,535,058	57.4
	Domestic U.S. 50 States	5,891,481,028	14,349	1,937	43,191,000,202	136.3
	International U.S. 50 States	1,331,784,289	6,117	826	18,412,169,613	58.1
2001*	Domestic U.S. 50 States and U.S. Territories	5,360,977,447	13,121	1,771	39,493,457,147	124.6
	International U.S. 50 States and U.S. Territories	1,171,130,679	5,402	729	16,259,550,186	51.3
	Domestic U.S. 50 States	5,268,687,772	12,832	1,732	38,625,244,409	121.9
	International U.S. 50 States	1,191,000,288	5,470	739	16,465,804,174	51.9
2002*	Domestic U.S. 50 States and U.S. Territories	5,219,345,344	12,774	1,725	38,450,076,259	121.3
	International U.S. 50 States and U.S. Territories	1,140,190,481	5,259	710	15,829,987,794	49.9
	Domestic U.S. 50 States	5,129,493,877	12,493	1,687	37,604,800,905	118.6
	International U.S. 50 States	1,159,535,153	5,326	719	16,030,792,741	50.6
2003*	Domestic U.S. 50 States and U.S. Territories	5,288,138,079	12,942	1,747	38,956,861,262	122.9
	International U.S. 50 States and U.S. Territories	1,155,218,577	5,328	719	16,038,632,384	50.6
	Domestic U.S. 50 States	5,197,102,340	12,658	1,709	38,100,444,893	120.2

	International U.S. 50 States	1,174,818,219	5,396	728	16,242,084,008	51.2
2004*	Domestic U.S. 50 States and U.S. Territories	5,371,498,689	13,146	1,775	39,570,965,441	124.8
	International U.S. 50 States and U.S. Territories	1,173,429,093	5,412	731	16,291,460,535	51.4
	Domestic U.S. 50 States	5,279,027,890	12,857	1,736	38,701,048,784	122.1
	International U.S. 50 States	1,193,337,698	5,481	740	16,498,119,309	52.1
2005	Domestic U.S. 50 States and U.S. Territories	6,476,007,697	13,976	1,887	42,067,562,737	132.7
	International U.S. 50 States and U.S. Territories	1,373,543,928	5,858	791	17,633,508,081	55.6
	Domestic U.S. 50 States	6,370,544,998	13,654	1,843	41,098,359,387	129.7
	International U.S. 50 States	1,397,051,323	5,936	801	17,868,972,965	56.4
2006*	Domestic U.S. 50 States and U.S. Territories	5,894,323,482	14,426	1,948	43,422,531,461	137.0
	International U.S. 50 States and U.S. Territories	1,287,642,623	5,939	802	17,877,159,421	56.4
	Domestic U.S. 50 States	5,792,852,211	14,109	1,905	42,467,943,091	134.0
	International U.S. 50 States	1,309,488,994	6,015	812	18,103,932,940	57.1
2007*	Domestic U.S. 50 States and U.S. Territories	6,009,247,818	14,707	1,986	44,269,160,525	139.7
	International U.S. 50 States and U.S. Territories	1,312,748,383	6,055	817	18,225,718,619	57.5
	Domestic U.S. 50 States	5,905,798,114	14,384	1,942	43,295,960,105	136.6
	International U.S. 50 States	1,335,020,703	6,132	828	18,456,913,646	58.2
2008*	Domestic U.S. 50 States and U.S. Territories	5,475,092,456	13,400	1,809	40,334,124,033	127.3
	International U.S. 50 States and U.S. Territories	1,196,059,638	5,517	745	16,605,654,741	52.4
	Domestic U.S. 50 States	5,380,838,282	13,105	1,769	39,447,430,318	124.5
	International U.S. 50 States	1,216,352,196	5,587	754	16,816,299,099	53.1
2009*	Domestic U.S. 50 States and U.S. Territories	5,143,268,671	12,588	1,699	37,889,631,668	119.5
	International U.S. 50 States and U.S. Territories	1,123,571,175	5,182	700	15,599,251,424	49.2
	Domestic U.S. 50 States	5,054,726,871	12,311	1,662	37,056,676,966	116.9
	International U.S. 50 States	1,142,633,881	5,248	709	15,797,129,457	49.8
2010	Domestic U.S. 50 States and U.S. Territories	5,652,264,576	11,931	1,611	35,912,723,830	113.3

	International U.S. 50 States and U.S. Territories	1,474,839,733	6,044	816	18,192,953,916	57.4
	Domestic U.S. 50 States	5,554,043,585	11,667	1,575	35,116,863,245	110.8
	International U.S. 50 States	1,497,606,695	6,113	825	18,398,996,825	58.0
2011	Domestic U.S. 50 States and U.S. Territories	5,767,378,664	12,067	1,629	36,321,170,730	114.6
	International U.S. 50 States and U.S. Territories	1,576,982,962	6,496	877	19,551,631,939	61.7
	Domestic U.S. 50 States	5,673,689,481	11,823	1,596	35,588,754,827	112.3
	International U.S. 50 States	1,596,797,398	6,554	885	19,727,043,614	62.2
2012	Domestic U.S. 50 States and U.S. Territories	5,735,605,432	11,932	1,611	35,915,745,616	113.3
	International U.S. 50 States and U.S. Territories	1,619,012,587	6,464	873	19,457,378,739	61.4
	Domestic U.S. 50 States	5,636,910,529	11,672	1,576	35,132,961,140	110.8
	International U.S. 50 States	1,637,917,110	6,507	879	19,587,140,347	61.8
2013	Domestic U.S. 50 States and U.S. Territories	5,808,034,123	12,031	1,624	36,212,974,471	114.3
	International U.S. 50 States and U.S. Territories	1,641,151,400	6,611	892	19,898,871,458	62.8
	Domestic U.S. 50 States	5,708,807,315	11,780	1,590	35,458,690,595	111.9
	International U.S. 50 States	1,661,167,498	6,657	899	20,036,865,038	63.2
2014	Domestic U.S. 50 States and U.S. Territories	5,825,999,388	12,131	1,638	36,514,970,659	115.2
	International U.S. 50 States and U.S. Territories	1,724,559,209	6,980	942	21,008,818,741	66.3
	Domestic U.S. 50 States	5,725,819,482	11,882	1,604	35,764,791,774	112.8
	International U.S. 50 States	1,745,315,059	7,027	949	21,152,418,387	66.7
2015	Domestic U.S. 50 States and U.S. Territories	5,900,440,363	12,534	1,692	37,727,860,796	119.0
	International U.S. 50 States and U.S. Territories	1,757,724,661	7,227	976	21,752,301,359	68.6
	Domestic U.S. 50 States	5,801,594,806	12,291	1,659	36,997,658,406	116.7
	International U.S. 50 States	1,793,787,700	7,310	987	22,002,733,062	69.4
2016	Domestic U.S. 50 States and U.S. Territories	5,929,429,373	12,674	1,711	38,148,578,811	120.4
	International U.S. 50 States and U.S. Territories	1,817,739,570	7,453	1,006	22,434,619,940	70.8
	Domestic U.S. 50 States	5,827,141,640	12,422	1,677	37,391,339,601	118.0

	International U.S. 50 States	1,839,651,091	7,504	1,013	22,588,366,704	71.3
2017	Domestic U.S. 50 States and U.S. Territories	6,264,650,997	13,475	1,819	40,560,206,261	128.0
	International U.S. 50 States and U.S. Territories	1,944,104,275	7,841	1,059	23,602,935,694	74.5
	Domestic U.S. 50 States	6,214,083,068	13,358	1,803	40,207,759,885	126.9
	International U.S. 50 States	1,912,096,739	7,755	1,047	23,343,627,689	73.6
2018	Domestic U.S. 50 States and U.S. Territories	6,408,870,104	13,650	1,843	41,085,494,597	129.6
	International U.S. 50 States and U.S. Territories	2,037,055,865	8,402	1,134	25,291,329,878	79.8
	Domestic U.S. 50 States	6,318,774,158	13,425	1,812	40,410,478,534	127.5
	International U.S. 50 States	2,066,756,708	8,254	1,114	24,843,232,462	78.4
2019	Domestic U.S. 50 States and U.S. Territories	6,721,417,987	14,397	1,944	43,334,968,184	136.7
	International U.S. 50 States and U.S. Territories	1,980,425,952	7,908	1,068	23,803,403,228	75.1
	Domestic U.S. 50 States	6,617,074,577	14,131	1,908	42,535,165,758	134.2
	International U.S. 50 States	2,008,158,986	7,973	1,076	23,997,773,004	75.7
2020	Domestic U.S. 50 States and U.S. Territories	4,391,123,811	9,613	1,298	28,934,254,672	91.3
	International U.S. 50 States and U.S. Territories	910,801,671	3,863	521	11,626,780,467	36.7
	Domestic U.S. 50 States	4,297,034,877	9,358	1,263	28,167,145,166	88.9
	International U.S. 50 States	944,600,496	3,954	534	11,900,792,661	37.5
2021	Domestic U.S. 50 States and U.S. Territories	5,930,926,254	12,527	1,691	37,706,548,317	119.0
	International U.S. 50 States and U.S. Territories	1,287,078,625	5,013	677	15,089,773,728	47.6
	Domestic U.S. 50 States	5,800,480,719	12,207	1,648	36,742,811,013	115.9
	International U.S. 50 States	1,346,199,492	5,156	696	15,520,560,694	49.0

*Estimates for these years were derived from previously reported tools and methods.

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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 2022).[61] 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 2021, 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 2022).[62] 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.

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP[63] 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.

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[61] 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.

[62] Underground coal mines report to EPA under subpart FF of EPA's GHGRP (40 CFR part 98). In 2021, 60 underground coal mines reported to the program.

[63] 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).

Table A-97: 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)

[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.

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).

Twenty mines employed degasification systems in 2021, and all of these mines reported the CH_4 liberated through these systems to the EPA's GHGRP (EPA 2022). Twelve of the 20 mines with degasification systems had operational CH_4 recovery and use projects, including two mines with 2 recovery and use projects each, and the other eight 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 15 of the 20 mines that used degasification systems in 2021.

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.[64] 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 four mines with degasification systems that include pre-mining wells that were mined through in 2021, 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 2022; DMME 2022; WVGES 2022; JWR 2010; El Paso 2009; ERG 2022). 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 2021 subpart FF data.

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

There were 12 active coal mines with operational CH_4 recovery and use projects in 2021, including two mines that had two recovery and use projects, each. Thirteen of these projects involved degasification systems, in place at twelve mines, and one involved ventilation air methane (VAM). Ten of these 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 CH_4 using flares and one mine destroyed the recovered CH_4 (VAM) using Regenerative Thermal Oxidation (RTO) without energy recovery and enclosed flares. One mine used CH_4 to heat mine ventilation air, however data are unavailable for estimating CH_4 recovery at this mine.

The CH_4 recovered and used (or destroyed) at the twelve 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 2021. Based on weekly measurements of gas flow and CH_4 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 2021 (DMME 2022; GSA 2022; ERG 2022; and WVGES 2022). Four of these mines intersected pre-mining wells in 2021. 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 2021 data came from state gas production databases (DMME 2022; GSA 2022; ERG 2022; and WVGES 2022), as well as mine-specific information on the timing of mined-through, pre-mining wells (JWR 2010; El Paso 2009, ERG 2019-2022). 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.
- For the single mine that employed VAM for CH_4 recovery and use, the estimates of CH_4 recovered and used were obtained from the mine's offset verification statement (OVS) submitted to the California Air Resources Board (CARB) (McElroy OVS 2022).

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*

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

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-98, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2022) 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-98. 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-99 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-100 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.

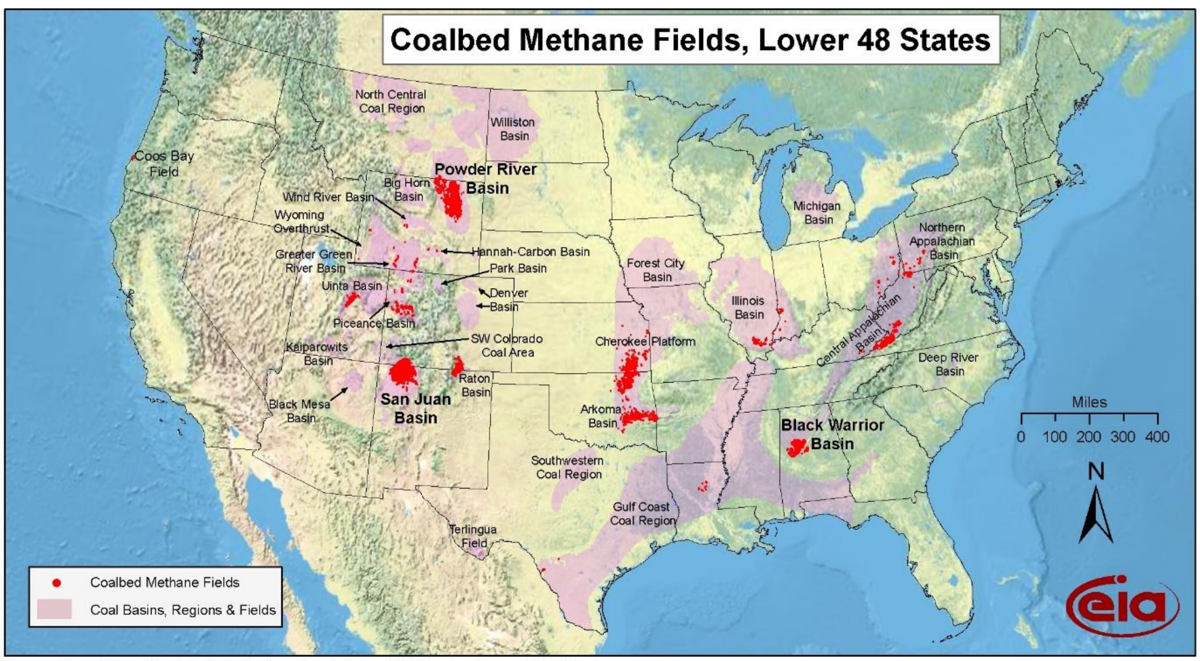
Table A-98 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-6, several coal basins span several states. Table A-99 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-100 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-101 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 recovered and used. Table A-102 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities.

Table A-98: 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
South West 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	South West and Rockies Basin
Arkansas	West Interior Basin
California	South West and Rockies Basin
Colorado	South West 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	South West 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	South West 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-6: 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-99: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2017	2018	2019	2020	2021
Underground Coal Production	**423,556**	**368,612**	**273,129**	**275,361**	**267,373**	**195,528**	**220,597**
N. Appalachia	103,865	111,151	97,741	97,070	97,905	71,998	84,265
Cent. Appalachia	198,412	123,082	46,053	45,306	39,957	30,249	34,562
Warrior	17,531	13,295	10,491	12,199	11,980	10,451	7,959
Illinois	69,167	59,180	80,855	85,416	81,061	54,334	62,667
S. West/Rockies	32,754	60,866	30,047	25,387	27,257	20,049	20,702
N. Great Plains	1,722	572	7,600	9,777	9,213	8,447	10,442
West Interior	105	465	343	206	0	0	0
Northwest	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,190**	**500,782**	**480,080**	**438,445**	**339,450**	**356,203**
N. Appalachia	60,761	28,873	9,396	9,219	8,476	6,215	6,677
Cent. Appalachia	94,343	112,222	31,796	33,799	32,742	17,921	20,299
Warrior	11,413	11,599	4,974	5,523	4,841	4,288	4,581
Illinois	72,000	33,703	22,427	21,405	18,591	13,098	9,713
S. West/Rockies	43,863	42,756	19,390	19,599	18,394	13,420	12,872
N. Great Plains	249,356	474,056	372,874	362,664	329,164	262,968	283,424
West Interior	64,310	52,262	38,966	26,969	25,261	20,519	17,595
Northwest	6,707	6,720	959	902	975	1,021	1,042
Total Coal Production	**1,026,309**	**1,130,802**	**773,911**	**755,442**	**705,818**	**534,978**	**576,800**
N. Appalachia	164,626	140,023	107,137	106,289	106,381	78,213	90,942
Cent. Appalachia	292,755	235,305	77,848	79,105	72,700	48,170	54,861
Warrior	28,944	24,894	15,464	17,723	16,822	14,739	12,540
Illinois	141,167	92,883	103,282	106,821	99,652	67,432	72,380
S. West/Rockies	76,617	103,622	49,437	44,987	45,652	33,469	33,574
N. Great Plains	251,078	474,629	380,474	372,441	338,376	271,415	293,866
West Interior	64,415	52,727	39,309	27,175	25,261	20,519	17,595
Northwest	6,707	6,720	959	902	975	1,021	1,042

Note: Totals may not sum due to independent rounding.

Table A-100: 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-101: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2017	2018	2019	2020	2021
Ventilation Output	112	75	78	73	62	60	57
Adjustment Factor for Mine Data	98%	98%	100%	100%	100%	100%	100%
Adjusted Ventilation Output	114	77	78	73	62	60	57
Degasification System Liberated	54	47	42	47	42	39	38
Total Underground Liberated	168	124	121	120	104	99	95
Recovered & Used	(14)	(37)	(36)	(39)	(33)	(34)	(34)
Total	**154**	**87**	**84**	**81**	**71**	**65**	**61**

Note: Totals may not sum due to independent rounding.

Table A-102: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2017	2018	2019	2020	2021
Underground Mining	154	87	84	81	71	65	61
Surface Mining	22	25	15	15	13	10	11
Post-Mining (Underground)	19	16	11	11	11	8	9
Post-Mining (Surface)	5	5	3	3	3	2	2
Total	**200**	**133**	**114**	**110**	**98**	**86**	**83**

Note: Totals may not sum due to independent rounding.

Table A-103: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2017	2018	2019	2020	2021
Alabama	32,097	15,831	11,044	12,119	9,494	9,767	8,220
Alaska	50	42	28	26	28	30	30
Arizona	151	161	83	87	51	0	0
Arkansas	5	+	770	71	0	0	0
California	1	0	0	0	0	0	0
Colorado	10,187	13,441	1,940	1,616	1,730	1,380	1,392
Illinois	10,180	6,488	8,513	6,530	5,661	4,100	4,267
Indiana	2,232	3,303	6,036	6,729	6,807	6,067	6,388
Iowa	24	0	0	0	0	0	0
Kansas	45	11	0	0	0	0	0
Kentucky	10,018	6,898	4,636	4,636	2,264	1,765	2,164
Louisiana	64	84	42	129	36	14	6
Maryland	474	361	152	113	119	92	113
Mississippi	0	199	146	165	151	145	179
Missouri	166	37	15	16	12	10	3
Montana	1,373	1,468	1,102	1,172	1,038	775	816
New Mexico	363	2,926	1,728	1,360	1,446	723	1,661
North Dakota	299	306	294	303	276	270	271
Ohio	4,406	3,120	1,473	1,342	1,283	793	852
Oklahoma	226	825	2,407	2,317	116	367	+
Pennsylvania	21,864	18,605	19,662	20,695	23,528	18,931	19,100
Tennessee	276	115	14	23	17	7	0
Texas	1,119	922	730	498	468	395	346
Utah	3,587	4,787	678	629	811	845	770
Virginia	46,041	8,649	7,663	7,051	6,959	6,726	6,198
Washington	146	154	0	0	0	0	0
West Virginia	48,335	29,745	33,182	28,736	25,556	24,277	21,420
Wyoming	6,671	14,745	11,497	13,201	10,409	8,099	8,621
Total	**200,399**	**133,224**	**113,837**	**109,565**	**98,262**	**85,579**	**82,817**

+ 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.

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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 2021 please see the spreadsheet file annexes for the current (i.e., 1990 to 2021) Inventory, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2021-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 2022a) 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 combines all other basins into one grouping. This methodology is applied to pneumatic controllers, chemical injection pumps, wellpad equipment leaks, and production storage tanks (EPA 2023). Produced Water CH_4 estimates are calculated using annual produced water quantities (Enverus DrillingInfo 2021 and EPA 2021b 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 2022a) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990-2009). 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 2020 emissions. The national emission totals for each activity were divided by refinery feed rates for those four Inventory years (2010-2013) 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 2021a-d; EPA 2022a; EPA 2020). Emission factors are calculated for offshore facilities located in the Gulf of Mexico, 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, and chemical injection pumps, GHGRP Subpart W data were used to develop activity factors (i.e., 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 years 1990 to 1995. 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 GOM, 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 2020) are not yet available, year 2019 or prior 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 DrillingInfo 2021), 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. 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 1990-2021 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
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- 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
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- 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 2021 please see the spreadsheet file annexes for the current (i.e., 1990 to 2021) Inventory, available at https://www.epa.gov/ghgemissions/stakeholder-process-natural-gas-and-petroleum-systems-1990-2021-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 2022c), and others.

The EPA/GRI 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 2022c) 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 EPA/GRI 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 EPA/GRI 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.
- For gas well completions without hydraulic fracturing, separate emissions estimates were developed for completions that vent and completions that flare.

- 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>1990-2021 Inventory updates to emission factors</u>

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in a memorandum,[65] *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2021: Update for Incorporating Additional Geographically Disaggregated Data for the Production Segment* (EPA 2023), 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 sources, either 2020 data were used as proxy for 2021 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.

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

EPA used DrillingInfo and Prism datasets from Enverus (Enverus 2021), 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

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

(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 2012a).

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 applied a refracture rate of 1 percent (i.e., 1 percent of all wells with hydraulic fracturing are assumed to be refractured in a given year) to the total counts of wells with hydraulic fracturing from the Enverus datasets. 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-specific GHGRP data (applying year 2011 factors to earlier years). EPA assumed no REC use from 1990 through 2000, used a REC use percentage calculated from GHGRP data for 2011 forward, and then used linear interpolation between the 2000 and 2011 percentages. For flaring, EPA used an assumption of 10 percent (the average of the percent of completions and workovers that were flared in 2011 through 2013 GHGRP data) 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.

Reductions Data

As described under "Emission Factors" above, some sources in Natural Gas Systems rely on CH_4 emission factors developed from the 1996 EPA/GRI 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.

<u>Voluntary reductions</u>

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.

<u>Federal regulations</u>

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.

In 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 1990-2021 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 here 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 2021), 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 2021.

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).
- 2011-2021: MSW combustion tonnages are from EPA's GHGRP data.

Table A-104 provides the estimated tons of MSW combusted including and excluding tires.

Table A-104: Municipal Solid Waste Combusted (Short Tons)

Year	Waste Combusted *(excluding tires)*	Waste Combusted *(including tires)*
1990	33,344,839	33,766,239
2005	26,486,414	28,631,054
2017	28,574,258	30,310,598
2018	29,162,364	30,853,949

2019	28,174,311	29,821,141
2020	27,586,271	29,106,686
2021	27,867,446	29,261,446

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 2021.

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-105.

Table A-105: Calculated Fossil CO_2 Content per Ton Waste Combusted (kg CO_2/Short Ton Combusted)

	1990		2005		2017	2018	2019	2020	2021
CO_2 Emission Factors	366		366		360	361	363	377	365

CO_2 from Combustion of Synthetic Rubber and Carbon Black in Tires

Calculating emissions from tire combustion require two pieces of information: the amount of tires combusted and the C content of the tires. "2021 U.S. Scrap Tire Management Summary" (USTMA 2022) reports that 1,394 thousand of the 3,273 thousand tons of scrap tires generated in 2021 (approximately 43 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.[66] Table A-106 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-107. 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-106 (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. Tire production and fuel use for 1990 through 2021 were taken from USTMA 2006; USTMA 2009; USTMA 2013; USTMA 2014; USTMA 2016; USTMA 2018; USTMA 2020; USTMA 2022. 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).

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

Table A-106: 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-107: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Combustion in 2021

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	1.0
Carbon Black	0.4	98%	100%	1.3
Total	**0.6**	**NA**	**NA**	**2.3**

NA (Not Applicable)

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 2020a) 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) for aviation and naval fuels. DLA Energy prepared a special report based on data in the Fuels Automated System (FAS) for calendar year 2021 fuel sales in the Continental United States (CONUS).[67] The following steps outline the methodology used for estimating emissions from international bunker fuels used by the U.S. Military.

Step 1: Omit Extra-Territorial Fuel Deliveries

Beginning with the complete FAS data set for each year, the first step in quantifying DoD-related emissions from international bunker fuels was to identify data that would be representative of international bunker fuel consumption as defined by decisions of the UNFCCC (i.e., fuel sold to a vessel, aircraft, or installation within the United States or its territories and used in international maritime or aviation transport). Therefore, fuel data were categorized by the location of fuel delivery in order to identify and omit all international fuel transactions/deliveries (i.e., sales abroad).

Step 2: Allocate Jet Fuel between Aviation and Land-based Vehicles

As a result of DoD[68] and NATO[69] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with jet fuel in compression ignition and turbine engines of land-based equipment. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of jet fuel consumption should be attributed to ground vehicle use. Based on available Military Service data and expert judgment, a small fraction of jet fuel use (i.e., between 1.78 and 2.7 times the quantity of diesel fuel used, depending on the Service) was reallocated from the aviation subtotal to a new land-based jet fuel category for 1997 and subsequent years. As a result of this reallocation, the jet fuel use reported for aviation was reduced and the fuel use for land-based equipment increased. DoD's total fuel use did not change. DoD has been undergoing a transition from JP-8 jet fuel to commercial specification Jet A fuel with additives (JAA) for non-naval aviation and ground assets. To account for this transition jet fuel used for ground-based vehicles was reallocated from JP8 prior to 2014 and from JAA in 2014 and subsequent years. The transition was completed in 2016.

Table A-108 displays DoD's consumption of transportation fuels, summarized by fuel type, that remain at the completion of Step 1, and reflects the adjustments for jet fuel used in land-based equipment, as described above.

Step 3: Omit Land-Based Fuels

Navy and Air Force land-based fuels (i.e., fuel not used by ships or aircraft) were omitted for the purpose of calculating international bunker fuels. The remaining fuels, listed below, were considered potential DoD international bunker fuels.

- **Aviation:** jet fuels (JP8, JP5, JP4, JAA, JA1, and JAB).
- **Marine:** naval distillate fuel (F76), marine gas oil (MGO), and intermediate fuel oil (IFO).

Step 4: Omit Fuel Transactions Received by Military Services that are not considered to be International Bunker Fuels

Only Navy and Air Force were deemed to be users of military international bunker fuels after sorting the data by Military Service and applying the following assumptions regarding fuel use by Service.

- Only fuel delivered to a ship, aircraft, or installation in the United States was considered a potential international bunker fuel. Fuel consumed in international aviation or marine transport was included in the

[67] 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.

[68] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Instruction 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2015.

[69] NATO Standard Agreement NATO STANAG 4362, Fuels for Future Ground Equipment Using Compression Ignition or Turbine Engines, 2012.

bunker fuel estimate of the country where the ship or aircraft was fueled. Fuel consumed entirely within a country's borders was not considered a bunker fuel.

- Based on previous discussions with the Army staff, only an extremely small percentage of Army aviation emissions, and none of Army watercraft emissions, qualified as bunker fuel emissions. The magnitude of these emissions was judged to be insignificant when compared to Air Force and Navy emissions. Based on this research, Army bunker fuel emissions were assumed to be zero.
- Marine Corps aircraft operating while embarked consumed fuel that was reported as delivered to the Navy. Bunker fuel emissions from embarked Marine Corps aircraft were reported in the Navy bunker fuel estimates. Bunker fuel emissions from other Marine Corps operations and training were assumed to be zero.
- Bunker fuel emissions from other DoD and non-DoD activities (i.e., other federal agencies) that purchased fuel from DLA Energy were assumed to be zero.

Step 5: Determine Bunker Fuel Percentages

It was necessary to determine what percent of the aviation and marine fuels were used as international bunker fuels. Military aviation bunkers include international operations (i.e., sorties that originate in the United States and end in a foreign country), operations conducted from naval vessels at sea, and operations conducted from U.S. installations principally over international water in direct support of military operations at sea (e.g., anti-submarine warfare flights). Methods for quantifying aviation and marine bunker fuel percentages are described below.

- **Aviation:** The Air Force Aviation bunker fuel percentage was determined to be 13.2 percent. A bunker fuel weighted average was calculated based on flying hours by major command. International flights were weighted by an adjustment factor to reflect the fact that they typically last longer than domestic flights. In addition, a fuel use correction factor was used to account for the fact that transport aircraft burn more fuel per hour of flight than most tactical aircraft. This percentage was multiplied by total annual Air Force aviation fuel delivered for U.S. activities, producing an estimate for international bunker fuel consumed by the Air Force.

  The Naval Aviation bunker fuel percentage was calculated to be 40.4 percent by using flying hour data from Chief of Naval Operations Flying Hour Projection System Budget for fiscal year 1998 and estimates of bunker fuel percent of flights provided by the fleet. This Naval Aviation bunker fuel percentage was then multiplied by total annual Navy aviation fuel delivered for U.S. activities, yielding total Navy aviation bunker fuel consumed.
- **Marine:** For marine bunkers, fuels consumed while ships were underway were assumed to be bunker fuels. The Navy maritime bunker fuel percentage was determined to be 79 percent because the Navy reported that 79 percent of vessel operations were underway, while the remaining 21 percent of operations occurred in port (i.e., pierside) in the year 2000.[70]

Table A-109 and Table A-110 display DoD bunker fuel use totals for the Navy and Air Force.

Step 6: Calculate Emissions from International Bunker Fuels

Bunker fuel totals were multiplied by appropriate emission factors to determine greenhouse gas (GHG) emissions. CO_2 emissions from Aviation Bunkers and distillate Marine Bunkers are the total of military aviation and marine bunker fuels, respectively.

The rows labeled "U.S. Military" and "U.S. Military Naval Fuels" in the tables in the International Bunker Fuels section of the Energy chapter were based on the totals provided in Table A-109 and Table A-110, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-114, and are based on emissions from fuels tallied in Table A-109 and Table A-110.

[70] Note that 79 percent is used because it is based on Navy data, but the percentage of time underway may vary from year-to-year depending on vessel operations. For example, for years prior to 2000, the bunker fuel percentage was 87 percent.

Table A-108: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Aviation	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.1**	**1,663.9**	**1,663.7**	**1,558.0**	**1,537.7**	**1,482.2**	**1,487.6**	**1,435.7**	**1,513.7**
Total Jet Fuels	**4,598.4**	**3,099.9**	**2,664.4**	**2,338.0**	**1,663.7**	**1,663.5**	**1,557.7**	**1,537.5**	**1,481.9**	**1,487.4**	**1,435.5**	**1,513.5**
JP8	285.7	2,182.8	2,122.7	1,838.8	1,100.1	126.6	(9.5)	(11.3)	1.9	4.7	(4.3)	3.0
JP5	1,025.4	691.2	472.1	421.6	399.3	316.4	320.4	316.3	304.1	314.4	309.0	308.6
Other Jet Fuels	3,287.3	225.9	69.6	77.6	164.3	1,220.5	1,246.9	1,232.7	1,175.9	1,168.2	1,130.9	1,201.8
Aviation Gasoline	**+**	**+**	**+**	**0.1**	**0.2**	**0.3**	**0.3**	**0.2**	**0.3**	**0.2**	**0.2**	**0.2**
Marine	**686.8**	**438.9**	**454.4**	**604.9**	**578.8**	**421.7**	**412.4**	**395.2**	**370.9**	**365.4**	**384.1**	**369.7**
Middle Distillate (MGO)	0.0	0.0	48.3	54.0	48.4	56.0	23.1	24.4	19.9	23.2	26.1	17.6
Naval Distillate (F76)	686.8	438.9	398.0	525.9	513.7	363.3	389.1	370.8	351.0	342.2	358.0	352.1
Intermediate Fuel Oil (IFO)[b]	0.0	0.0	8.1	25.0	16.7	2.4	0.1	0.0	0.0	0.0	0.0	0.0
Other[c]	**717.1**	**310.9**	**248.2**	**205.6**	**224.0**	**181.1**	**178.3**	**165.8**	**170.4**	**161.4**	**130.3**	**145.3**
Diesel	93.0	119.9	126.6	56.8	64.1	54.8	54.7	50.4	51.8	48.7	39.2	44.6
Gasoline	624.1	191.1	74.8	24.3	25.5	16.2	15.9	15.6	14.7	14.9	12.5	12.5
Jet Fuel[d]	0.0	0.0	46.7	124.4	134.4	110.1	107.6	99.9	104.0	97.7	78.6	88.2
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,367.0**	**3,148.6**	**2,466.7**	**2,266.5**	**2,148.7**	**2,098.7**	**2,023.4**	**2,014.3**	**1,950.1**	**2,028.6**

+ Indicates value does not exceed 0.05 million gallons.

[a] Includes fuel distributed in the United States and U.S. Territories.

[b] Intermediate fuel oil (IFO 180 and IFO 380) is a blend of distillate and residual fuels. IFO is used by the Military Sealift Command.

[c] Prior to 2001, gasoline and diesel fuel totals were estimated using data provided by the Military Services for 1990 and 1996. The 1991 through 1995 data points were interpolated from the Service inventory data. The 1997 through 1999 gasoline and diesel fuel data were initially extrapolated from the 1996 inventory data. Growth factors used for other diesel and gasoline were 5.2 and -21.1 percent, respectively. However, prior diesel fuel estimates from 1997 through 2000 were reduced according to the estimated consumption of jet fuel that is assumed to have replaced the diesel fuel consumption in land-based vehicles. Datasets for other diesel and gasoline consumed by the military in 2000 were estimated based on ground fuels consumption trends. This method produced a result that was more consistent with expected consumption for 2000. Since 2001, other gasoline and diesel fuel totals were generated by DLA Energy.

[d] The fraction of jet fuel consumed in land-based vehicles was estimated based on DLA Energy data as well as Military Service and expert judgment.

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.

Table A-109: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Jet Fuels												
JP8	**56.7**	**300.4**	**307.6**	**285.6**	**182.5**	**17.2**	**2.4**	**2.5**	**2.9**	**1.2**	**0.6**	**1.5**
Navy	56.7	38.3	53.4	70.9	60.8	0.8	5.5	6.4	4.8	2.5	2.8	1.7
Air Force	+	262.2	254.2	214.7	121.7	16.4	(3.1)	(3.8)	(1.9)	(1.2)	(2.1)	(0.2)
JP5	**370.5**	**249.8**	**160.3**	**160.6**	**152.5**	**124.1**	**126.1**	**124.7**	**120.1**	**123.9**	**122.0**	**121.9**
Navy	365.3	246.3	155.6	156.9	149.7	122.6	124.7	123.4	118.9	122.5	120.7	120.8
Air Force	5.3	3.5	4.7	3.7	2.8	1.5	1.4	1.3	1.2	1.4	1.2	1.2
JP4	**420.8**	**21.5**	**+**	**+**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	+	+	0.0	+	+	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Air Force	420.8	21.5	+	+	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JAA	**13.7**	**9.2**	**12.5**	**15.5**	**31.4**	**199.8**	**203.7**	**198.9**	**191.8**	**192.5**	**185.2**	**197.5**
Navy	8.5	5.7	7.9	11.6	13.7	71.7	72.9	67.8	68.1	71.2	66.1	70.7
Air Force	5.3	3.5	4.5	3.9	17.7	128.1	130.8	131.1	123.7	121.4	119.1	126.8
JA1	**+**	**+**	**+**	**0.5**	**0.3**	**0.3**	**0.5**	**0.2**	**0.5**	**0.3**	**0.3**	**0.2**
Navy	+	+	+	+	0.1	+	0.1	(+)	+	+	(+)	+
Air Force	+	+	+	0.5	0.1	0.3	0.5	0.2	0.5	0.3	0.3	0.2
JAB	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
Navy	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Air Force	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
Navy Subtotal	**430.5**	**290.2**	**216.9**	**239.4**	**224.4**	**195.0**	**203.2**	**197.5**	**191.8**	**196.1**	**189.6**	**193.2**
Air Force Subtotal	**431.3**	**290.7**	**263.5**	**222.9**	**142.4**	**146.4**	**129.5**	**128.8**	**123.5**	**121.8**	**118.5**	**127.8**
Total	**861.8**	**580.9**	**480.4**	**462.3**	**366.7**	**341.4**	**332.8**	**326.3**	**315.3**	**317.9**	**308.1**	**321.1**

+ Does not exceed 0.05 million gallons.

NO (Not Occurring)

Notes: Totals may not sum due to independent rounding. Parentheses indicate negative values. The negative values in this table represent returned products.

Table A-110: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Navy – MGO	0.0	0.0	23.8	38.0	32.9	37.8	5.7	13.2	8.5	10.6	13.5	7.1
Navy – F76	522.4	333.8	298.6	413.1	402.2	286.7	307.8	293.3	276.9	270.0	282.6	277.5
Navy – IFO	0.0	0.0	6.4	19.7	12.9	1.9	+	0.0	0.0	0.0	0.0	0.0
Total	**522.4**	**333.8**	**328.8**	**470.7**	**448.0**	**326.3**	**313.6**	**306.5**	**285.4**	**280.6**	**296.1**	**284.5**

+ Does not exceed 0.05 million gallons.

Note: Totals may not sum due to independent rounding.

Table A-111: Aviation and Marine Carbon Contents (MMT Carbon/QBtu) and Fraction Oxidized

Mode (Fuel)	Carbon Content Coefficient	Fraction Oxidized
Aviation (Jet Fuel)	Variable	1.00
Marine (Distillate)	Variable	1.00
Marine (Residual)	20.48	1.00

Source: EPA (2010) and IPCC (2006).

Table A-112: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Jet Fuel	19.40	19.34	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70	19.70

Source: EPA (2010).

Table A-113: Annual Variable Carbon Content Coefficient for Distillate Fuel Oil (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Distillate Fuel Oil	20.17	20.17	20.39	20.37	20.24	20.22	20.21	20.21	20.22	20.22	20.22	20.22

Source: EPA (2020).

Table A-114: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	2000	2005	2010	2015	2016	2017	2018	2019	2020	2021
Aviation	8.2	5.7	4.8	4.6	3.6	3.4	3.3	3.3	3.2	3.2	3.1	3.2
Marine	5.4	3.4	3.4	4.9	4.6	3.4	3.2	3.1	2.9	2.9	3.0	2.9
Total	**13.6**	**9.1**	**8.2**	**9.5**	**8.3**	**6.8**	**6.6**	**6.4**	**6.1**	**6.1**	**6.1**	**6.1**

Note: Totals may not sum due to independent rounding.

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3.9. Methodology and QA/QC and Verification Details for Estimating HFC, PFC, and CO_2 Emissions from Substitution of Ozone Depleting Substances

Methodology for Estimating HFC, PFC, and CO_2 Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs, PFCs, and CO_2 from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model[71] was developed as a tool for estimating the annual chemical emissions from industrial sectors that have historically used ODS in their products. Under the terms of the Montreal Protocol and the United States Clean Air Act Amendments of 1990, the domestic U.S. consumption of ODS—chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and hydrochlorofluorocarbons (HCFCs)—has been drastically reduced, forcing these industrial sectors to transition to more ozone friendly chemicals. As these industries have moved toward ODS alternatives such as hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and carbon dioxide (CO_2), the Vintaging Model has evolved into a tool for estimating the rise in consumption and emissions of these alternatives, and the decline of ODS consumption and emissions.

The Vintaging Model estimates emissions from five ODS substitute (i.e., HFC-emitting) end-use sectors: refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 78 independently modeled end-uses. The model requires information on the market growth for each of the end-uses, a history of the market transition from ODS to alternatives, and the characteristics of each end-use such as market size or charge sizes and loss rates. As ODS are phased out, a percentage of the market share originally filled by the ODS is allocated to each of its substitutes.

The model, named for its method of tracking the emissions of annual “vintages” of new equipment that enter into service, is a “bottom-up” model. It models the consumption of chemicals based on estimates of the quantity of equipment or products sold, serviced, and retired each year, and the amount of the chemical required to manufacture and/or maintain the equipment. The Vintaging Model makes use of this market information to build an inventory of the in-use stocks of the equipment and ODS and ODS substitute in each of the end-uses. The simulation is considered to be a “business-as-usual” baseline case and does not incorporate measures to reduce or eliminate the emissions of these gases other than those regulated by U.S. law or otherwise common in the industry. Emissions are estimated by applying annual leak rates, service emission rates, and disposal emission rates to each population of equipment. By aggregating the emission and consumption output from the different end-uses, the model produces estimates of total annual use and emissions of each chemical.

The Vintaging Model synthesizes data from a variety of sources, including data from the ODS Tracking System maintained by the Stratospheric Protection Division, the Greenhouse Gas Reporting Program maintained by the Climate Change Division, and information from submissions to EPA under the Significant New Alternatives Policy (SNAP) program. Published sources include documents prepared by the United Nations Environment Programme (UNEP) Technical Options Committees, reports from the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS), and conference proceedings from the International Conferences on Ozone Protection Technologies and Earth Technologies Forums. EPA also coordinates extensively with numerous trade associations and individual companies. For example, the Alliance for Responsible Atmospheric Policy; the Air-Conditioning, Heating and Refrigeration Institute; the Association of Home Appliance Manufacturers; the American Automobile Manufacturers Association; and many of their member companies have provided valuable information over the years.

In some instances, the unpublished information that the EPA uses in the model is classified as Confidential Business Information (CBI). The annual emissions inventories of chemicals are aggregated in such a way that CBI cannot be inferred. Full public disclosure of the inputs to the Vintaging Model would jeopardize the security of the CBI that has been entrusted to the EPA. In addition, emissions of certain gases (including HFC-152a, HFC-227ea, HFC-245fa, HFC 365mfc, HFC-43-10mee, HCFO-1233zd(E), HFO-1234yf, HFO-1234ze(E), HFO-1336mzz(Z), C_4F_{10}, and PFC/PFPEs, the latter being a proxy for a diverse collection of PFCs and perfluoropolyethers (PFPEs) employed for solvent applications) are marked as confidential because they are produced or imported by a small number of chemical providers and in such

[71] Vintaging Model version VM IO file_v5.1_10.05.22 was used for all Inventory estimates.

small quantities or for such discrete applications that reporting national data would effectively be reporting the chemical provider's output, which is considered confidential business information. These gases are modeled individually in the Vintaging Model but are aggregated and reported as an unspecified mix of HFCs and PFCs.

The Vintaging Model is regularly updated to incorporate up-to-date market information, including equipment stock estimates, leak rates, and sector transitions. In addition, comparisons against published emission and consumption sources are performed when available. Independent peer reviews of the Vintaging Model are periodically performed, including one conducted in 2017 (EPA 2018), to confirm Vintaging Model estimates and identify updates.

The following sections discuss the emission equations used in the Vintaging Model for each broad end-use category. These equations are applied separately for each chemical used within each of the different end-uses. In the majority of these end-uses, more than one ODS substitute chemical is used.

In general, the modeled emissions are a function of the amount of chemical consumed in each end-use market. Estimates of the consumption of ODS alternatives can be inferred by determining the transition path of each regulated ODS used in the early 1990s. Using data gleaned from a variety of sources, assessments are made regarding which alternatives have been used, and what fraction of the ODS market in each end-use has been captured by a given alternative. By combining this with estimates of the total end-use market growth, a consumption value can be estimated for each chemical used within each end-use.

Methodology

The Vintaging Model estimates the use and emissions of ODS alternatives by taking the following steps:

1. *Gather historical data*. The Vintaging Model is populated with information on each end-use, taken from published sources and industry experts.

2. *Simulate the implementation of new, non-ODS technologies*. The Vintaging Model uses detailed characterizations of the existing uses of the ODS, as well as data on how the substitutes are replacing the ODS, to simulate the implementation of new technologies that enter the market in compliance with ODS phase-out policies. As part of this simulation, the ODS substitutes are introduced in each of the end-uses over time as seen historically and as needed to comply with the ODS phase-out and other regulations.

3. *Estimate emissions of the ODS substitutes*. The chemical use is estimated from the amount of substitutes that are required each year for the manufacture, installation, use, or servicing of products. The emissions are estimated from the emission profile for each vintage of equipment or product in each end-use. By aggregating the emissions from each vintage, a time profile of emissions from each end-use is developed.

Each set of end-uses is discussed in more detail in the following sections.

Refrigeration and Air-Conditioning

For refrigeration and air conditioning products, emission calculations are split into three categories: emissions at first-fill, which arise during manufacture or installation, emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. This methodology is consistent to the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, where the total refrigerant emissions from Ref/AC equipment is the sum of first-fill emissions, annual operational and servicing emissions, and disposal emissions under the Tier 2a emission factor approach (IPCC 2006). Three separate steps are required to calculate the lifetime emissions from installation, leakage and service, and the emissions resulting from disposal of the equipment. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). For any given year, these first-fill emissions (for new equipment), lifetime emissions (for existing equipment), and disposal emissions (from discarded equipment) are summed to calculate the total emissions from refrigeration and air-conditioning. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates, due to improvement in technology and equipment/component design, such as the use of micro-channel heat exchangers, reduction in piping and joints, more advanced controls and leak detection to identify leaks faster, and other optimizations.

At disposal, refrigerant that is recovered from discarded equipment is assumed to be reused to the extent necessary in the following calendar year. The Vintaging Model does not make any explicit assumption whether recovered refrigerant is reused as-is (allowed under U.S. regulations if the refrigerant is reused in the same owner's equipment), recycled (commonly practiced even when re-used directly), or reclaimed (brought to new refrigerant purity standards and available to be sold on the open market).

Step 1: Calculate first-fill emissions

The first-fill emission equation assumes that a certain percentage of the chemical charge will be emitted to the atmosphere when the equipment is charged with refrigerant during manufacture or installation. First-fill emissions are considered for all Ref/AC equipment that are charged with refrigerant within the United States, including those which are produced for export, and excluding those that are imported pre-charged. First-fill emissions are thus a function of the quantity of chemical contained in new equipment and the proportion of equipment that are filled with refrigerant in the United States:

Equation A-8: Calculation of Emissions from Refrigeration and Air-conditioning Equipment First-fill

$$Ef_j = Qc_j \times l_f \times A_j$$

where:

Ef	=	Emissions from Equipment First-fill. Emissions in year *j* from filling new equipment.
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year *j*, by weight.
l_f	=	First-fill Leak Rate. Average leak rate during installation or manufacture of new equipment (expressed as a percentage of total chemical charge).
A	=	Applicability of First-fill Leak Rate. Percentage of new equipment that are filled with refrigerant in the United States in year *j*.
j	=	Year of emission.

Step 2: Calculate lifetime emissions

Emissions from any piece of equipment include both the amount of chemical leaked during equipment operation and the amount emitted during service. Emissions from leakage and servicing can be expressed as follows:

Equation A-9: Calculation of Emissions from Refrigeration and Air-conditioning Equipment Serviced

$$Es_j = (l_a + l_s) \times \sum Qc_{j-i+1} \quad \text{for } i = 1 \rightarrow k$$

where:

Es	=	Emissions from Equipment Serviced. Emissions in year *j* from normal leakage and servicing (including recharging) of equipment.
l_a	=	Annual Leak Rate. Average annual leak rate during normal equipment operation (expressed as a percentage of total chemical charge).
l_s	=	Service Leak Rate. Average leakage during equipment servicing (expressed as a percentage of total chemical charge).
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in a given year by weight.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Step 3: Calculate disposal emissions

The disposal emission equations assume that a certain percentage of the chemical charge will be emitted to the atmosphere when that vintage is discarded, while remaining refrigerant is assumed to be recovered and reused. Disposal emissions are thus a function of the quantity of chemical contained in the retiring equipment fleet and the proportion of chemical released at disposal:

Equation A-10: Calculation of Emissions from Refrigeration and Air-conditioning Equipment Disposed

$$Ed_j = Qc_{j-k+1} \times [1 - (rm \times rc)]$$

where:

Ed	=	Emissions from Equipment Disposed. Emissions in year *j* from the disposal of equipment.
Qc	=	Quantity of Chemical in New Equipment. Total amount of a specific chemical used to charge new equipment in year *j-k+1*, by weight.
rm	=	Chemical Remaining. Amount of chemical remaining in equipment at the time of disposal (expressed as a percentage of total chemical charge).
rc	=	Chemical Recovery Rate. Amount of chemical that is recovered just prior to disposal (expressed as a percentage of chemical remaining at disposal *(rm)*).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Step 4: Calculate total emissions

Finally, first-fill, lifetime, and disposal emissions are summed to provide an estimate of total emissions.

Equation A-11: Calculation of Total Emissions from Refrigeration and Air-conditioning Equipment

$$E_j = Ef_j + Es_j + Ed_j$$

where:

E	=	Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j.*
Ef	=	Emissions from first Equipment Fill. Emissions in year *j* from filling new equipment.
Es	=	Emissions from Equipment Serviced. Emissions in year *j* from leakage and servicing (including recharging) of equipment.
Ed	=	Emissions from Equipment Disposed. Emissions in year *j* from the disposal of equipment.
j	=	Year of emission.

Assumptions

The assumptions used by the Vintaging Model to trace the transition of each type of equipment away from ODS are presented in Table A-115, below. As new technologies replace older ones, it is generally assumed that there are improvements in their leak, service, and disposal emission rates. Additionally, the market for each equipment type is assumed to grow independently, according to annual growth rates, which are applied to new equipment within each end-use.

Table A-115: Refrigeration and Air-Conditioning Market Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[a]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[a]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[a]	Tertiary Substitute: Maximum Market Penetration	Average Growth Rate[b]
Centrifugal Chillers													
CFC-11	HCFC-123	1993	1993	45%	HCFO-1233zd(E)	2016	2016	1%	None				1.6%
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
	HCFC-22	1991	1993	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HFC-134a	1992	1993	39%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
CFC-12	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	HCFC-123	1993	1994	31%	HCFO-1233zd(E)	2016	2016	1%	None				
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
R-500	HFC-134a	1992	1994	53%	R-450A	2017	2017	1%	None				1.5%
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HCFC-22	1991	1994	16%	HFC-134a	2000	2010	100%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Average Growth Rate[b]**
									R-513A	2018	2024	49%	
	HCFC-123	1993	1994	31%	HCFO-1233zd(E)	2016	2016	1%	None				
					R-514A	2017	2017	1%	None				
					HCFO-1233zd(E)	2017	2020	49%	None				
					R-514A	2018	2020	49%	None				
CFC-114	HFC-236fa	1993	1996	100%	HFC-134a	1998	2009	100%	None				1.4%
Cold Storage													
CFC-12	HCFC-22	1990	1993	65%	R-404A	1996	2010	75%	R-407F	2017	2023	100%	3.1%
					R-507	1996	2010	25%	R-407F	2017	2023	100%	
	R-404A	1994	1996	26%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	9%	R-407F	2017	2023	100%	None				
HCFC-22	HCFC-22	1992	1993	100%	R-404A	1996	2009	8%	R-407F	2017	2023	100%	3.0%
					R-507	1996	2009	3%	R-407F	2017	2023	100%	
					R-404A	2009	2010	68%	R-407F	2017	2023	100%	
					R-507	2009	2010	23%	R-407F	2017	2023	100%	
R-502	HCFC-22	1990	1993	40%	R-404A	1996	2010	38%	R-407F	2017	2023	100%	2.6%
					R-507	1996	2010	12%	R-407F	2017	2023	100%	
					Non-ODP/GWP	1996	2010	50%	None				
	R-404A	1993	1996	45%	R-407F	2017	2023	100%	None				
	R-507	1994	1996	15%	R-407F	2017	2023	100%	None				
Commercial Unitary Air Conditioners (Large)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	2001	2005	5%	None				1.8%
					R-407C	2006	2009	1%	None				
					R-410A	2006	2009	9%	None				
					R-407C	2009	2010	5%	None				
					R-410A	2009	2010	81%	None				
Commercial Unitary Air Conditioners (Small)													
HCFC-22	HCFC-22	1992	1993	100%	R-410A	1996	2000	3%	None				2.0%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[a]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[a]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[a]	Tertiary Substitute: Maximum Market Penetration	Average Growth Rate[b]
Dehumidifiers													
HCFC-22	HFC-134a	1997	1997	89%	None								1.3%
	R-410A	2007	2010	11%	None								
Ice Makers													
CFC-12	HFC-134a	1993	1995	27%	None								2.1%
	R-404A	1993	1995	73%	R-410A	2013	2019	32%	None				
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	HCFO-1233zd(E)	2016	2016	2%	None				3.2%
					HCFO-1233zd(E)	2017	2020	98%	None				
	HFC-134a	1992	1994	15%	None								
	HCFC-22	1991	1994	15%	HFC-134a	1995	2010	100%	None				
CFC-12	HCFC-22	1991	1994	10%	HFC-134a	1995	2010	15%	None				3.1%
					R-404A	1995	2010	50%	None				
					R-410A	1999	2010	20%	None				
					R-507	1995	2010	15%	None				
	HCFC-123	1992	1994	35%	HCFO-1233zd(E)	2016	2016	2%	None				
					HCFO-1233zd(E)	2017	2020	98%	None				
	HFC-134a	1992	1994	50%	None								
	R-401A	1995	1996	5%	HFC-134a	1997	2000	100%	None				
HCFC-22	HFC-134a	1995	2009	2%	None								3.0%
	R-404A	1995	2009	5%	None								
	R-410A	1999	2009	2%	None								
	R-507	1995	2009	2%	None								
	HFC-134a	2009	2010	14%	None								
	R-404A	2009	2010	45%	None								
	R-410A	2009	2010	18%	None								
	R-507	2009	2010	14%	None								
Mobile Air Conditioners (Passenger Cars)													
CFC-12	HFC-134a	1992	1994	100%	HFO-1234yf	2012	2015	1%	None				0.3%
					HFO-1234yf	2016	2021	99%	None				

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[a]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[a]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[a]	Tertiary Substitute: Maximum Market Penetration	Average Growth Rate[b]
Mobile Air Conditioners (Light Duty Trucks)													
CFC-12	HFC-134a	1993	1994	100%	HFO-1234yf	2012	2015	1%	None				1.4%
					HFO-1234yf	2016	2021	99%	None				
Mobile Air Conditioners (Heavy Duty Vehicles)													
CFC-12	HFC-134a	1993	1994	100%	None								0.8%
Mobile Air Conditioners (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				0.3%
	HFC-134a	1994	1997	99.5%	None								
Mobile Air Conditioners (Transit Buses)													
HCFC-22	HFC-134a	1995	2009	100%	None								0.3%
Mobile Air Conditioners (Trains)													
HCFC-22	HFC-134a	2002	2009	50%	None								0.3%
	R-407C	2002	2009	50%	None								
Packaged Terminal Air Conditioners and Heat Pumps													
HCFC-22	R-410A	2006	2009	10%	None								3.0%
	R-410A	2009	2010	90%	None								
Positive Displacement Chillers (Reciprocating and Screw)													
CFC-12													
HCFC-22[c]	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Average Growth Rate[b]**
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	2.5%
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2000	2009	1%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
					R-410A	2010	2020	40%	R-450A	2017	2017	1%	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
	R-407C	2009	2010	9%	R-450A	2017	2017	1%	None				
					R-513A	2017	2017	1%	None				
					R-450A	2018	2024	49%	None				
					R-513A	2018	2024	49%	None				
Positive Displacement Chillers (Scroll)													
HCFC-22	HFC-134a	2000	2009	9%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	2.5%
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	
	R-407C	2000	2009	1%	R-452B	2024	2024	100%	None				
	HFC-134a	2009	2010	81%	R-407C	2010	2020	60%	R-452B	2024	2024	100%	
					R-410A	2010	2020	40%	R-452B	2024	2024	100%	
	R-407C	2009	2010	9%	R-452B	2024	2024	100%	None				

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Average Growth Rate[b]
Refrigerated Appliances													
CFC-12	HFC-134a	1994	1995	100%	Non-ODP/GWP	2019	2021	86%	None				1.7%
					R-450A	2021	2021	7%	None				
					R-513A	2021	2021	7%	None				
Refrigerated Food Processing and Dispensing Equipment													
CFC-12	HCFC-22	1990	1994	100%	HFC-134a	1995	1998	70%	None				2.1%
					R-404A	1995	1998	30%	R-448A	2021	2021	50%	
									R-449A	2021	2021	50%	
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				2.8%
					R-410A	2010	2010	71%	None				
	R-410A	2000	2005	5%	R-410A	2006	2006	100%	None				
	R-410A	2000	2006	5%	None								
	R-410A	2006	2006	20%	None								
Retail Food (Large; Technology Transition)													
DX[d]	DX	2001	2006	67.5%	DX	2006	2015	62%	None				1.7%
					DR[e]	2000	2015	23%	None				
					SLS[f]	2000	2015	15%	None				
	DR	2000	2006	22.5%	None								
	SLS	2000	2006	10%	None								
Retail Food (Large; Refrigerant Transition)													
CFC-12	R-404A	1995	2000	17.5%	R-404A	2000	2000	3.3%	R-407A	2017	2017	100%	1.7%
R-502[g]					R-407A	2011	2015	63.3%	None				
					R-407A	2017	2017	33.3%	None				
	R-507	1995	2000	7.5%	R-404A	2006	2010	71%	R-407A	2017	2017	100%	
					R-407A	2006	2010	30%	None				
	HCFC-22	1995	2000	75%	R-404A	2006	2010	13.3%	R-407A	2011	2015	100%	
					R-407A	2001	2005	1.3%	None				
					R-404A	2001	2005	12%	R-407A	2017	2017	100%	
					R-507	2001	2005	6.7%	R-407A	2011	2015	100%	
					R-404A	2006	2010	34%	R-407A	2011	2015	100%	
					R-404A	2006	2010	7.3%	R-407A	2017	2017	100%	
					R-407A	2006	2010	25.3%	None				
Retail Food (Large Condensing Units)													
HCFC-22	R-402A	1995	2005	5%	R-404A	2006	2006	100%	R-407A	2018	2018	100%	1.5%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Average Growth Rate[b]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	
	R-404A	1995	2005	25%	R-407A	2018	2018	100%	None				
	R-507	1995	2005	10%	R-407A	2018	2018	100%	None				
	R-404A	2008	2010	45%	R-407A	2018	2018	100%	None				
	R-507	2008	2010	15%	R-407A	2018	2018	100%	None				
Retail Food (Small Condensing Units)													
HCFC-22	R-401A	1995	2005	6%	HFC-134a	2006	2006	100%	None				1.6%
	R-402A	1995	2005	4%	HFC-134a	2006	2006	100%	None				
	HFC-134a	1993	2005	30%	None								
	R-404A	1995	2005	30%	R-407A	2018	2018	100%					
	R-404A	2008	2010	30%	R-407A	2018	2018	100%					
Retail Food (Small)													
CFC-12	HCFC-22	1990	1993	91%	HFC-134a	1993	1995	91%	CO_2	2012	2015	1%	2.2%
									Non-ODP/GWP	2012	2015	3.7%	
									Non-ODP/GWP	2014	2019	31%	
									Non-ODP/GWP	2016	2016	17.3%	
									R-450A	2016	2020	23%	
									R-513A	2016	2020	23%	
					HFC-134a	2000	2009	9%	Non-ODP/GWP	2014	2019	30%	
									R-450A	2016	2020	35%	
									R-513A	2016	2020	35%	
	R-404A	1990	1993	9%	Non-ODP/GWP	2016	2016	30%	None				
					R-448A	2019	2020	35%	None				
					R-449A	2019	2020	35%	None				
Transport Refrigeration (Road Transport)													
CFC-12	HFC-134a	1993	1995	10%	None								5.5%
	R-404A	1993	1995	60%	R-452A	2017	2021	5%					
					R-452A	2021	2022	95%					
	HCFC-22	1993	1995	30%	R-410A	2000	2003	5%	None				
					R-404A	2006	2010	95%	R-452A	2017	2021	5%	
									R-452A	2021	2022	95%	
Transport Refrigeration (Intermodal Containers)													
CFC-12	HFC-134a	1993	1993	60%	CO_2	2017	2021	5%	None				7.3%

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Average Growth Rate[b]
	R-404A	1993	1993	5%	CO_2	2017	2021	5%	None				
	HCFC-22	1993	1993	35%	HFC-134a	2000	2010	100%	CO_2	2017	2021	5%	
Transport Refrigeration (Merchant Fishing Transport)													
HCFC-22	HFC-134a	1993	1995	10%	None								5.7%
	R-507	1994	1995	10%	None								
	R-404A	1993	1995	10%	None								
	HCFC-22	1993	1995	70%	R-407C	2000	2005	3%	R-410A	2005	2007	100%	
					R-507	2006	2010	49%	None				
					R-404A	2006	2010	49%	None				
Transport Refrigeration (Reefer Ships)													
HCFC-22	HFC-134a	1993	1995	3.3%	None								4.2%
	R-507	1994	1995	3.3%	None								
	R-404A	1993	1995	3.3%	None								
	HCFC-22	1993	1995	90%	HFC-134a	2006	2010	25%	None				
					R-507	2006	2010	25%	None				
					R-404A	2006	2010	25%	None				
					R-407C	2006	2010	25%	None				
Transport Refrigeration (Vintage Rail Transport)													
CFC-12	HCFC-22	1993	1995	100%	HFC-134a	1996	2000	100%	None				-100%
Transport Refrigeration (Modern Rail Transport)													
HFC-134a	R-404A	1999	1999	50%	R-452A	2022	2022	50%	None				0.3%
	HFC-134a	2005	2005	50%	None								
Vending Machines													
CFC-12	HFC-134a	1995	1998	90%	CO_2	2012	2012	1%	Propane	100%	2019	2019	-0.03%
					Propane	2013	2017	39%	None				
					Propane	2014	2014	1%	None				
					Propane	2019	2019	49%	None				
					R-450A	2019	2019	5%	None				
					R-513A	2019	2019	5%	None				
	R-404A	1995	1998	10%	R-450A	2019	2019	50%	None				
					R-513A	2019	2019	50%	None				
Water-Source and Ground-Source Heat Pumps													
HCFC-22	R-407C	2000	2006	5%	None								1.3%
	R-410A	2000	2006	5%	None								
	HFC-134a	2000	2009	2%	None								
	R-407C	2006	2009	2.5%	None								

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Average Growth Rate[b]
	R-410A	2006	2009	4.5%	None								
	HFC-134a	2009	2010	18%	None								
	R-407C	2009	2010	22.5%	None								
	R-410A	2009	2010	40.5%	None								
Window Units													
HCFC-22	R-410A	2008	2009	10%	HFC-32	2015	2019	50%	None				2.6%
	R-410A	2009	2010	90%	HFC-32	2015	2019	50%	None				

[a] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

[b] Growth Rate is the average annual growth rate for individual market sectors from the base year of the Vintaging Model to 2030.

[c] The CFC-12 reciprocating chillers market for new systems transitioned to HCFC-22 overnight in 1993. This transition is not shown in the table in order to provide the HFC transitions in greater detail.

[d] DX refers to direct expansion systems where the compressors are mounted together in a rack and share suction and discharge refrigeration lines that run throughout the store, feeding refrigerant to the display cases in the sales area.

[e] DR refers to distributed refrigeration systems that consist of multiple smaller units that are located close to the display cases that they serve such as on the roof above the cases, behind a nearby wall, or on top of or next to the case in the sales area.

[f] SLS refers to secondary loop systems wherein a secondary fluid such as glycol or carbon dioxide is cooled by the primary refrigerant in the machine room and then pumped throughout the store to remove heat from the display equipment.

[g] The CFC-12 large retail food market for new systems transitioned to R-502 from 1988 to 1990, and subsequently transitioned to HCFC-22 from 1990 to 1993. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

Table A-116 presents the average equipment lifetimes, HFC charge sizes, one-time HFC emissions rates (for first-fill and disposal), and annual HFC emission rates (for servicing and leaks) for each refrigeration and air-conditioning end-use assumed by the Vintaging Model.

Table A-116: Refrigeration and Air-Conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Charge Size (kg)	HFC Emission Rates (First-fill)[a] (%)	HFC Emission Rates (Servicing and Leaks) (%)	HFC Emission Rates (Disposal)[b] (%)
Centrifugal Chillers	20 – 27	440-926	0.2	1 – 10.9	10
Cold Storage	20 – 25	0.01[c]	1	10.5 – 15.0	10
Commercial Unitary A/C (Large)	15	12.8–13.2	1	8.6	15 – 35
Commercial Unitary A/C (Small)	15	6.6	0.5	7.9	20 – 40
Condensing Units (Medium Retail Food)	20	2.6–25	0.5	7.8 – 14.8	10 – 20
Dehumidifiers	11	0.2	0.5	0.5	50
Ice Makers	8	2.6	1	3.0	49
Industrial Process Refrigeration	25	598 – 9100	1	3.6 – 12.3	10
Large Retail Food	18	408 – 1800	2	17 – 33	10
Mobile A/C (Heavy-duty Vehicles)	16	1.1	0.2	13-25	43
Mobile A/C (Light-duty Trucks)	16	0.8 – 1.1	0.2	6.4 – 37.3	43
Mobile A/C (Passenger Cars)	16	0.6 – 0.9	0.2	6.4 – 37.3	43
Mobile A/C (School & Tour Buses)	12	4.9	0.2	9.6	50
Mobile A/C (Trains)	5	18.6	0.2	2.3	50
Mobile A/C (Transit Buses)	12	7.2	0.2	9.6	50
Positive Displacement Chillers	20	240 – 300	0.2	0.5 – 1.5	10
PTAC/PTHP	12	0.6	1	3.9	40
Refrigerated Appliances	14	0.1	0.6	0.6 – 0.8	42
Refrigerated Food Processing and Dispensing Equipment	10	0.5	1	1	68
Residential Unitary A/C	15	2.6 – 3.7	0.2	5.3 – 11	20 – 40
Small Retail Food	10	0.4 – 0.5	1	1	19 – 65
Transport Refrigeration (Intermodal Containers)	15	4.5	0.2	19.4 – 31.4	32.5
Transport Refrigeration (Merchant Fishing)	25	176 – 385	1	33.2 – 44.1	10
Transport Refrigeration (Modern Rail)	9	7.5	0.2	33.2 – 36.4	18 – 33
Transport Refrigeration (Reefer Ships)	25	750	1	23 – 31	10
Transport Refrigeration (Road)	12	4.5	0.2	23 – 36	33
Transport Refrigeration (Vintage Rail)	40	15	N/A[d]	36.4	65
Vending Machines	10	4.5	0.5	1	68– 79
Water & Ground Source Heat Pumps	20	3.5 – 3.6	1	3.9	43
Window Units	12	0.3 – 0.6	0.5	0.6	50

[a] For some equipment, first-fill emissions are adjusted to account for equipment that are produced in the United States, including those which are produced for export, and excluding those that are imported pre-charged.
[b] Disposal emissions rates are developed based on consideration of the original charge size, the percentage of refrigerant likely to remain in equipment at the time of disposal, and recovery practices assumed to vary by gas type. Because equipment lifetime emissions are annualized, equipment is assumed to reach the end of its lifetime with a full charge. Therefore, recovery rate is equal to 100 percent - Disposal Loss Rate (%).
[c] Charge sizes for cold storage are modeled on a kilogram per cubic foot of refrigerated space basis.
[d] Vintage rail transport HFC systems are assumed to be retrofitted from CFC-12 systems and therefore have no HFC first-fill emission rate.

Aerosols

ODSs, HFCs, and many other chemicals are used as propellant aerosols. Pressurized within a container, a nozzle releases the chemical, which allows the product within the can to also be released. Three types of aerosol products are modeled: metered dose inhalers (MDI), consumer aerosols, and technical aerosols. In the United States, the use of CFCs in consumer aerosols was banned in 1978, and many products transitioned to hydrocarbons or "not-in-kind" technologies, such as solid deodorants and finger-pump hair sprays. However, MDIs and certain technical aerosols continued to use

CFCs and HCFCs as propellants because their use was deemed essential. Essential use exemptions granted to the United States under the Montreal Protocol for CFC use in MDIs were limited to the treatment of asthma and chronic obstructive pulmonary disease. Under the Clean Air Act, the use of CFCs and HCFCs was also exempted in technical aerosols for several applications, including industrial cleaners, pesticides, mold release agents, certain dusters, and lubricants.

All HFCs used in aerosols are assumed to be emitted in the year of manufacture. Since there is currently no aerosol recycling, it is assumed that all of the annual production of aerosol propellants is released to the atmosphere. The following equation describes the emissions from the aerosols sector.

Equation A-12: Calculation of Emissions from Aerosols

$$E_j = Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year j from use in aerosol products, by weight.
Qc	=	Quantity of Chemical. Total quantity of a specific chemical contained in aerosol products sold in year j, by weight.
j	=	Year of emission.

Transition Assumptions

Transition assumptions and growth rates for those items that use ODSs or HFCs as propellants, including vital medical devices and specialty consumer products, are presented in Table A-117.

Table A-117: Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Growth Rate[b]
MDIs													
CFC Mix[c]	HFC-134a	1997	1997	6%	None								3.8%
	Non-ODP/GWP	1998	2007	7%	None								
	CFC Mix[a]	2000	2000	87%	HFC-134a	2001	2011	28%	Non-ODP/GWP	2012	2018	64%	
									HFC-227ea	2015	2015	1%	
					Non-ODP/GWP	2001	2014	67%	None				
					HFC-227ea	2007	2013	5%	Non-ODP/GWP	2015	2018	44%	
Consumer Aerosols (Non-MDIs)													
NA[d]	HFC-152a	1990	1991	50%	None								4.2%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	None				
					HFC-152a	2001	2005	38%	None				
					HFO-1234ze(E)	2016	2018	16%	None				
Technical Aerosols (Non-MDIs)													
CFC-12	HCFC-142b	1994	1994	10%	HFC-152a	2001	2010	90%	None				4.2%
					HFC-134a	2001	2010	10%	None				
	Non-ODP/GWP	1994	1994	5%	None								
	HCFC-22	1994	1994	50%	HFC-134a	2001	2010	100%	HFO-1234ze(E)	2012	2016	10%	
	HFC-152a	1994	1994	10%	None								
	HFC-134a	1994	1994	25%	None								

[a] Transitions between the start year and date of full penetration in new products are assumed to be linear so that in total 100% of the market is assigned to the original ODS or the various ODS substitutes.

[b] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

[c] CFC Mix consists of CFC-11, CFC-12 and CFC-114 and represents the weighted average of several CFCs consumed for essential use in MDIs from 1993 to 2008. It is assumed that CFC mix was stockpiled in the United States and used in new products through 2013.

[d] Consumer Aerosols transitioned away from ODS prior to 1985, the year in which the Vintaging Model begins. The portion of the market that is now using HFC propellants is modeled.

Solvents

ODSs, HFCs, PFCs and other chemicals are used as solvents to clean items. For example, electronics may need to be cleaned after production to remove any manufacturing process oils or residues left. Solvents are applied by moving the item to be cleaned within a bath or stream of the solvent. Generally, most solvents are assumed to remain in the liquid phase and are not emitted as gas. Thus, emissions are considered “incomplete,” and are a fixed percentage of the amount of solvent consumed in a year. The solvent is assumed to be recycled or continuously reused through a distilling and cleaning process until it is eventually almost entirely emitted. The remainder of the consumed solvent is assumed to be entrained in sludge or wastes and disposed of by incineration or other destruction technologies without being released to the atmosphere (U.S. EPA 2004). The following equation calculates emissions from solvent applications.

Equation A-13: Calculation of Emissions from Solvents

$$E_j = l \times Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year *j* from use in solvent applications, by weight.
l	=	Percent Leakage. The percentage of the total chemical that is leaked to the atmosphere, assumed to be 90 percent.
Qc	=	Quantity of Chemical. Total quantity of a specific chemical sold for use in solvent applications in the year j, by weight.
j	=	Year of emission.

Transition Assumptions

The transition assumptions and growth rates used within the Vintaging Model for electronics cleaning, metals cleaning, precision cleaning, and adhesives, coatings and inks, are presented in Table A-118.

Table A-118: Solvent Market Transition Assumptions

	Primary Substitute				Secondary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Growth Rate[b]
Adhesives									
CH_3CCl_3	Non-ODP/GWP	1994	1995	100%	None				2.0%
									Electronics
CFC-113	Semi-Aqueous	1994	1995	52%	None				2.0%
	HCFC-225ca/cb	1994	1995	0.2%	Unknown				
	HFC-43-10mee	1995	1996	0.7%	None				
	HFE-7100	1994	1995	0.7%	None				
	nPB	1992	1996	5%	None				
	Methyl Siloxanes	1992	1996	0.8%	None				
	No-Clean	1992	2013[c]	40%	None				
CH_3CCl_3	Non-ODP/GWP	1996	1997	99.8%	None				2.0%
	PFC/PFPE	1996	1997	0.2%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
Metals									
CH_3CCl_3	Non-ODP/GWP	1992	1996	100%	None				2.0%
CFC-113	Non-ODP/GWP	1992	2013[c]	100%	None				2.0%
CCl_4	Non-ODP/GWP	1992	1996	100%	None				2.0%
Precision									
CH_3CCl_3	Non-ODP/GWP	1995	1996	99.3%	None				2.0%
	HFC-43-10mee	1995	1996	0.6%	None				

Initial Market Segment	Primary Substitute				Secondary Substitute				Growth Rate[b]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	
CFC-113	PFC/PFPE	1995	1996	0.1%	Non-ODP/GWP	2000	2003	90%	2.0%
					Non-ODP/GWP	2005	2009	10%	
	Non-ODP/GWP	1995	2013[c]	90%	None				
	Methyl Siloxanes	1995	1996	6%					
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

[a] Transitions between the start year and date of full penetration in new equipment or chemical supply are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.
[b] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.
[c] Transition assumed to be completed in 2013 to mimic CFC-113 stockpile use.
Note: Non-ODP/GWP includes chemicals with zero ODP and low GWP, such as hydrocarbons and ammonia, as well as not-in-kind alternatives such as "no clean" technologies.

Fire Extinguishing

ODSs, HFCs, PFCs and other chemicals are used as fire-extinguishing agents, in both hand-held "streaming" applications as well as in built-up "flooding" equipment similar to water sprinkler systems. Although these systems are generally built to be leak-tight, some leaks do occur and emissions occur when the agent is released. Total emissions from fire extinguishing are assumed, in aggregate, to equal a percentage of the total quantity of chemical in operation at a given time. For modeling purposes, it is assumed that fire extinguishing equipment leaks at a constant rate for an average equipment lifetime, as shown in the equation below. In streaming systems, non-halon emissions are assumed to be 3.5 percent of all chemical in use in each year, while in flooding systems 2.5 percent of the installed base of chemical is assumed to leak annually. Halon systems are assumed to leak at higher rates. The equation is applied for a single year, accounting for all fire protection equipment in operation in that year. The model assumes that equipment is serviced annually so that the amount equivalent to average annual emissions for each product (and hence for the total of what was added to the bank in a previous year in equipment that has not yet reached end-of-life) is replaced/applied to the starting charge size (or chemical bank). Each fire protection agent is modeled separately. In the Vintaging Model, streaming applications have a 24-year lifetime and flooding applications have a 33-year lifetime. At end-of-life, remaining agent is recovered from equipment being disposed and is reused.

Equation A-14: Calculation of Emissions from Fire Extinguishing

$$E_j = r \times \sum Qc_{j-i+1} \quad for\ i=1 \rightarrow k$$

where:

E	=	Emissions. Total emissions of a specific chemical in year *j* for fire extinguishing equipment, by weight.
r	=	Percent Released. The percentage of the total chemical in operation that is released to the atmosphere.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used in new fire extinguishing equipment in a given year, *j*-*i*+1, by weight.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of the equipment.

Transition Assumptions

Transition assumptions and growth rates for these two fire extinguishing types are presented in Table A-119.

Table A-119: Fire Extinguishing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				
Initial Market Segment	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Name of Substitute**	**Start Date**	**Date of Full Penetration in New Equipment[a]**	**Maximum Market Penetration**	**Growth Rate[b]**
Flooding Agents									
Halon-1301	Halon-1301[c]	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	50.2%	FK-5-1-12	2003	2020	35%	
					HFC-125	2001	2012	10%	
					Non-ODP/GWP	2005	2020	13%	
	Non-ODP/GWP	1994	1994	22%	FK-5-1-12	2003	2020	7%	
	Non-ODP/GWP	1995	2003	7%	None				
	CO_2	1998	2006	7%	None				
	C_4F_{10}	1994	1999	0.5%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	9.1%	FK-5-1-12	2003	2020	35%	
					Non-ODP/GWP	2005	2020	10%	
					Non-ODP/GWP	2005	2019	3%	
Streaming Agents									
Halon-1211	Halon-1211[c]	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1995	0.1%	Unknown				
	Halotron	1996	2000	5.4%	Non-ODP/GWP	2020	2020	56%	
	Non-ODP/GWP	1993	1994	56%	None				
	Non-ODP/GWP	1995	2024	20%	None				
	Non-ODP/GWP	1999	2018	10%	None				

[a] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

[b] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

[c] Despite the 1994 consumption ban, a small percentage of new halon systems are assumed to continue to be built and filled with stockpiled or recovered supplies.

Foam Blowing

ODSs, HFCs, and other chemicals are used to produce foams, including such items as the foam insulation panels around refrigerators, insulation sprayed on buildings, etc. The chemical is used to create pockets of gas within a substrate, increasing the insulating properties of the item. Foams are given emission profiles depending on the foam type (open cell or closed cell). Open cell foams are assumed to be 100 percent emissive in the year of manufacture. Closed cell foams are assumed to emit a portion of their total HFC content upon manufacture, a portion at a constant rate over the lifetime of the foam, a portion at disposal, and a portion after disposal; these portions vary by end-use.

Step 1: Calculate manufacturing emissions (open-cell and closed-cell foams)

Manufacturing emissions occur in the year of foam manufacture and are calculated as presented in the following equation. Manufacturing emissions are considered for all foam equipment that are filled with foam within the United States, including those which are produced for export, and excluding those that are imported pre-filled.

Equation A-15: Calculation of Emissions from Foam Blowing Manufacturing

$$Em_j = lm \times Qc_j$$

where:

Em_j	=	Emissions from manufacturing. Total emissions of a specific chemical in year *j* due to manufacturing losses, by weight.
lm	=	Loss Rate. Percent of original blowing agent emitted during foam manufacture. For open-cell foams, *lm* is 100%.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
j	=	Year of emission.

Step 2: Calculate lifetime emissions (closed-cell foams)

Lifetime emissions occur annually from closed-cell foams throughout the lifetime of the foam, as calculated as presented in the following equation.

Equation A-16: Calculation of Emissions from Foam Blowing Lifetime Losses (Closed-cell Foams)

$$Eu_j = lu \times \sum Qc_{j-i+1} \quad \text{for } i=1 \rightarrow k$$

where:

Eu_j	=	Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
lu	=	Leak Rate. Percent of original blowing agent emitted each year during lifetime use.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
i	=	Counter, runs from 1 to lifetime (k).
j	=	Year of emission.
k	=	Lifetime. The average lifetime of foam product.

Step 3: Calculate disposal emissions (closed-cell foams)

Disposal emissions occur in the year the foam is disposed, and are calculated as presented in the following equation.

Equation A-17: Calculation of Emissions from Foam Blowing Disposal (Closed-cell Foams)

$$Ed_j = ld \times Qc_{j-k}$$

where:

Ed_j	=	Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.
ld	=	Loss Rate. Percent of original blowing agent emitted at disposal.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
j	=	Year of emission.
k	=	Lifetime. The average lifetime of foam product.

Step 4: Calculate post-disposal emissions (closed-cell foams)

Post-disposal emissions occur in the years after the foam is disposed; for example, emissions might occur while the disposed foam is in a landfill. Currently, five foam types are assumed to have post-disposal emissions.

Equation A-18: Calculation of Emissions from Foam Blowing Post-disposal (Closed-cell Foams)

$$Ep_j = lp \times \sum Qc_{j-m} \quad \text{for } m=k \rightarrow k+26$$

where:

Ep_j	=	Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.
lp	=	Leak Rate. Percent of original blowing agent emitted post disposal.
Qc	=	Quantity of Chemical. Total amount of a specific chemical used to manufacture closed-cell foams in a given year.
k	=	Lifetime. The average lifetime of foam product.
m	=	Counter. Runs from lifetime (k) to (k+26).
j	=	Year of emission.

Step 5: Calculate total emissions (open-cell and closed-cell foams)

To calculate total emissions from foams in any given year, emissions from all foam stages must be summed, as presented in the following equation.

Equation A-19: Calculation of Total Emissions from Foam Blowing (Open-cell and Closed-cell Foams)

$$E_j = Em_j + Eu_j + Ed_j + Ep_j$$

where:

E_j	=	Total Emissions. Total emissions of a specific chemical in year *j*, by weight.
Em_j	=	Emissions from manufacturing. Total emissions of a specific chemical in year *j* due to manufacturing losses, by weight.
Eu_j	=	Emissions from Lifetime Losses. Total emissions of a specific chemical in year j due to lifetime losses during use, by weight.
Ed_j	=	Emissions from disposal. Total emissions of a specific chemical in year j at disposal, by weight.
Ep_j	=	Emissions from post disposal. Total post-disposal emissions of a specific chemical in year j, by weight.

Assumptions

The Vintaging Model contains thirteen foam types, whose transition assumptions away from ODS and growth rates are presented in Table A-120. The emission profiles of these thirteen foam types are shown in Table A-121.

Table A-120: Foam Blowing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Growth Rate[b]
Vending Machine Foam													
CFC-11	HCFC-141b	1993	1995	100%	HFC-245fa	2001	2004	100%	Non-ODP/GWP	2004	2006	45%	-0.03%
									Non-ODP/GWP	2007	2009	5%	
									Non-ODP/GWP	2007	2009	25%	
									Non-ODP/GWP	2010	2010	10%	
									Non-ODP/GWP	2017	2017	2%	
									Non-ODP/GWP	2017	2017	8%	
Stand-alone Equipment Foam													
CFC-11	HCFC-141b	1990	1995	40%	HFC-245fa	2003	2005	80%	HCFO-1233zd(E)	2019	2020	25%	2.2%
					HFC-134a	2003	2005	40%	None				
					Non-ODP/GWP	2003	2005	40%	None				
	HCFC-22	1990	1995	56%	HFC-134a	2004	2008	46%	Non-ODP/GWP	2010	2018	32%	
									HCFO-1233zd(E)	2019	2020	36%	
					Non-ODP/GWP	2004	2008	54%	None				
Ice Machine Foam													
CFC-11	HCFC-141b	1989	1996	40%	CO_2	2002	2003	69%	None				2.1%
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-142b	1989	1996	8%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
	HCFC-22	1989	1996	52%	CO_2	2002	2003	69%	None				
					HFC-134a	2002	2003	31%	CO_2	2017	2020	47%	
									HCFO-1233zd(E)	2017	2020	20%	
Refrigerated Food Processing and Dispensing Equipment Foam													
CFC-11	HCFC-22	1989	1997	100%	HFC-134a	2004	2008	75%	Non-ODP/GWP	2015	2021	30%	2.1%
						2009	2010	20%	HCFO-1233zd(E)	2020	2021	3%	
									HFO-1234ze	2020	2021	3%	
					Non-ODP/GWP	2004	2008	25%	None				
Small Walk-in Cooler Foam													
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.6%
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None				
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%	

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate[b]
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	
					HFC-134a	2009	2010	40%	None				
Large Walk-in Cooler Foam													
CFC-11	HCFC-141b	1990	1995	50%	HFC-245fa	2001	2003	100%	None				1.5%
	HCFC-22	1990	1995	50%	HFC-134a	2000	2001	10%	None				
					HFC-245fa	2009	2010	50%	HCFO-1233zd(E)	2020	2020	20%	
					HFC-134a	2009	2010	40%	None				
Display Case Foam													
CFC-11	HCFC-141b	1991	1992	50%	HFC-245fa	2003	2003	100%	None				1.7%
	HCFC-142b	1991	1992	50%	HFC-245fa	2004	2004	100%	None				
CFC-12	HCFC-22	1991	1993	100%	HFC-134a	2003	2007	100%	HCFO-1233zd(E)	2015	2020	60%	
Road Transport Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	5.5%
					CO_2	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd(E)	2020	2020	76%	
Intermodal Container Foam													
CFC-11	HCFC-141b	1989	1996	19%	HCFC-22	1999	2001	37%	HFC-245fa	2005	2007	100%	7.3%
					CO_2	1999	2001	11%	None				
					Non-ODP/GWP	1999	2001	53%	None				
	HCFC-22	1989	1996	81%	HFC-134a	2005	2007	37%	None				
					HFC-245fa	2005	2007	63%	HCFO-1233zd(E)	2020	2020	76%	
Flexible PU Foam: Integral Skin Foam													
HCFC-141b[c]	HFC-134a	1996	2000	50%	HFC-245fa	2003	2010	96%	HCFO-1233zd(E)	2017	2017	83%[e]	2.0%
									Non-ODP/GWP	2017	2017	6%	
									HFO-1336mzz(Z)	2017	2017	10%	
					Non-ODP/GWP	2003	2010	4%	None				
	CO_2	1996	2000	50%	None								
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								2.0%

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[a]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[a]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[a]	Tertiary Substitute: Maximum Market Penetration	Growth Rate[b]
Phenolic Foam													
CFC-11	HCFC-141b	1989	1990	100%	Non-ODP/GWP	1992	1992	100%	None				2.0%
Polyolefin Foam													
CFC-114	HFC-152a	1989	1993	10%	Non-ODP/GWP	2005	2010	100%	None				2.0%
	HCFC-142b	1989	1993	90%	Non-ODP/GWP	1994	1996	100%	None				
PU and PIR Rigid: Boardstock													
CFC-11	HCFC-141b	1993	1996	100%	Non-ODP/GWP	2000	2003	100%	None				4.8%
PU Rigid: Domestic Refrigerator and Freezer Insulation													
CFC-11	HCFC-141b	1993	1995	100%	HFC-134a	1996	2001	7%	Non-ODP/GWP	2002	2003	100%	0.8%
					HFC-245fa	2001	2003	50%	Non-ODP/GWP	2015	2020	50%	
									HCFO-1233zd(E)	2015	2020	50%	
					HFC-245fa	2006	2009	10%	Non-ODP/GWP	2015	2020	50%	
									HCFO-1233zd(E)	2015	2020	50%	
					Non-ODP/GWP	2002	2005	10%	None				
					Non-ODP/GWP	2006	2009	3%	None				
					Non-ODP/GWP	2009	2014	20%	None				
PU Rigid: One Component Foam													
CFC-12	HCFC-142b/22 Blend	1989	1996	70%	Non-ODP/GWP	2009	2010	80%	None				4.0%
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
					HFC-152a	2009	2010	10%	None				
	HCFC-22	1989	1996	30%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-134a	2009	2010	10%	HFO-1234ze(E)	2018	2020	100%	
					HFC-152a	2009	2010	10%	None				
PU Rigid: Other: Slabstock Foam													
CFC-11	HCFC-141b	1989	1996	100%	CO_2	1999	2003	45%	None				2.0%

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Growth Rate[b]
					Non-ODP/GWP	2001	2003	45%	None				
					HCFC-22	2003	2003	10%	Non-ODP/GWP	2009	2010	100%	
PU Rigid: Sandwich Panels: Continuous and Discontinuous													
HCFC-141b[d]	HCFC-22/Water Blend	2001	2003	20%	HFC-245fa/CO_2 Blend	2009	2010	50%	HCFO-1233zd(E)	2015	2020	100%	6.0%
					Non-ODP/GWP	2009	2010	50%	None				
	HFC-245fa/CO_2 Blend	2002	2004	20%	HCFO-1233zd(E)	2015	2020	100%	None				
	Non-ODP/GWP	2001	2004	40%	None								
	HFC-134a	2002	2004	20%	Non-ODP/GWP	2015	2020	100%	None				
HCFC-22	HFC-245fa/CO_2 Blend	2009	2010	40%	HCFO-1233zd(E)	2015	2020	100%	None				
	Non-ODP/GWP	2009	2010	20%	None								
	CO_2	2009	2010	20%	None								
	HFC-134a	2009	2010	20%	Non-ODP/GWP	2015	2020	100%	None				
PU Rigid: High Pressure Two-Component Spray Foam													
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	C	HFO-1336mzz(Z)	2016	2020	100%	0.8%
					HFC-245fa/CO_2 Blend	2002	2003	C	HFO-1336mzz(Z)/CO_2 Blend	2016	2020	100%	
					HFC-227ea/HFC-365mfc Blend	2002	2003	C	HCFO-1233zd(E)	2016	2020	100%	
PU Rigid: Low Pressure Two-Component Spray Foam													
CFC-12	HCFC-22	1989	1996	100%	HFC-245fa	2002	2003	15%	HCFO-1233zd(E)	2017	2021	100%	0.8%
					HFC-134a	2002	2003	85%	HFO-1234ze	2017	2021	100%	

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Growth Rate[b]
XPS: Boardstock Foam													
CFC-12	HCFC-142b/22 Blend	1989	1994	10%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	2.5%
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
	HCFC-142b	1989	1994	90%	HFC-134a	2009	2010	70%	Non-ODP/GWP	2021	2021	100%	
					HFC-152a	2009	2010	10%	None				
					CO_2	2009	2010	10%	None				
					Non-ODP/GWP	2009	2010	10%	None				
XPS: Sheet Foam													
CFC-12	CO_2	1989	1994	1%	None								2.0%
	Non-ODP/GWP	1989	1994	99%	CO_2	1995	1999	9%	None				
					HFC-152a	1995	1999	10%	None				

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[a] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

[b] Growth Rate is the average annual growth rate for individual market sectors from the base year to 2030.

[c] CFC-11 was the initial blowing agent used for through 1989. This transition is not shown in the table in order to provide the HFC transitions in greater detail.

[d] The CFC-11 PU Rigid: Sandwich Panels: Continuous and Discontinuous market for new systems transitioned to 82 percent HCFC-141b and 18 percent HCFC-22 from 1989 to 1996. These transitions are not shown in the table in order to provide the HFC transitions in greater detail.

[e] A linear transition to HFO-1336mzz(Z) from the HCFO-1233zd(E) market is assumed to take place beginning in 2020 and reaching 88 percent of the market by 2030. This transition is not shown in the table.

Table A-121: Emission Profile for the Foam End-Uses

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Post-life Loss (%)	Total[a] (%)
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	0	100
Vending Machine Foam	4	0.25	10	93.5	0	100
Stand-alone Equipment Foam	4	0.25	10	93.5	0	100
Ice Machine Foam	4	0.25	8	94.0	0	100
Refrigerated Food Processing and Dispensing Equipment Foam	4	0.25	10	93.5	0	100
Small Walk-in Cooler Foam	4	0.25	20	91.0	0	100
Large Walk-in Cooler Foam	4	0.25	20	91.0	0	100
CFC-11 Display Case Foam	4	0.25	18	91.5	0	100
CFC-12 Display Case Foam	4	0.25	18	91.5	0	100
Road Transport Foam	4	0.25	12	93.0	0	100
Intermodal Container Foam	4	0.25	15	92.3	0	100
Rigid PU: High Pressure Two-Component Spray Foam	15	1.5	50	10.0	0	100
Rigid PU: Low Pressure Two-Component Spray Foam	15	1.5	50	10.0	0	100
Rigid PU: Slabstock and Other [a]	20	1	15	22.5	1.5	57.5
Phenolic Foam	28	0.875	32	44.0	0	100
Polyolefin Foam	40	3	20	0	0	100
Rigid PU: One Component Foam	95	2.5	2	0	0	100
XPS: Sheet Foam	50	25	2	0	0	100
XPS: Boardstock Foam	25	0.75	25	56.25	0	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation (HFC-134a)[a]	6.5	0.5	14	37.2	2.0	50.7
Rigid PU: Domestic Refrigerator and Freezer Insulation (all others)[a]	3.75	0.25	14	39.9	2.0	47.15
PU and PIR Rigid: Boardstock[a]	10	1	40	22.5	1.5	72.5
PU Sandwich Panels: Continuous and Discontinuous [a]	15	0.5	75	22.5	1.25	75

PIR (Polyisocyanurate)

PU (Polyurethane)

XPS (Extruded Polystyrene)

[a] Total emissions from foam end-uses are assumed to be 100 percent. In the Rigid PU: Slabstock and Other, Rigid PU Domestic Refrigerator and Freezer Insulation, PU and PIR Boardstock, and PU Sandwich Panels end-uses, the source of emission rates and lifetimes did not yield 100 percent emissions; the remainder is assumed to be emitted post-disposal.

Sterilization

Sterilants kill microorganisms on medical equipment and devices. The principal ODS used in this sector was a blend of 12 percent ethylene oxide (EtO) and 88 percent CFC-12, known as "12/88." In that blend, ethylene oxide sterilizes the equipment and CFC-12 is a diluent solvent to form a non-flammable blend. The sterilization sector is modeled as a single end-use. For sterilization applications, all chemicals that are used in the equipment in any given year are assumed to be emitted in that year, as shown in the following equation.

Equation A-20: Calculation of Total Emissions from Sterilization

$$E_j = Qc_j$$

where:

E	=	Emissions. Total emissions of a specific chemical in year *j* from use in sterilization equipment, by weight.
Qc	=	Quantity of Chemical. Total quantity of a specific chemical used in sterilization equipment in year *j*, by weight.
j	=	Year of emission.

Assumptions

The Vintaging Model contains one sterilization end-use, whose transition assumptions away from ODS and growth rates are presented in Table A-122.

Table A-122: Sterilization Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[a]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	Growth Rate
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	0.8%	None								
	HCFC-124/EtO Blend	1993	1994	1.4%	Non-ODP/GWP	2015	2015	100%	None				
	HCFC-22/HCFC-124/EtO Blend	1993	1994	3.1%	Non-ODP/GWP	2010	2010	100%	None				

[a] Transitions between the start year and date of full penetration in new equipment are assumed to be linear so that in total 100 percent of the market is assigned to the original ODS or the various ODS substitutes.

Model Output

By repeating these calculations for each year, the Vintaging Model creates annual profiles of use and emissions for ODS and ODS substitutes. The results can be shown for each year in two ways: 1) on a chemical-by-chemical basis, summed across the end-uses, or 2) on an end-use or sector basis. Values for use and emissions are calculated both in metric tons and in million metric tons of CO_2 equivalent (MMT CO_2 Eq.). The conversion of metric tons of chemical to MMT CO_2 Eq. is accomplished through a linear scaling of tonnage by the global warming potential (GWP) of each chemical.

Throughout its development, the Vintaging Model has undergone annual modifications. As new or more accurate information becomes available, the model is adjusted in such a way that both past and future emission estimates are often altered.

Bank of ODS and ODS Substitutes

The bank of an ODS or an ODS substitute is "the cumulative difference between the chemical that has been consumed in an application or sub-application and that which has already been released" (IPCC 2006). For any given year, the bank is equal to the previous year's bank, less the chemical in equipment disposed of during the year, plus chemical in new equipment entering the market during that year, less the amount emitted but not replaced, plus the amount added to replace chemical emitted prior to the given year, as shown in the following equation:

Equation A-21: Calculation of Chemical Bank (All Sectors)

$$Bc_j = Bc_{j-1} - Qd_j + Qp_j - E_e + Q_r$$

where:

Bc_j	=	Bank of Chemical. Total bank of a specific chemical in year *j*, by weight.
Qd_j	=	Quantity of Chemical in Equipment Disposed. Total quantity of a specific chemical in equipment disposed of in year *j*, by weight.
Qp_j	=	Quantity of Chemical Penetrating the Market. Total quantity of a specific chemical that is entering the market in year *j*, by weight.
E_e	=	Emissions of Chemical Not Replaced. Total quantity of a specific chemical that is emitted during year j but is not replaced in that year. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors except foam blowing.
Q_r	=	Chemical Replacing Previous Year's Emissions. Total quantity of a specific chemical that is used to replace emissions that occurred prior to year j. The Vintaging Model assumes all chemical emitted from refrigeration, air conditioning and fire extinguishing equipment is replaced in the year it is emitted, hence this term is zero for all sectors.
j	=	Year of emission.

Table A-9 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2021.

Comparisons to Other Information on Supply and Emissions of HFCs

Comparison of Reported Consumption to Modeled Consumption of HFCs

As discussed in Section 4.24 of the Inventory report, EPA conducted a quality assurance check of the Vintaging Model used for estimating emissions of HFCs, PFCs, and CO_2 used as ODS Substitutes. We evaluated the consumption of saturated HFCs that the model estimates on an end-use by end-use ("bottom up") manner and compared these results to the supply of saturated HFCs as reported under subparts OO and QQ of the Greenhouse Gas Reporting Program (GHGRP).

Comparison Results and Discussion

Comparing the estimates of consumption from these two approaches (i.e., reported and modeled) ultimately supports and improves estimates of emissions, as noted in the *2006 IPCC Guidelines* (which refer to fluorinated greenhouse gas consumption based on supplies as "potential emissions"):

> [W]hen considered along with estimates of actual emissions, the potential emissions approach can assist in validation of completeness of sources covered and as a QC check by comparing total domestic consumption as calculated in this 'potential emissions approach' per compound with the sum of all activity data of the various uses (IPCC 2006).

There are eleven saturated HFC species modeled in the Vintaging Model: HFC-23, HFC-32, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-365mfc, and HFC-43-10mee. Some amounts of additional, less-used, saturated HFCs, including isomers of those included in the Vintaging Model, are reportable under EPA's GHGRP. The GHGRP data are believed to represent an amount comparable to the modeled estimates as a quality assurance check.

Table A-123 and Figure A-7 compare the published net supply of saturated HFCs in MMT CO_2 Eq. as determined from Subpart OO (supply of HFCs in bulk) and Subpart QQ (supply of HFCs in products and foams) of EPA's GHGRP for the years 2012 through 2021 (EPA 2021; EPA 2023) and the chemical demand as calculated by the Vintaging Model for the same time series. For comparison purposes, Vintaging Model estimates are presented using 100-year global warming potentials (GWPs) provided in the IPCC Fourth Assessment Report (AR4) (IPCC 2007), as reported net supply from GHGRP is estimated using AR4 GWPs.

Table A-123: U.S. HFC Supply (MMT CO_2 Eq.)

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Reported Net Supply (GHGRP)	260	307	294	318	271	322	340	344	344	475
Industrial GHG Suppliers	242	290	269	292	243	290	306	314	309	462
HFCs in Products and Foams	18	17	25	26	28	32	34	30	35	13
Modeled Supply (Vintaging Model)	274	279	283	282	285	276	280	273	270	253
Percent Difference	**6%**	**-9%**	**-4%**	**-11%**	**5%**	**-14%**	**-18%**	**-21%**	**-22%**	**-47%**

Figure A-7: U.S. HFC Consumption (MMT CO_2 Eq.)

As shown, the estimates from the Vintaging Model are lower than the GHGRP data by an average of 13.5 percent across the time series (i.e., 2012 through 2021), with the difference growing to an average of 20 percent over the last three years excluding 2021 (i.e., 2018 through 2020) and 27 percent over the last 4 years (i.e., 2018 through 2021). The difference in 2021 is much larger, showing that supply exceeded the estimated demand, and is addressed by the sub-bullets below. Potential reasons for the differences between the reported and modeled data include:

- A temporal effect results from the stockpiling of chemicals by suppliers and distributors. Suppliers might decide to produce or import additional quantities of HFCs for various reasons such as expectations that prices may increase, or supplies may decrease, in the future. Such stockpiled material could be used for new equipment produced at a later time and for on-going servicing. Based on information collected by the EPA at the time, such stockpiling behavior was seen during ODS phasedowns, and it is concluded that such behavior similarly exists amongst HFC suppliers in anticipation of current and recently promulgated controls on HFCs. Any such activity would increase the GHGRP data as compared to the modeled data. This effect is likely the major reason why there is a divergence in the comparison above, with the GHGRP data in 2017 through 2020 (i.e., the years following agreement of the Kigali Amendment to the Montreal Protocol) significantly higher than the modeled data. Improvements of the model methodology to incorporate a temporal factor could be investigated. Information on U.S. HFC stockpiles could also be used to assess this source of discrepancy; however, this data is not collected from suppliers under the GHGRP. Future reporting under the AIM Act may provide useful information in evaluating this issue.
    - The 2021 data follow a similar pattern as was seen during the ODS phasedowns. This was the year before HFC consumption was controlled by the EPA under the AIM Act. The so-called "campaign consumption" in 2021 is obvious when looking at the 2021 data and may be evident even in the 2017-2020 timeframe. This is not unlike the year 2003, the year in which the HCFC allocation program started, when the HCFC supply (in ODP-tons) was 42% higher than the average consumption from 1996 to 2002 (UNEP 2023).
    - As noted below, additional comparison of the emissions from the Vintaging Model to atmosphere-based emission estimates also show a more apparent difference in the years 2017 through 2020 for three main HFCs. This could be an indication of a systemic issue wherein the model is underestimating

the portion of the supply that is used to replace leaked chemical that has been emitted. This might be related to the supply issues noted above. For instance, if supply of HFCs were plentiful during these years, that could lead to some practices wherein emissions, and supply to replace those emissions, were significantly higher than estimated by the model.

- The fact that the top-down data are reported at the time of actual production or import, and the bottom-up supply data are calculated at the time of placement on the market (e.g., in new equipment or to service existing equipment) introduces another temporal discrepancy when comparing data. A potential improvement would be to incorporate a time lag into the model, which would require obtaining data on the movement of supplies through the point of actual use. Because the GHGRP data and the Vintaging Model estimates generally increase over time (although some year-to-year variations exist), EPA would expect the modeled estimates to be slightly lower than the corresponding GHGRP data due to this temporal effect. Regulations under the AIM Act require the reporting of chemical supplies held at the close of the calendar year; such reports may help investigate this possible factor.
- Under EPA's GHGRP, all facilities that produce HFCs are required to report their quantities, whereas importers or exporters of HFCs or pre-charged equipment and closed-cell foams that contain HFCs are only required to report if either their total imports or their total exports of greenhouse gases are greater than or equal to 25,000 metric tons of CO_2 Eq. per year. Thus, some imports or exports may not be accounted for in the GHGRP data, leading to further underestimation or overestimation of the model if imports or exports, respectively, are not represented in the reported GHGRP data. In 2021, some companies below the reporting threshold for imports and exports reported to the GHGRP, including data from as early as 2011, for AIM-listed HFCs as part of data collection efforts for the U.S. production and consumption baselines; this data is included in the totals presented above. Additional reporting under the AIM Act, if released, would likewise be included in the reported totals in the future.
- In some years, imports and exports may be greater than consumption because the excess is being used to increase chemical or equipment stockpiles as discussed above; in other years, the opposite may hold true. Similarly, relocation of manufacturing facilities or recovery from the recessions and the COVID-19 pandemic could contribute to variability in imports or exports. The Vintaging Model does not reflect the dynamic nature of reported HFC consumption, with significant differences seen in each year. Whereas the Vintaging Model projects demand increasing or decreasing slowly, with some annual fluctuations, actual consumption for specific chemicals or equipment may vary over time and could even switch from positive to negative (indicating more chemical exported, transformed, and destroyed than produced and imported in a given year). Furthermore, consumption as calculated in the Vintaging Model is a function of demand not met by recovery of HFCs from equipment that is being disposed. If, in any given year, a significant number of units are disposed, there will be a large amount of additional recovery in that year that can cause an unexpected and not modeled decrease in demand and thus a decrease in consumption. On the other hand, if market, economic, or other factors cause less than expected disposal or recovery, actual supply would decrease, and hence consumption would increase to meet that demand not satisfied by recovered quantities, increasing the GHGRP amounts. EPA has published reclamation data, which would encompass a portion of the refrigerant recovered annually. This data could be reviewed to determine if it can be used to improve the modeling of these factors.
- The Vintaging Model is used to estimate the emissions that occur in the United States. As such, all equipment or products that contain ODSs or alternatives, including saturated HFCs, are assumed to consume and emit chemicals equally as like equipment or products originally produced in the United States. The GHGRP data from Subpart OO (industrial greenhouse gas suppliers) includes HFCs produced or imported and used to fill or manufacture products that are then exported from the United States. The Vintaging Model estimates of demand and supply are not meant to incorporate such chemical. Likewise, chemicals may be used outside the United States to create products or charge equipment that is then imported to and used in the United States. The Vintaging Model estimates of demand and supply are meant to capture this chemical, as it will lead to emissions inside the United States. The GHGRP data from Subpart QQ (supply of HFCs in products) accounts for most of these differences; however, the scope of Subpart QQ does not cover all such equipment or products and the chemical contained therein. Depending on whether the United States is a net importer or net exporter of such chemical, this factor may account for some of the difference shown above or might lead to a further discrepancy.

- The Vintaging Model does not include every saturated HFC that is reported to EPA's GHGRP. Potential improvements in the modeling could include investigation of what sources use and emit such chemicals—which are not necessarily used as ODS substitutes—and to add them into the Inventory. However, the additional reported HFCs represent a small fraction of total HFC use for this source category, both in GWP-weighted and unweighted terms, and as such, it is not expected that the additional HFCs reported to EPA are a major driver for the difference between the two sets of estimates. To the extent lower-GWP isomers were used in lieu of the modeled chemicals (e.g., HFC-134 instead of HFC-134a), lower CO_2 Eq. amounts in the GHGRP data compared to the modeled estimates would be expected.

One factor, however, would only lead to modeled estimates to be even higher than the estimates shown and hence for some years possibly higher than GHGRP data:

- Saturated HFCs are also known to be used and emitted from other sources, such as electronics manufacturing and magnesium production and processing. The Vintaging Model estimates here do not include the amount of HFCs used for these applications, but rather only the amount used for applications that traditionally were served by ODSs. Nonetheless, EPA expects the quantities of HFCs used for electronics and magnesium production to be very small compared to the ODS substitute use for the years analyzed. EPA estimates that electronics and magnesium production respectively consumed 0.3 MMT CO_2 Eq. and 0.05 MMT CO_2 Eq. of HFCs in 2020, which is much less than the ODS substitute sector in that year (166.1 MMT CO_2 Eq.) (U.S. EPA 2022a).

Comparison of Emissions Derived from Atmospheric Measurements to Modeled Emissions

As discussed in Section 4.24 of the Inventory report, EPA conducted another quality assurance check of the Vintaging Model estimated emissions. In this analysis, we compared the emissions of HFC-32, HFC-125, HFC-134a and HFC-143a as estimated by the bottom-up model to two sets of top-down estimates derived by the National Oceanic and Atmospheric Administration (NOAA) using inverse analysis methods using atmospheric measurements at numerous sites through much of North America.

Comparison of Results

Table A-124 lists the emissions from EPA's Vintaging Model and from NOAA derived for the contiguous United States from atmospheric measurements as described in Hu et al. (2017) and updated in their recent studies (Hu et al. 2022; Montzka et al. 2023). NOAA's estimates were derived from inverse modeling driven by two different meteorological inputs, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model and the Stochastic Time-Inverted Lagrangian Transport (STILT) model and are available on NOAA's U.S. Potent GHG Tracker website (Hu et al. 2023). Figure A-8 below shows the derived emissions graphically for HFC-32, HFC-125, HFC-134a, and HFC-143a. The full time series of 2008 through 2020 is not yet available for each of the four HFCs from both models. In Hu et al. (2017), uncertainty results were provided that represented one standard deviation of the spread of several inversion calculations, including uncertainties associated with the different meteorological inputs. Uncertainty results representing one standard deviation derived from individual meteorological input data were also provided in Hu et al. (2022) and Montzka et al. (2023). These are provided in the tables and figures below. There is also uncertainty in the EPA results. Overall, the uncertainty in EPA's total Substitution of ODS emissions (i.e., total CO_2-equivalent emissions from HFCs, PFCs, and CO_2 used as alternatives to ODS) range from -4.2 percent to 14.7 percent (95 percent confidence interval), as shown in Section 4.24. The nature of the model and the uncertainty analysis, however, does not allow EPA to provide specific uncertainties to each species and hence comparisons below are to the EPA estimates without consideration of the uncertainty involved in those estimates.

Table A-124: U.S. Emissions of HFC-32, HFC-125, HFC-134a and HFC-143a (Gg)

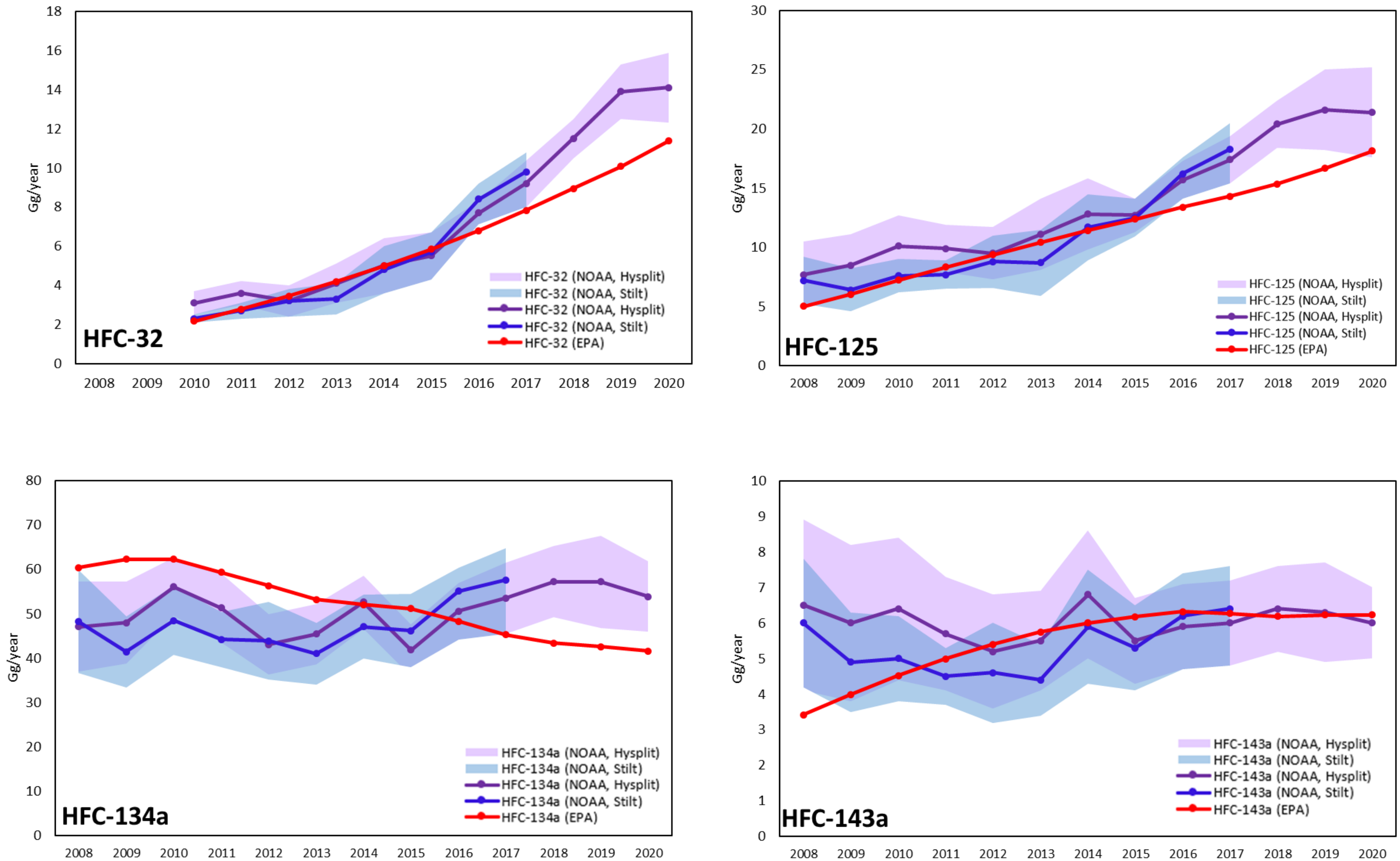
Gas	HFC-32[a]			HFC-125			HFC-134a			HFC-143a		
Source	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)	EPA	NOAA (HYSPLIT)	NOAA (STILT)
2008	1.2	NA	NA	5.0	7.7±1.4	7.2±1.0	60.4	47.1±5.1	48.2±5.8	3.4	6.5±1.2	6.0±0.9
2009	1.6	NA	NA	6.0	8.5±1.3	6.4±0.9	62.3	48.0±4.6	41.4±4.0	4.0	6.0±1.1	4.9±0.7
2010	2.2	3.1±0.3	2.3±0.1	7.2	10.1±1.3	7.6±0.7	62.3	56.1±3.3	48.5±3.9	4.5	6.4±1.0	5.0±0.6
2011	2.8	3.6±0.3	2.7±0.2	8.3	9.9±1.0	7.7±0.6	59.3	51.3±3.9	44.2±3.1	5.0	5.7±0.8	4.5±0.4
2012	3.4	3.2±0.4	3.2±0.3	9.4	9.5±1.1	8.8±1.1	56.3	43.1±3.4	43.9±4.4	5.4	5.2±0.8	4.6±0.7
2013	4.2	4.1±0.5	3.3±0.4	10.4	11.1±1.5	8.7±1.4	53.2	45.4±3.4	41.0±3.5	5.7	5.5±0.7	4.4±0.5
2014	5.0	5.0±0.7	4.8±0.6	11.4	12.8±1.5	11.7±1.4	52.1	52.6±3.0	47.1±3.6	6.0	6.8±0.9	5.9±0.8
2015	5.8	5.5±0.6	5.7±0.5	12.4	12.7±0.7	12.5±0.8	51.2	41.8±2.9	46.2±4.1	6.2	5.5±0.6	5.3±0.6
2016	6.8	7.7±0.3	8.4±0.4	13.4	15.7±0.8	16.2±0.7	48.3	50.6±3.2	55.1±2.6	6.3	5.9±0.6	6.2±0.6
2017	7.8	9.2±0.6	9.8±0.5	14.3	17.4±1.0	18.3±1.1	45.3	53.5±4.0	57.6±3.6	6.3	6.0±0.6	6.4±0.6
2018	8.9	11.5±0.5	NA	15.3	20.4±1.0	NA	43.4	57.2±4.0	NA	6.2	6.4±0.6	NA
2019	10.1	13.9±0.7	NA	16.7	21.6±1.7	NA	42.6	57.2±5.2	NA	6.2	6.3±0.7	NA
2020	11.4	14.1±0.9	NA	18.2	21.4±1.9	NA	41.6	53.9±4.0	NA	6.2	6.0±0.5	NA

[a] Estimates for HFC-32 during 2008 and 2009 were not available from NOAA's atmospheric-based estimates (Hu et al. 2022; Hu et al. 2023; Montzka et al. 2023) and are excluded from this analysis. For information on emissions of HFC-32 during those years, the reader is referred to Hu et al. (2017)

Note: NOAA uncertainty values represent one standard deviation

NA is not available

Figure A-8: U.S. Emissions of HFC-32, HFC-125, HFC-134a, and HFC-143a



Blue and purple shading represent the 2 s.d. uncertainty range around the NOAA estimates using the STILT and HYSPLIT atmospheric models, respectively.

As shown, modeled estimates of HFC-32 were comparable with those derived from atmospheric measurements for the years 2010 to 2015, with only small differences (in Gg y^{-1}), but estimates differed from both the atmospheric-based estimates by more than two standard deviations (2 s.d.) in 2016 through 2020.[72] Both atmosphere-derived and inventory-modeled estimates show a similar trend of increasing emissions, but inventory-modeled estimates of HFC-32 increase slower than the atmospheric-based estimates from both the HYSPLIT and STILT models after 2015 and through 2019. Inventory-modeled emissions of HFC-134a have a tendency of being above the atmosphere-based estimates before 2014, but below after 2017 and through 2020. While the mean values from NOAA show year-to-year variability, the data with uncertain ranges may suggest a slight upward trend in HFC-134a emissions after 2015, unlike the inventory-modeled result which shows a downward trend; however, confidence in the trend derived from atmospheric measurements is limited because the magnitude of uncertainties are similar to the overall change and because increasing or decreasing trends of the mean values do not persist for more than four years. Inventory-modeled estimates for HFC-125 were consistently within 2 s.d. uncertainty of atmosphere-based estimates through 2015 but were smaller by more than 2 s.d. between 2016 and 2019. Both the inventory-modeled and atmospheric-based results suggest an upward trend for HFC-125 emissions. As with HFC-32, the estimates derived from atmospheric measurement increase more quickly than the inventory-modeled estimates after 2015. HFC-143a emissions calculated for the inventory were comparable to the mean atmospheric-based estimates with either the HYSPLIT or STILT model, but uncertainties ranges were slightly higher than for the other gases on a relative basis. Considering these uncertainty ranges, HFC-143a inventory-modeled values agree within 2 s.d. with both sets of NOAA values for all years except 2008, where the modeled estimates are lower than 2 s.d. compared to both sets of NOAA results. Inventory-modeled estimates for HFC-143a trend upward until 2015 and then remain relatively constant between 2015 and 2020. In the NOAA estimates, no secular trend is discernable from 2008 to 2020 for HFC-143a considering the annual mean uncertainties of approximately 13 percent; however, the mean values from the NOAA estimates are also relatively constant between 2016 and 2020.

Table A-125 shows the differences in the emissions results from EPA's Vintaging Model and the mean results from NOAA (averaged across the HYSPLIT and STILT model results, as applicable) for those years where modeled estimates were not within the given 1 s.d. uncertainty range in the NOAA results. Years when modeled estimates are within the uncertainty range reported by NOAA are not shown as those differences are assumed to be insignificant. We also look at the 2 s.d. range in the NOAA results, which for these results are simply two times the 1 s.d. uncertainty magnitudes. Emissions differences found to be outside that range are shown in bold in the table, indicating more attention may be warranted to understand these results. As shown in the Uncertainty discussion under Section 4.24, the inventory-based estimates from EPA only provide an overall uncertainty estimate for all emissions, not by gas; therefore, it is likely that Table A-125 overstates the actual differences. Comparing the results from the individual gases shows changes over time, for example:

a. For HFC-32, while the differences for 2016 to 2020 were not within the 1 s.d. uncertainty ranges for NOAA estimates, the differences averaged only -2.4 Gg per year during these five years. Results were within the 1 s.d. uncertainty range of the NOAA estimates for the earlier years of 2010 to 2015. For 2016 to 2020, the modeled results were an average of 21 percent below the mean of the atmospherically derived values.

b. For HFC-125, the differences were within the uncertainty range of the NOAA estimates for 2009 to 2015. The results in 2008 and 2020 were within the twice uncertainty range. For 2016 to 2019, inventory-modeled results 21 percent below the mean of the atmospherically derived values, on average.

c. For HFC-134a, the differences ranged from 18 percent below the 1 s.d. uncertainty range in 2018 and 2019 to 18 percent above the 1 s.d. uncertainty range in 2009. With the exception of 2014 and 2016, all differences were greater than the NOAA estimates at the 1 s.d. uncertainty range. Furthermore, of these differences outside 1 s.d. uncertainty, only the 2010 and 2015 estimates were within the NOAA estimates at twice the uncertainty.

d. For HFC-143a, the inventory-modeled results were within the 1 s.d. uncertainty range in 2010 through 2014, and again in 2016 to 2020. The 2009 and 2015 model results were within the twice uncertainty range. The most significant difference was in 2008, where the modeled result was below the NOAA estimates by 46

[72] To determine if EPA results agreed with the 1 s.d. range of uncertainty in the atmosphere-based estimates from NOAA, we compared to the range represented by the lowest mean value less one s.d. and the highest mean value plus one s.d., even if these two values came from different atmospheric models (i.e., HYSPLIT and STILT). A similar process was used for 2 s.d. comparisons.

percent compared to the mean of the atmospherically derived values, or 17% below the 2 s.d. uncertainty range.

Table A-125: Gigagram (Percentage) Differences between EPA and NOAA HFC Emission Estimates

Year	HFC-32[a]	HFC-125[a]	HFC-134a[a]	HFC-143a[a]
2008	NA	-2.45 (-33%)	**12.8 (26.8%)**	**-2.9 (-46%)**
2009	NA		**17.6 (39.4%)**	-1.5 (-27%)
2010			10.0 (19.1%)	
2011			**11.6 (24.2%)**	
2012			**12.8 (29.4%)**	
2013			**10.0 (23.1%)**	
2014				
2015			7.20 (16.4%)	0.8 (15%)
2016	**-1.3 (-16%)**	**-2.55 (-16.0%)**		
2017	**-1.7 (-18%)**	**-3.55 (-19.9%)**	**-10.3 (-18.5%)**	
2018	**-2.6 (-23%)**	**-5.10 (-25.0%)**	**-13.8 (-24.1%)**	
2019	**-3.80 (-27.3%)**	**-4.90 (-22.7%)**	**-14.6 (-25.5%)**	
2020	**-2.70 (-19.1%)**	-3.20 (-15.0%)	**-12.3 (-22.8%)**	
Average[b]	-1.1 (-9.7%)	-2.0 (-14%)	2.2 (6.4%)	-0.28 (-4.3%)
Average of Absolute Values[b]	1.1 (12%)	2.1 (15%)	11 (22%)	0.68 (12%)

[a]The values for 1 s.d. and 2 s.d. were derived separately for the HYSPLIT and STILT values plus or minus the respective uncertainties for each HFC and year. These maximum and minimum values from these values were then compared to the EPA estimates (with unknown uncertainty) for each year to see if the inventory-modeled emissions are within 1 s.d. or twice the 1 s.d. (i.e., 2 s.d.) of the atmospherically-derived emissions.

[b]Averages are for all years 2008-2020, except HFC-32, where averages are for all years 2010-2020.

Notes: Differences smaller than the 1 s.d. uncertainty on the annual NOAA-based estimates are not shown. Differences greater than 2 s.d. shown in bold font. Uncertainties associated with the Vintaging model have not been estimated by compound and year so are not included and could imply fewer differences than shown in this table.

Discussion and Areas for Additional Research

The following are potential contributing factors to the variation between the results and possible ways these could inform changes to the model that would reduce the differences seen.

- When examining the NOAA estimates and uncertainties at the 2 s.d., only a few differences from EPA model results are identified. In general, the uncertainties in the NOAA estimates are primarily driven by the frequency and spatial density of the atmospheric sampling, and the transport model simulations. There is also inherent uncertainty in the consistency of the setup of each gas chromatography measurement taken–e.g., variation in calibration, impurities in the carrier gas used, among others (Barwick 1999); however, that uncertainty is likely less than 1 percent for HFC-125, HFC-134a, and HFC-143a, and less than 5 percent for HFC-32. For HFC-134a and HFC-143a, there is no consistent upward or downward trend in the atmosphere-derived emissions through the entire time period, as overall changes are similar to or smaller than the associated uncertainties. For HFC-134a, however, the atmospheric data are inconsistent with the downward emission trends derived from the activity-based modeling. In the case of HFC-32 and HFC-125, an increasing trend is seen in both the atmosphere and inventory-based estimates, albeit with slightly different rates throughout the entire time interval. As discussed above, there is also uncertainty in the EPA estimates. Although these are not available by individual species, these uncertainties may also explain some of the differences seen. See Section 4.24 for a discussion of planned improvements to the modeled estimates that could address some of these discrepancies.

- A thorough discussion of the uncertainties and influencing factors in the NOAA estimates is provided in Hu et al. (2017). That study notes that emissions estimated from inverse modeling of atmospheric data can depend on assumed prior emission distributions and magnitudes, and accordingly the quoted uncertainties on the NOAA results have been augmented to include these influences. In general, in a region where there are fewer atmospheric observations, the NOAA results will inherently tend towards the prior and be impacted by neighboring regions and populations (NOAA/EPA 2020). If the emissions or emissions per person (depending on which prior is used) are significantly different in these areas compared to the nearby areas, derived emissions for these regions can be biased.
- Uncertainty in atmospheric emission estimates is influenced by the number of NOAA's atmospheric sampling sites, which changed between 2008 and 2014. Uncertainties were greatest in 2008 and 2009—i.e., early on in the North American sampling program (Hu et al. 2017)—due to the fewer number of tower sites and available measurements in those startup years. This may help explain why none of the EPA results for 2008 were within one standard deviation of the NOAA estimates, although HFC-32 and HFC-125 were within twice the uncertainty range. Also, changes in the number and location of measurement sites within the air sampling network, which contains over 25 sites, can lead to biases in the year-to-year emission estimates. Uncertainties related to network changes were estimated with separate inversion runs in which sites were removed from the analysis and differences ascertained in Hu et al. (2017), but were not included in NOAA's current estimates.
- The Vintaging Model estimated emissions for the entire United States, including all 50 states and territories. Conversely, NOAA limits scope to the contiguous 48 states and the District of Columbia (NOAA/EPA 2020). In that regard, EPA would expect the model to estimate slightly higher emissions than those reported by NOAA, by roughly 2 percent based on population data (U.S. Census 2021). Activity data for Hawaii, Alaska and territories could be researched and, if they were available, adjustments could be made to allow for a more direct comparison to the estimates supplied by NOAA.
- For HFC-125, the EPA model suggests lower emissions, outside the 2 s.d. uncertainty range, for 2016 through 2019 relative to the average of the atmosphere-derived estimates. For HFC-143a, the EPA model suggests lower emissions in 2008, but within 2 s.d. of the atmosphere-derived estimates for all other years. Further research into the refrigeration market might improve the agreement in the estimates for these two gases. As stated in the Introduction to Section 4.24, emissions from the large retail food end-use (e.g., supermarkets) were estimated to have the second highest contribution to the overall HFC emissions. Research in this industry on the shift away from blends such as R-404A (which contains both HFC-125 and HFC-143a) or success in lowering emission rates could be used to improve the bottom-up model.
- After a number of years of good consistency in emission estimates and trends for both HFC-32 and HFC-125, deviations grew beginning in 2016, with the atmosphere-derived estimates increasingly larger than the modeled estimates. The modeled emissions of HFC-32 agreed well with the atmospheric inversion results in absolute terms (within 2 s.d.) through 2015, with atmosphere-derived estimates higher by slightly more than 2 s.d. in 2016 and 2017, and higher deviations in 2018 through 2020 compared to the modeled estimates, although both data sets show the same year-to-year increasing trend. Slightly lower model results might imply that the actual emissions from R-410A (a 50:50 by mass ratio of HFC-32 and HFC-125) equipment were slightly higher than modeled. Lower model results could also imply that the model assumed a higher than actual use of "dry-charge" residential AC equipment in lieu of R-410A. EPA investigated the amount of dry-charge unitary air-conditioning imports by reviewing dry-shipped condensing unit estimates from air-conditioner manufacturer surveys to determine whether the Vintaging Model may be overestimating the number of dry-charged units. EPA determined that there were only small differences between survey results and Vintaging Model estimates for dry-shipped condensing unit shipments, which indicates that the way the Vintaging Model currently addresses dry-charged units is not the cause for the differences between Vintaging Model and NOAA emission estimates for HFC-32 and HFC-125. Therefore, updates to the Vintaging Model were not implemented (EPA 2022b). This might imply that the assumption of a consistent average emission rate during operation, which is used for all products in the Inventory, is not accurately representing these gases, in particular from the stationary air conditioning sector. As noted earlier in the GHGRP comparison, the supply reported under the GHGRP in these later years is also higher than predicted by the Vintaging Model. This might imply that these differences are driven in part by an underestimate of the emissions from existing equipment or recovery from discarded equipment, which would result in the Vintaging Model estimating lower emissions and lower supply, respectively, which could explain such differences.

- The modeled inventory results for HFC-134a are complicated by an assumed decrease in emissions from motor vehicle air conditioning (due to previous shifts towards lower charge sizes and emission rates, as well as the on-going transition to HFO-1234yf) with concurrent increases in other sectors using HFC-134a, such as for foam blowing given the HCFC bans in foam blowing and other uses. While the inter-annual changes in the NOAA mean values for this gas are small compared to the uncertainties, they show relatively consistent emissions over the time period, with a possible increase seen in later years. However, the NOAA atmosphere-based results do not appear to show a subsequent decrease apparent in the bottom-up inventory-based emission estimates after 2010. If the EPA model is underestimating the increased use in foam blowing and/or overestimating the decrease in emissions from the motor vehicle air conditioning end-use, that might account for some of the differences seen. Further, other uses of HFC-134a not included in the model could account for these differences. For instance, although the *new* vehicle market has been transitioning out of HFC-134a as modeled, it is not clear whether the *existing* fleet of vehicles has an increasing rate of HFC-134a emissions, either from those older vehicles designed for HFC-134a or possibly the illegal use of HFC-134a in vehicle air conditioners designed for HFO-1234yf.
- There are data limitations inherent in the bottom-up model. As described above, emissions are estimated by applying assumed emission profiles to multiple end-uses, each of which can have thousands or millions of individual uses in the United States. In some cases where equipment stocks or sales are unknown, estimates are made using an average growth rate and by taking the most recent year where the starting stock or sales of equipment is known, then accounting for equipment lifetimes, and subsequently estimating the amount of equipment in future and/or preceding years where a value was not available. Such assumptions are evident in the approximately constant slope of the EPA emission estimates for HFC-32, HFC-125, and HFC-143a, compared to the more varying nature found in NOAA's mean results. Future work could look at whether these variations might be consistent with other factors that influence emissions, such as equipment installations, sales, retirements, or pandemic-related supply issues, which could vary from year to year.

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Data are also taken from various government sources, including rulemaking analyses from the U.S. Department of Energy and from the Motor Vehicle Emission Simulator (MOVES) model from EPA's Office of Transportation and Air Quality.