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 emission factors and 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-87 through Table A-92.

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 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, February 2017* (EIA 2017a). 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 2017b) and Jacobs (2010).[38] Fuel consumption for the industrial sector was adjusted to subtract out construction and agricultural use, which is reported under mobile sources.[39] Construction and agricultural fuel use was obtained from EPA (2016c) and FHWA (1996 through 2016). 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-87 provides annual energy consumption data for the years 1990 through 2015.

In this Inventory, the emission estimation methodology for the electric power sector used a Tier 2 methodology as fuel consumption by technology-type for the electricity generation sector was obtained from the Acid Rain Program Dataset (EPA 2016a). This combustion technology-and fuel-use data was available by facility from 1996 to 2015. Since there was a difference between the EPA (2016a) and EIA (2017a) total energy consumption estimates, the remainder between total energy consumption using EPA (2016a) and EIA (2017a) was apportioned to each combustion technology type and fuel combination using a ratio of energy consumption by technology type from 1996 to 2015.

Energy consumption estimates were not available from 1990 to 1995 in the EPA (2016a) dataset, and as a result, consumption was calculated using total electric power consumption from EIA (2017a) and the ratio of combustion technology and fuel types from EPA 2016a. The consumption estimates from 1990 to 1995 were estimated by applying the 1996 consumption ratio by combustion technology type to the total EIA 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 (consistent across sectors) were also assumed for U.S. Territories. The CH_4 emission factors by fuel type for U.S. Territories were estimated based on the emission factor for the primary sector in which each fuel was combusted. Table A-88 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

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[38] 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.

[39] 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.

Tier 2 IPCC emission factors shown in Table A-89. Emission factors were used from the *2006 IPCC Guidelines* as the factors presented in these IPCC guidelines were taken directly from U.S. Environmental Protection Agency (EPA) publications on emissions rates for combustion sources.

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 2016b), 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, etc.) 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 (2016b) is represented by the following equation:

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

where,

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

The 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 the IPCC (IPCC 2006).

Table A-87: Fuel Consumption by Stationary Combustion for Calculating CH_4 and N_2O Emissions (TBtu)

Fuel/End-Use Sector	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Coal	**19,610**	**20,888**	**23,080**	**22,391**	**22,343**	**22,576**	**22,636**	**22,949**	**22,458**	**22,710**	**22,225**	**19,670**	**20,697**	**18,989**	**16,715**	**17,393**	**17,366**	**15,110**
Residential	31	17	11	12	12	12	11	8	6	8	0	0	0	0	0	0	0	0
Commercial	124	117	92	97	90	82	103	97	65	70	81	73	70	62	44	41	40	31
Industrial	1,640	1,527	1,349	1,358	1,244	1,249	1,262	1,219	1,189	1,131	1,081	877	952	866	782	800	799	696
Electric Power	17,807	19,217	21,618	20,920	20,987	21,199	21,228	21,591	21,161	21,465	21,026	18,682	19,639	18,024	15,852	16,521	16,483	14,339
U.S. Territories	7	10	10	4	11	34	32	33	37	37	37	37	37	37	37	31	44	44
Petroleum	**6,162**	**5,656**	**6,144**	**6,628**	**6,006**	**6,391**	**6,559**	**6,483**	**6,196**	**6,091**	**5,240**	**4,665**	**4,742**	**4,410**	**4,066**	**4,198**	**3,942**	**4,527**
Residential	1,375	1,262	1,429	1,465	1,361	1,468	1,468	1,368	1,202	1,220	1,202	1,138	1,116	1,039	847	936	989	982
Commercial	869	695	695	720	647	765	764	716	678	680	635	669	643	619	506	540	524	960
Industrial	2,750	2,380	2,283	2,535	2,371	2,496	2,669	2,776	3,111	2,996	2,427	1,949	2,054	1,988	1,924	2,038	1,804	1,944
Electric Power	797	860	1,269	1,279	1,074	1,043	1,007	1,004	590	618	488	383	412	266	273	180	153	169
U.S. Territories	370	459	468	629	552	618	652	620	616	577	488	526	516	497	517	504	472	472
Natural Gas	**17,266**	**19,337**	**20,919**	**20,224**	**20,908**	**20,894**	**21,152**	**20,938**	**20,626**	**22,019**	**22,286**	**21,952**	**22,912**	**23,115**	**24,137**	**24,949**	**25,741**	**26,460**
Residential	4,491	4,954	5,105	4,889	4,995	5,209	4,981	4,946	4,476	4,835	5,010	4,883	4,878	4,805	4,242	5,023	5,242	4,769
Commercial	2,682	3,096	3,252	3,097	3,212	3,261	3,201	3,073	2,902	3,085	3,228	3,187	3,165	3,216	2,960	3,380	3,572	3,309
Industrial	7,716	8,723	8,656	7,949	8,086	7,845	7,914	7,330	7,323	7,521	7,571	7,125	7,683	7,873	8,203	8,525	8,837	8,820
Electric Power	2,376	2,564	3,894	4,266	4,591	4,551	5,032	5,565	5,899	6,550	6,447	6,730	7,159	7,194	8,683	7,964	8,033	9,505
U.S. Territories	0	0	13	23	23	27	25	24	26	27	29	27	28	27	49	57	57	57
Wood	**2,216**	**2,370**	**2,262**	**2,006**	**1,995**	**2,002**	**2,121**	**2,137**	**2,099**	**2,089**	**2,059**	**1,931**	**1,981**	**2,010**	**2,010**	**2,170**	**2,230**	**2,043**
Residential	580	520	420	370	380	400	410	430	380	420	470	500	440	450	420	580	580	432
Commercial	66	72	71	67	69	71	70	70	65	70	73	73	72	69	61	70	73	73
Industrial	1,442	1,652	1,636	1,443	1,396	1,363	1,476	1,452	1,472	1,413	1,339	1,178	1,273	1,309	1,339	1,312	1,325	1,295
Electric Power	129	125	134	126	150	167	165	185	182	186	177	180	196	182	190	207	251	244
U.S. Territories	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE	NE

NE (Not Estimated)

Note: Totals may not sum due to independent rounding.

Table A-88: 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
Electric Power	1	1.5
U.S. Territories	1	1.5
Petroleum		
Residential	10	0.6
Commercial	10	0.6
Industrial	3	0.6
Electric Power	3	0.6
U.S. Territories	5	0.6
Natural Gas		
Residential	5	0.1
Commercial	5	0.1
Industrial	1	0.1
Electric Power	4	0.1
U.S. Territories	1	0.1
Wood		
Residential	300	4.0
Commercial	300	4.0
Industrial	30	4.0
Electric Power	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-89: 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	NA
Solid Fuels			
Pulverized Bituminous Combination Boilers	Dry Bottom, wall fired	0.7	0.5
	Dry Bottom, tangentially fired	0.7	1.4
	Wet bottom	0.9	1.4
Bituminous Spreader Stoker Boilers	With and without re-injection	1	0.7
Bituminous Fluidized Bed Combustor	Circulating Bed	1	61
	Bubbling Bed	1	61
Bituminous Cyclone Furnace		0.2	0.6
Lignite Atmospheric Fluidized Bed		NA	71
Natural Gas			
Boilers		1	1
Gas-Fired Gas Turbines >3MW		1	1
Large Dual-Fuel Engines		258	NA
Combined Cycle		4	3
Peat			
Peat Fluidized Bed Combustion	Circulating Bed	3	7
	Bubbling Bed	3	3
Biomass			
Wood/Wood Waste Boilers		11	7
Wood Recovery Boilers		1	1

NA (Not Applicable)

[a] Ibid.

Table A-90: NO_x Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**6,045**	**5,792**	**4,829**	**4,454**	**4,265**	**3,930**	**3,595**	**3,434**	**3,249**	**3,064**	**2,847**	**2,552**	**2,226**	**1,893**	**1,779**	**1,666**	**1,552**	**1,321**
Coal	5,119	5,061	4,130	3,802	3,634	3,349	3,063	2,926	2,768	2,611	2,426	2,175	1,896	1,613	1,516	1,419	1,323	1,126
Fuel Oil	200	87	147	149	142	131	120	114	108	102	95	85	74	63	59	55	52	44
Natural gas	513	510	376	325	310	286	262	250	236	223	207	186	162	138	129	121	113	96
Wood	NA	NA	36	37	36	33	30	29	27	26	24	21	19	16	15	14	13	11
Other Fuels[a]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Internal Combustion	213	134	140	140	143	132	121	115	109	103	95	86	75	63	60	56	52	44
Industrial	**2,559**	**2,650**	**2,278**	**2,296**	**1,699**	**1,641**	**1,580**	**1,515**	**1,400**	**1,285**	**1,165**	**1,126**	**1,087**	**1,048**	**1,028**	**1,009**	**990**	**990**
Coal	530	541	484	518	384	371	357	342	316	290	263	254	245	237	232	228	223	223
Fuel Oil	240	224	166	153	114	110	106	101	94	86	78	75	73	70	69	67	66	66
Natural gas	877	999	710	711	526	508	489	469	433	398	361	348	336	324	318	312	306	306
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	119	111	109	116	86	83	80	76	70	65	59	57	55	53	52	51	50	50
Internal Combustion	792	774	809	798	591	570	549	527	486	446	405	391	378	364	357	351	344	344
Commercial	**671**	**607**	**507**	**428**	**438**	**408**	**378**	**490**	**471**	**452**	**433**	**445**	**456**	**548**	**534**	**519**	**443**	**443**
Coal	36	35	21	21	19	19	19	19	18	17	15	15	15	15	14	14	14	14
Fuel Oil	88	94	52	52	50	49	49	49	46	43	39	39	38	37	37	36	36	36
Natural gas	181	210	161	165	157	156	156	155	145	135	124	122	120	118	116	115	113	113
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	366	269	273	189	212	183	154	267	263	258	254	269	284	378	366	353	280	280
Residential	**749**	**813**	**439**	**446**	**422**	**422**	**420**	**418**	**390**	**363**	**335**	**329**	**324**	**318**	**314**	**310**	**306**	**306**
Coal[b]	NA	NA	NA	NA	NA	NA	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	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	42	44	21	22	21	21	21	20	19	18	16	16	16	16	15	15	15	15
Other Fuels[a]	707	769	417	424	402	401	400	398	371	345	318	313	308	302	298	295	291	291
Total	**10,023**	**9,862**	**8,053**	**7,623**	**6,825**	**6,401**	**5,973**	**5,858**	**5,511**	**5,163**	**4,780**	**4,452**	**4,092**	**3,807**	**3,655**	**3,504**	**3,291**	**3,061**

NA (Not Applicable)

[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2016b).

[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2016b).

Note: Totals may not sum due to independent rounding.

Table A-91: CO Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**329**	**337**	**439**	**439**	**594**	**591**	**586**	**582**	**609**	**637**	**660**	**676**	**693**	**710**	**690**	**669**	**649**	**649**
Coal	213	227	221	220	298	296	294	292	305	319	330	339	347	356	346	335	325	325
Fuel Oil	18	9	27	28	38	37	37	37	38	40	42	43	44	45	44	42	41	41
Natural gas	46	49	96	92	125	124	123	122	128	134	138	142	145	149	145	140	136	136
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	31	32	44	43	43	43	45	47	48	50	51	52	51	49	48	48
Internal Combustion	52	52	63	67	91	90	90	89	93	97	101	103	106	108	105	102	99	99
Industrial	**797**	**958**	**1,106**	**1,137**	**1,150**	**1,116**	**1,081**	**1,045**	**968**	**892**	**815**	**834**	**853**	**872**	**871**	**869**	**868**	**868**
Coal	95	88	118	125	127	123	119	115	107	98	90	92	94	96	96	96	96	96

Fuel Oil	67	64	48	45	46	44	43	42	39	35	32	33	34	35	35	35	35	35
Natural gas	205	313	355	366	370	359	348	336	312	287	262	268	274	281	280	280	279	279
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	253	270	300	321	325	316	306	295	274	252	230	236	241	247	246	246	245	245
Internal Combustion	177	222	285	279	282	274	266	257	238	219	200	205	209	214	214	213	213	213
Commercial	**205**	**211**	**151**	**154**	**177**	**173**	**169**	**166**	**156**	**146**	**137**	**138**	**140**	**142**	**135**	**129**	**122**	**122**
Coal	13	14	14	13	15	15	15	14	14	13	12	12	12	12	12	11	11	11
Fuel Oil	16	17	17	17	20	19	19	19	18	16	15	16	16	16	15	14	14	14
Natural gas	40	49	83	84	97	95	93	91	86	80	75	76	77	78	74	71	67	67
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	136	132	36	38	44	43	42	41	39	37	34	35	35	35	34	32	30	30
Residential	**3,668**	**3,877**	**2,644**	**2,648**	**3,044**	**2,982**	**2,919**	**2,856**	**2,690**	**2,524**	**2,357**	**2,387**	**2,416**	**2,446**	**2,331**	**2,217**	**2,103**	**2,103**
Coal[b]	NA	NA	NA	NA	NA	NA	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	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	3,430	3,629	2,416	2,424	2,787	2,730	2,673	2,615	2,463	2,310	2,158	2,185	2,212	2,239	2,134	2,030	1,925	1,925
Other Fuels[a]	238	248	228	224	257	252	247	241	227	213	199	202	204	207	197	187	178	178
Total	**5,000**	**5,383**	**4,340**	**4,377**	**4,965**	**4,862**	**4,756**	**4,648**	**4,423**	**4,198**	**3,969**	**4,036**	**4,103**	**4,170**	**4,027**	**3,884**	**3,741**	**3,741**

NA (Not Applicable)
[a] Other Fuels include LPG, waste oil, coke oven gas, coke, and non-residential wood (EPA 2016b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the Other Fuels category (EPA 2016b).
Note: Totals may not sum due to independent rounding.

Table A-92: NMVOC Emissions from Stationary Combustion (kt)

Sector/Fuel Type	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Electric Power	**43**	**40**	**56**	**55**	**45**	**45**	**44**	**44**	**42**	**41**	**40**	**39**	**38**	**37**	**36**	**35**	**34**	**34**
Coal	24	26	27	26	21	21	21	21	20	20	19	18	18	18	17	17	16	16
Fuel Oil	5	2	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3	3
Natural Gas	2	2	12	12	10	10	10	10	9	9	9	9	8	8	8	8	8	8
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	NA	NA	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Internal Combustion	11	9	11	10	9	9	8	8	8	8	8	7	7	7	7	7	6	6
Industrial	**165**	**187**	**157**	**159**	**138**	**132**	**126**	**120**	**113**	**105**	**97**	**99**	**100**	**101**	**101**	**100**	**100**	**100**
Coal	7	5	9	10	9	9	8	8	7	7	6	6	7	7	7	7	7	7
Fuel Oil	11	11	9	9	7	7	7	6	6	6	5	5	5	5	5	5	5	5
Natural Gas	52	66	53	54	47	45	43	41	38	36	33	33	34	34	34	34	34	34
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	46	45	27	29	25	24	23	22	21	19	18	18	18	19	19	19	18	18
Internal Combustion	49	60	58	57	49	47	45	43	40	37	35	35	36	36	36	36	36	36
Commercial	**18**	**21**	**28**	**29**	**61**	**54**	**48**	**33**	**34**	**35**	**36**	**38**	**40**	**42**	**40**	**39**	**35**	**35**
Coal	1	1	1	1	1	1	1	1	1	+	+	+	+	+	+	+	+	+
Fuel Oil	3	3	4	4	6	5	3	2	2	2	2	2	2	2	2	2	1	1
Natural Gas	7	10	14	14	23	18	14	9	8	7	6	7	7	7	7	6	6	6
Wood	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Fuels[a]	8	8	9	10	31	30	30	22	24	26	28	29	31	32	31	30	27	27
Residential	**686**	**725**	**837**	**836**	**1,341**	**1,067**	**793**	**518**	**465**	**411**	**358**	**378**	**399**	**419**	**392**	**365**	**338**	**338**
Coal[b]	NA	NA	NA	NA	NA	NA	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	NA	NA	NA	NA	NA	NA
Natural Gas[b]	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Wood	651	688	809	809	1,297	1,032	767	502	450	398	346	366	386	406	380	353	327	327
Other Fuels[a]	35	37	27	27	43	35	26	17	15	13	12	12	13	14	13	12	11	11
Total	**912**	**973**	**1,077**	**1,080**	**1,585**	**1,298**	**1,011**	**716**	**654**	**593**	**531**	**553**	**576**	**599**	**569**	**539**	**507**	**507**

+ 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 2016b).
[b] Residential coal, fuel oil, and natural gas emissions are included in the "Other Fuels" category (EPA 2016b).
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 GHG 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, LPG, and electricity), CO_2 emissions were calculated based on transportation sector-wide fuel consumption estimates from the Energy Information Administration (EIA 2016a and EIA 2016b) 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 2017), while CO_2 emissions from other aircraft jet fuel consumption is determined using a top down approach.

Based on interagency discussions between EPA, EIA, and 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. Estimated motor gasoline and diesel consumption data for on-road vehicles by vehicle type come from FHWA's *Highway Statistics*, Table VM-1 (FHWA 1996 through 2016),[40] and are based on federal and state fuel tax records.[41] These fuel consumption estimates were then combined with estimates of fuel shares by vehicle type from DOE's Transportation Energy Data Book Annex Tables A.1 through A.6 (DOE 1993 through 2016) to develop an estimate of fuel consumption for each vehicle type (i.e., passenger cars, light-duty trucks, buses, medium- and heavy-duty trucks, motorcycles). The on-road gas and diesel fuel consumption estimates by vehicle type were then adjusted for each year so that the sum of gasoline and diesel fuel consumption across all on-road vehicle categories matched the fuel consumption estimates in *Highway Statistics'* Table MF-27 (FHWA 1996 through 2016). This resulted in a final "bottom up" estimate of motor gasoline and diesel fuel use by vehicle type, consistent with the FHWA total for on-road motor gasoline and diesel fuel use.

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 the *Fuel Oil and Kerosene Sales* (FOKS) report 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 considered to be 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) in order for the consumption of all sectors combined to equal the "top-down" EIA value.[42]

In the case of motor gasoline, estimates of fuel use by recreational boats come from the NONROAD component of EPA's MOVES2014a model (EPA 2016d), and these estimates, along with those from other sectors (e.g., commercial

[40] In 2011 FHWA changed its methods for estimating vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007–15 time period. This resulted in large changes in VMT and fuel consumption data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[41] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion*.

[42] Adjustments made to other end-use sector fuel allocations for 2015 were greater than prior inventory years due to the change FHWA made in its methods for estimating the share of motor gasoline used in on-highway and off-highway applications.

sector, industrial sector), were adjusted for years in which the bottom-up on-road motor gasoline consumption estimate exceeded the EIA estimate for total gasoline consumption of all sectors. Similarly, to ensure consistency with EIA's total diesel estimate for all sectors, the diesel consumption totals for the residential, commercial, and industrial sectors were adjusted proportionately.

Estimates of diesel fuel consumption from rail were taken from the Association of American Railroads (AAR 2008 through 2016) for Class I railroads, the American Public Transportation Association (APTA 2007 through 2016 and APTA 2006) and Gaffney (2007) for commuter rail, the Upper Great Plains Transportation Institute (Benson 2002 through 2004) and Whorton (2006 through 2013) for Class II and III railroads, and DOE's *Transportation Energy Data Book* (DOE 1993 through 2016) for passenger rail. Estimates of diesel from ships and boats were taken from EIA's *Fuel Oil and Kerosene Sales* (1991 through 2016).

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 (2017) for domestic and international commercial aircraft, and DESC (2016) 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 2017), 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 Chapter 3.2 Carbon Emitted from Non-Energy Uses of Fossil Fuels under the methodology for Estimating CO_2 from Fossil Combustion, and in Chapter 3.10 Wood Biomass and Ethanol Consumption, and were not apportioned to specific transportation sources. Consumption estimates for biofuels were calculated based on data from the Energy Information Administration (EIA 2016).

Table A-93 displays estimated fuel consumption by fuel and vehicle type. Table A-94 displays estimated energy consumption by fuel and vehicle type. The values in both of these 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 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 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 2015 and biodiesel fuel volumes were removed from diesel fuel consumption volumes for years 2001 through 2015, as there was negligible use of biodiesel as a diesel blending competent 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.

In order to remove the volume of biodiesel blended into diesel fuel, the refinery and blender net volume inputs of renewable diesel fuel sourced from EIA Petroleum Supply Annual (EIA 2016) *Table 18 - Refinery Net Input of Crude Oil and Petroleum Products* and *Table 20 - Blender Net Inputs of Petroleum Products* 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 fuel ethanol blended into motor gasoline, ethanol energy consumption data sourced from MER *Table 10.2b - Renewable Energy Consumption: Industrial and Transportation Sectors* (EIA 2016) were subtracted from the total EIA and FHWA transportation motor gasoline energy consumption estimates.

Total ethanol and biodiesel consumption estimates are shown separately in Table A-95.[43]

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[43] 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-95. 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-93 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-93: Fuel Consumption by Fuel and Vehicle Type (million gallons unless otherwise specified)

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013	2014	2015
Motor Gasoline[b,c,d]	**110,417**	**117,429**	**128,174**	**133,294**	**131,337**	**130,768**	**125,050**	**124,189**	**123,175**	**120,497**	**120,035**	**120,138**	**123,576**	**120,689**
Passenger Cars	69,763	67,496	72,320	73,856	70,791	88,607	84,714	83,918	83,230	82,621	82,464	82,463	84,497	82,448
Light-Duty Trucks	34,698	44,074	50,398	53,733	54,798	34,933	33,074	33,473	33,262	31,612	31,270	31,305	33,807	31,930
Motorcycles	194	199	208	182	210	472	487	468	411	401	459	437	436	412
Buses	39	41	43	41	41	79	81	84	82	80	92	95	104	101
Medium- and Heavy-Duty Trucks	4,350	4,044	4,065	3,922	3,961	5,164	5,220	4,798	4,773	4,383	4,358	4,455	4,604	4,428
Recreational Boats[e]	1,374	1,575	1,140	1,560	1,536	1,514	1,474	1,448	1,417	1,401	1,391	1,382	127	1,370
Distillate Fuel Oil (Diesel Fuel)[b,c]	**25,631**	**31,604**	**39,241**	**44,658**	**45,844**	**46,427**	**44,026**	**39,873**	**41,477**	**42,280**	**42,045**	**42,672**	**44,038**	**45,320**
Passenger Cars	771	765	356	414	403	403	363	354	367	399	401	399	408	423
Light-Duty Trucks	1,119	1,452	1,961	2,518	2,611	1,327	1,184	1,180	1,227	1,277	1,271	1,265	1,364	1,370
Buses	781	851	997	1,030	1,034	1,520	1,436	1,335	1,326	1,419	1,515	1,525	1,658	1,703
Medium- and Heavy-Duty Trucks	18,574	23,240	30,179	35,159	36,089	37,517	35,726	32,364	33,683	33,859	33,877	34,426	35,529	36,335
Recreational Boats	190	228	270	311	319	327	335	343	351	357	364	368	376	384
Ships and and Non-Recreational Boats	735	1,204	1,372	780	724	794	767	768	726	993	733	741	606	1,184
Rail[f]	3,461	3,863	4,106	4,446	4,664	4,538	4,215	3,529	3,798	3,975	3,884	3,948	4,096	3,922
Jet Fuel[g]	**19,186**	**17,991**	**20,002**	**19,420**	**18,695**	**18,407**	**17,749**	**15,809**	**15,537**	**15,036**	**14,705**	**15,088**	**15,237**	**16,176**
Commercial Aircraft	11,569	12,136	14,672	13,976	14,426	14,708	13,400	12,588	11,931	12,067	11,932	12,031	12,131	12,534
General Aviation Aircraft	4,034	3,361	3,163	3,583	2,590	2,043	2,682	1,787	2,322	1,895	1,659	2,033	1,676	2,257
Military Aircraft	3,583	2,495	2,167	1,860	1,679	1,656	1,667	1,434	1,283	1,074	1,114	1,024	1,430	1,384
Aviation Gasoline[g]	**374**	**329**	**302**	**294**	**278**	**263**	**235**	**221**	**225**	**225**	**209**	**186**	**181**	**176**
General Aviation Aircraft	374	329	302	294	278	263	235	221	225	225	209	186	181	176
Residual Fuel Oil[g, h]	**2,006**	**2,587**	**2,963**	**1,713**	**2,046**	**2,579**	**1,812**	**1,241**	**1,818**	**1,723**	**1,410**	**1,345**	**517**	**378**
Ships and Boats	2,006	2,587	2,963	1,713	2,046	2,579	1,812	1,241	1,818	1,723	1,410	1,345	517	378
Natural Gas[g] (trillion cubic feet)	**0.7**	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**	**0.7**	**0.7**	**0.7**	**0.7**	**0.8**	**0.9**	**0.7**	**0.7**
Passenger Cars	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Light-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium- and Heavy-Duty Trucks	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Buses	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Pipelines	0.7	0.7	0.7	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.7	0.7
LPG[g]	**265**	**206**	**138**	**327**	**320**	**257**	**468**	**331**	**348**	**404**	**442**	**524**	**560**	**574**
Passenger Cars	1	0.9	0.6	2	3	3	5	5	2	1	1	2	10	13
Light-Duty Trucks	36	28	19	64	82	61	85	83	82	77	44	58	120	168
Medium- and Heavy-Duty Trucks	211	163	110	239	195	150	279	187	206	279	342	395	365	332
Buses	17	13	9	23	40	43	98	56	59	47	54	69	65	60
Electricity[g, i]	**4,751**	**4,975**	**5,382**	**7,506**	**7,358**	**8,173**	**7,653**	**7,768**	**7,712**	**7,672**	**7,320**	**7,625**	**7,758**	**7,637**
Rail	4,751	4,975	5,382	7,506	7,358	8,173	7,653	7,768	7,712	7,672	7,320	7,625	7,758	7,637

+ Does not exceed 0.05 million cubic feet

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

[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.2 in the EIA Annual 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 VM-1 (FHWA 1996 through 2016) . Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.
[d] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion*.
[e] Fluctuations in recreational boat gasoline estimates reflect the use of this category to reconcile bottom-up values with EIA total gasoline estimates.
[f] Class II and Class II diesel consumption data for 2015 is not available yet, therefore 2013 data is used as a proxy.
[g] 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 (2016). 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 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in this year's Inventory and apply to the 1990–2015 time period.
[h] Fluctuations in reported fuel consumption may reflect data collection problems.
[i] Million kilowatt-hours

Table A-94: Energy Consumption by Fuel and Vehicle Type (Tbtu)

Fuel/Vehicle Type	1990	1995	2000	2005	2006	2007[a]	2008	2009	2010	2011	2012	2013	2014	2015
Motor Gasoline[b, c, d]	**13,810**	**14,687**	**16,031**	**16,671**	**16,426**	**16,259**	**15,548**	**15,441**	**15,315**	**14,982**	**14,924**	**14,937**	**15,365**	**15,006**
Passenger Cars	8,725	8,442	9,045	9,237	8,854	11,017	10,533	10,434	10,348	10,272	10,253	10,253	10,506	10,251
Light-Duty Trucks	4,340	5,512	6,303	6,720	6,854	4,343	4,112	4,162	4,136	3,930	3,888	3,892	4,203	3,970
Motorcycles	24	25	26	23	26	59	61	58	51	50	57	54	54	51
Buses	5	5	5	5	5	10	10	10	10	10	11	12	13	12
Medium- and Heavy-Duty Trucks	544	506	508	491	495	642	649	597	593	545	542	554	572	551
Recreational Boats[e]	172	197	143	195	192	188	183	180	176	174	173	172	16	170
Distillate Fuel Oil (Diesel Fuel)[c]	**3,555**	**4,379**	**5,437**	**6,186**	**6,334**	**6,394**	**6,059**	**5,488**	**5,706**	**5,814**	**5,780**	**5,866**	**6,053**	**6,229**
Passenger Cars	107	106	49	57	56	55	50	49	51	55	55	55	56	58
Light-Duty Trucks	155	201	272	349	361	183	163	162	169	176	175	174	187	188
Buses	108	118	138	143	143	209	198	184	182	195	208	210	228	234
Medium- and Heavy-Duty Trucks	2,576	3,220	4,181	4,870	4,986	5,167	4,917	4,455	4,634	4,656	4,657	4,733	4,884	4,994
Recreational Boats	26	32	37	43	44	45	46	47	48	49	50	51	52	53
Ships and Non-Recreational Boats	102	167	190	108	100	109	106	106	100	137	101	102	83	163
Rail[f]	480	535	569	616	644	625	580	486	523	547	534	543	563	539
Jet Fuel[g]	**2,590**	**2,429**	**2,700**	**2,622**	**2,524**	**2,485**	**2,396**	**2,134**	**2,097**	**2,030**	**1,985**	**2,037**	**2,057**	**2,184**
Commercial Aircraft	1,562	1,638	1,981	1,887	1,948	1,986	1,809	1,699	1,611	1,629	1,611	1,624	1,638	1,692
General Aviation Aircraft	545	454	427	484	350	276	362	241	314	256	224	274	226	305
Military Aircraft	484	337	293	251	227	224	225	194	173	145	150	138	193	187
Aviation Gasoline[g]	**45**	**40**	**36**	**35**	**33**	**32**	**28**	**27**	**27**	**27**	**25**	**22**	22	21
General Aviation Aircraft	45	40	36	35	33	32	28	27	27	27	25	22	22	21
Residual Fuel Oil[g, h]	**300**	**387**	**443**	**256**	**306**	**386**	**271**	**186**	**272**	**258**	**211**	**201**	**77**	**57**

Ships and Boats	300	387	443	256	306	386	271	186	272	258	211	201	77	57
Natural Gas[g]	**680**	**724**	**672**	**624**	**625**	**663**	**692**	**715**	**719**	**734**	**780**	**887**	**760**	**732**
Passenger Cars	+	+	0.1	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Light-Duty Trucks	+	+	0.4	0.6	0.6	0.5	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Medium- and Heavy-Duty Trucks	+	+	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5
Buses	+	+	3	12	13	14	14	15	15	15	15	15	15	14
Pipelines	680	724	668	611	611	649	677	699	703	718	765	872	744	716
LPG[g]	**23**	**18**	**12**	**28**	**27**	**22**	**40**	**28**	**29**	**34**	**37**	**44**	**47**	**48**
Passenger Cars	0.1	0.1	0.1	0.1	0.2	0.2	0.5	0.4	0.2	0.1	0.1	0.2	0.8	1
Light-Duty Trucks	3	2	2	5	7	5	7	7	7	6	4	5	10	14
Medium- and Heavy-Duty Trucks	18	14	9	21	17	13	24	16	17	23	29	33	31	28
Buses	1	1	0.8	2	3	4	8	5	5	4	5	6	6	5
Electricity[g]	**3**	**3**	**3**	**5**	**5**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**
Rail	3	3	3	5	5	5	5	4	4	4	4	4	4	4
Total	**21,006**	**22,667**	**25,335**	**26,428**	**26,281**	**26,246**	**25,039**	**24,023**	**24,171**	**23,883**	**23,747**	**24,000**	**24,385**	**24,280**

+ Does not exceed 0.05 tBtu

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in fuel consumption data by vehicle class between 2006 and 2007.

[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.

[c] Gasoline and diesel highway vehicle fuel consumption estimates are based on data from FHWA Highway Statistics Table MF-21, MF-27, and VM-1 (FHWA 1996 through 2016). Data from Table VM-1 is used to estimate the share of consumption between each on-road vehicle class. These fuel consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.

[d] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion*.

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

[f] Class II and Class II diesel consumption data for 2014 and 2015 is not available yet, therefore 2013 data is used as a proxy.

[g] 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 (2016). 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 2017) is now used to determine each vehicle class's share of the total natural gas and LPG consumption. These changes were first incorporated in this year's Inventory and apply to the 1990–2015 time period.

[h] Fluctuations in reported fuel consumption may reflect data collection problems. Residual fuel oil for ships and boats data is based on EIA's February 2017 Monthly Energy Review data.

Table A-95: Transportation Sector Biofuel Consumption by Fuel Type (million gallons)

Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Ethanol	712	1,326	1,590	3,860	5,207	6,563	9,263	10,537	12,282	12,329	12,324	12,646	12,908	13,096
Biodiesel	NA	NA	NA	91	261	354	304	322	260	886	899	1,429	1,417	1,494

NA (Not Available)

Note: According to the MER, there was no biodiesel consumption prior to 2001.

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 similar to that outlined in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006).

Activity data were obtained from a number of U.S. government agencies and other publications. Depending on the category, these 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

VMT by vehicle type (e.g., passenger cars, light-duty trucks, medium- and heavy-duty trucks,[44] buses, and motorcycles) were obtained from the Federal Highway Administration's (FHWA) *Highway Statistics* (FHWA 1996 through 2016).[45] As these vehicle categories are not fuel-specific, VMT for each vehicle type was disaggregated by fuel type (gasoline, diesel) so that the appropriate emission factors could be applied. VMT from *Highway Statistics* Table VM-1 (FHWA 1996 through 2016) was allocated to fuel types (gasoline, diesel, other) using historical estimates of fuel shares reported in the Appendix to the *Transportation Energy Data Book, Tables A.5 and A.6* (DOE 1993 through 2016). These fuel shares are drawn from various sources, including the Vehicle Inventory and Use Survey, the National Vehicle Population Profile, and the American Public Transportation Association. Fuel shares were first adjusted proportionately such that gasoline and diesel shares for each vehicle/fuel type category equaled 100 percent of national VMT. 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.[46] The resulting national VMT estimates for gasoline and diesel on-road vehicles are presented in Table A-96 and Table A-97, 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 vehicles, and motorcycles) were distributed across 30 model years shown for 2015 in Table A-98. 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 MOVES2014a model for years 2009 forward (EPA 2016d).[47] Age-specific vehicle mileage accumulations were also obtained from EPA's MOVES2014a model (EPA 2016d).[48]

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-104 through Table A-107. 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 LEV refer to U.S. emission regulations, rather than control technologies; however, each does correspond to particular combinations of control technologies and engine design. EPA Tier 2 and its predecessors EPA Tier 1 and Tier 0 apply to vehicles equipped with three-way catalysts. The introduction of "early three-way catalysts," and

[44] Medium- and heavy-duty trucks correspond to FHWA's reporting categories of single-unit trucks and combination trucks. Single-unit trucks are defined as single frame trucks that have 2-axles and at least 6 tires or a gross vehicle weight rating (GVWR) exceeding 10,000 lbs.

[45] In 2011 FHWA changed its methods for estimated vehicle miles traveled (VMT) and related data. These methodological changes included how vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. These changes were first incorporated for the 2010 Inventory and apply to the 2007–15 time period. This resulted in large changes in VMT data by vehicle class, thus leading to a shift in emissions among on-road vehicle classes. For example, the category "Passenger Cars" has been replaced by "Light-duty Vehicles-Short Wheelbase" and "Other 2 axle-4 Tire Vehicles" has been replaced by "Light-duty Vehicles, Long Wheelbase." This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this emission inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007.

[46] In Inventories through 2002, gasoline-electric hybrid vehicles were considered part of an "alternative fuel and advanced technology" category. However, vehicles are now only separated into gasoline, diesel, or alternative fuel categories, and gas-electric hybrids are now considered within the gasoline vehicle category.

[47] Age distributions were held constant for the period 1990 to 1998, and reflect a 25-year vehicle age span. EPA (2015b) provides a variable age distribution and 31-year vehicle age span beginning in year 1999.

[48] The updated vehicle distribution and mileage accumulation rates by vintage obtained from the MOVES 2014a model resulted in a decrease in emissions due to more miles driven by newer light-duty gasoline vehicles.

"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 1998b).[49] EPA Tier 2 regulations affect vehicles produced starting in 2004 and are responsible for a noticeable decrease in N_2O emissions compared EPA Tier 1 emissions technology (EPA 1999b).

Control technology assignments for light and heavy-duty conventional fuel vehicles for model years 1972 (when regulations began to take effect) through 1995 were estimated in EPA (1998). Assignments for 1998 through 2015 were determined using confidential engine family sales data submitted to EPA (EPA 2016f). Vehicle classes and emission standard tiers to which each engine family was certified were taken from annual certification test results and data (EPA 2016e). This information was used to determine the fraction of sales of each class of vehicle that met EPA Tier 0, EPA Tier 1, Tier 2, and LEV standards. Assignments for 1996 and 1997 were estimated based on the fact that EPA Tier 1 standards for light-duty vehicles were fully phased in by 1996. Tier 2 began initial phase-in by 2004.

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

Emission factors for gasoline and diesel on-road vehicles utilizing Tier 2 and Low Emission Vehicle (LEV) technologies were developed by ICF (2006b); all other gasoline and diesel on-road vehicle emissions factors were developed by ICF (2004). These factors were based on EPA, CARB and Environment Canada laboratory test results of different vehicle and control technology types. The EPA, CARB and Environment Canada tests were designed following the Federal Test Procedure (FTP), which 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 Segment 2 was used to define running emissions, and subtracted from the total FTP emissions to determine start emissions. These were then recombined based upon MOBILE6.2'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 then 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 "Methodology for Highway Vehicle Alternative Fuel GHG Projections Estimates" (Browning, 2017). 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.[50] 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 providers, propane providers, state agencies and transit agencies for calendar years 2003 through 2013. For 1992 to 2002, EIA Data Tables were used to estimate fuel consumption and vehicle counts by vehicle type. These tables give 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, 1991 and 2015, 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 5 years of data.

For the current Inventory, counts of electric vehicles (EVs) and plug-in hybrid-electric vehicles (PHEVs) were taken from data compiled by the Electric Drive Transportation Association from 2011 to 2015 (EDTA 2016). EVs were divided into cars and trucks using confidential engine family sales data submitted to EPA (EPA 2016f). Fuel use per vehicle

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

[50] 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.

for personal EVs and PHEVs were assumed to be the same as those for the public fleet vehicles surveyed by EIA and provided in their data tables.

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 GREET2016 model (ANL 2016). 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. Note that for AFVs capable of running on both/either traditional and alternative fuels, the VMT given reflects only those miles driven that were powered by the alternative fuel, as explained in Browning (2017). VMT estimates for AFVs by vehicle category (passenger car, light-duty truck, medium-duty and heavy-duty vehicles) are shown in Table A-98, while more detailed estimates of VMT by control technology are shown in Table A-99.

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) are calculated according to studies by Argonne National Laboratory (2006) and Lipman & Delucchi (2002), and are reported in ICF (2006a). In these studies, N_2O and CH_4 emissions for AFVs were expressed as a multiplier corresponding to conventional vehicle counterpart emissions. Emission estimates in these studies represent the current AFV fleet and were compared against Tier 1 emissions from light-duty gasoline vehicles to develop new multipliers. Alternative fuel heavy-duty vehicles were compared against gasoline heavy-duty vehicles as most alternative fuel heavy-duty vehicles use catalytic after treatment and perform more like gasoline vehicles than diesel vehicles. These emission factors are shown in Table A-109.

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-103. Consumption data for ships and boats (i.e., vessel bunkering) were obtained from DHS (2008) and EIA (1991 through 2016) for distillate fuel, and DHS (2008) and EIA (2016) for residual fuel; marine transport fuel consumption data for U.S. Territories (EIA 2015) were added to domestic consumption, and this total was reduced by the amount of fuel used for international bunkers.[51] Gasoline consumption by recreational boats was obtained from the NONROAD component of EPA's MOVES2014a model (EPA 2016d). Annual diesel consumption for Class I rail was obtained from the Association of American Railroads (AAR 2008 through 2016), diesel consumption from commuter rail was obtained from APTA (2007 through 2016) and Gaffney (2007), and consumption by Class II and III rail was provided by Benson (2002 through 2004) and Whorton (2006 through 2013).[52] Diesel consumption by commuter and intercity rail was obtained from DOE (1993 through 2016). Data on the consumption of jet fuel and aviation gasoline in aircraft were obtained from EIA (2016) and FAA (2017), 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 (DESC 2016 and FAA 2017). Pipeline fuel consumption was obtained from EIA (2007 through 2016) (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 MOVES2014a model (EPA 2016d) for gasoline and diesel powered equipment, and from FHWA (1996 through 2016) for gasoline consumption by off-road trucks used in the agriculture, industrial,

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

[52] Diesel consumption from Class II and Class III railroad were unavailable for 2014 and 2015. Values are proxied from 2013, which is the last year the data was available.

commercial, and construction sectors.[53,54] 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_20 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.

Emissions of CH_4 and N_2O from non-road mobile sources were calculated by multiplying U.S. default emission factors in the *2006 IPCC Guidelines* by activity data for each source type (see Table A-110).

Estimates of NO_x, CO, and NMVOC Emissions

The emission estimates of NO_x, CO, and NMVOCs from mobile combustion (transportation) were obtained from preliminary data (EPA 2016g), which, in final iteration, will be published on the EPA's National Emission Inventory (NEI) Air Pollutant Emission Trends web site. 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. Table A-111 through Table A-113 provides complete emission estimates for 1990 through 2015.

Table A-96: Vehicle Miles Traveled for Gasoline On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[b]	Motorcycles
1990	1,391.4	554.8	25.8	9.6
1991	1,341.9	627.8	25.4	9.2
1992	1,355.1	683.4	25.1	9.6
1993	1,356.8	721.0	24.9	9.9
1994	1,387.7	739.2	25.3	10.2
1995	1,421.0	763.0	25.1	9.8
1996	1,455.1	788.6	24.5	9.9
1997	1,489.0	821.6	24.1	10.1
1998	1,537.1	837.7	24.1	10.3
1999	1,559.6	868.3	24.3	10.6
2000	1,592.2	887.6	24.2	10.5
2001	1,620.1	905.9	23.9	9.6
2002	1,650.0	926.8	23.9	9.6
2003	1,663.6	944.1	24.3	9.6
2004	1,691.2	985.5	24.6	10.1
2005	1,699.7	998.8	24.8	10.5
2006	1,681.9	1,038.6	24.8	12.0
2007[a]	2,093.7	562.8	34.2	21.4
2008	2,014.4	580.9	35.0	20.8
2009	2,005.4	592.5	32.5	20.8
2010	2,015.3	597.4	32.3	18.5
2011	2,035.6	579.6	30.2	18.5
2012	2,051.6	576.8	30.5	21.4
2013	2,062.1	578.7	31.2	20.4
2014	2,058.3	612.4	31.7	20.0
2015	2,132.6	606.0	31.8	19.6

[53] "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.

[54] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications. These method changes created a time-series inconsistency in this Inventory between 2015 and previous years in CH_4 and N_2O estimates for agricultural, construction, commercial, and industrial non-road mobile sources. The method updates are discussed further in the Planned Improvements section of Chapter 3.1. under CH_4 and N_2O from Mobile Combustion.

[a] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.
[b] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.
Note: 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 2014 Inventory and apply to the 1990–2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.
Note: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). These mileage consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.
Source: Derived from FHWA (1996 through 2015), Browning (2017).

Table A-97: Vehicle Miles Traveled for Diesel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	16.9	19.7	125.7
1991	16.3	21.6	129.5
1992	16.5	23.4	133.7
1993	17.9	24.7	140.6
1994	18.3	25.3	150.9
1995	17.3	26.9	159.1
1996	14.7	27.8	164.6
1997	13.5	29.0	173.8
1998	12.4	30.5	178.9
1999	9.4	32.6	185.6
2000	8.0	35.2	188.4
2001	8.1	37.0	191.5
2002	8.3	38.9	196.8
2003	8.4	39.7	199.6
2004	8.5	41.4	202.1
2005	8.5	41.9	203.4
2006	8.4	43.4	202.3
2007[b]	10.5	23.3	281.8
2008	10.1	24.1	288.1
2009	10.0	24.6	267.7
2010	10.1	24.8	265.8
2011	10.1	23.3	245.6
2012	10.1	23.1	247.9
2013	10.1	22.5	250.5
2014	10.0	23.9	255.0
2015	10.3	23.6	255.4

[a] Heavy-Duty Vehicles includes Medium-Duty Trucks, Heavy-Duty Trucks, and Buses.
[b] In 2011, FHWA changed its methodology for Table VM-1, which impacts estimates for the 2007 to 2015 time period. These methodological changes include how on-road vehicles are classified, moving from a system based on body-type to one that is based on wheelbase. This resulted in large changes in VMT data by vehicle class between 2006 and 2007.
Note: 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 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.
Note: Gasoline and diesel highway vehicle mileage are based on data from FHWA Highway Statistics Table VM-1 (FHWA 1996 through 2016). Table. These mileage consumption estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is used as a proxy.
Source: Derived from FHWA (1996 through 2016), Browning (2017).

Table A-98: Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (billion miles)

Year	Passenger Cars	Light-Duty Trucks	Heavy-Duty Vehicles[a]
1990	0.0	0.1	0.4
1991	0.0	0.1	0.4
1992	0.0	0.1	0.4
1993	0.0	0.1	0.5
1994	0.1	0.1	0.4
1995	0.1	0.1	0.4
1996	0.1	0.1	0.4
1997	0.1	0.1	0.4
1998	0.1	0.1	0.5
1999	0.1	0.1	0.4
2000	0.1	0.2	0.5
2001	0.1	0.2	0.6
2002	0.1	0.3	0.8
2003	0.2	0.3	0.8
2004	0.2	0.3	0.9
2005	0.2	0.3	1.3
2006	0.2	0.5	2.2
2007	0.3	0.6	2.6
2008	0.3	0.5	2.4
2009	0.3	0.5	2.5
2010	0.3	0.5	2.2
2011	0.6	1.2	5.5
2012	1.1	1.4	5.6
2013	2.3	2.1	8.5
2014	3.8	2.1	8.5
2015	4.9	2.3	8.9

[a] Heavy Duty-Vehicles includes medium-duty trucks, heavy-duty trucks, and buses.

Note: 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 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. In 2016, 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 first incorporated in this year's Inventory and apply to the 2005 to 2015 time period.

Source: Derived from Browning (2017).

Table A-99: Detailed Vehicle Miles Traveled for Alternative Fuel On-Road Vehicles (10^6 Miles)

Vehicle Type/Year	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Light-Duty Cars	**4.0**	**56.0**	**78.1**	**195.1**	**230.5**	**252.3**	**260.5**	**295.9**	**344.6**	**575.2**	**1,090.6**	**2,302.4**	**3,787.3**	**4,856.7**
Methanol-Flex Fuel ICE	+	48.9	15.2	+	+	+	+	+	+	+	+	+	+	+
Ethanol-Flex Fuel ICE	+	0.3	20.9	51.0	59.2	72.8	84.2	96.2	122.2	118.5	148.9	173.5	135.4	126.5
CNG ICE	+	0.1	5.5	15.9	14.5	14.1	12.5	11.5	10.8	11.5	11.9	12.9	12.4	14.2
CNG Bi-fuel	+	0.2	18.0	40.6	25.3	19.1	12.8	10.0	7.9	7.0	4.4	3.4	2.5	1.7
LPG ICE	1.1	1.2	1.2	0.1	0.2	1.6	1.7	1.7	+	0.2	0.2	0.4	3.5	6.1
LPG Bi-fuel	2.8	3.0	3.0	3.3	3.8	1.7	1.6	1.8	1.2	0.3	0.3	0.2	0.1	+
Biodiesel (BD100)	+	+	1.0	14.6	41.4	50.2	39.1	46.4	39.4	149.5	180.7	311.4	334.8	370.4
NEVs	+	2.0	11.9	67.5	81.7	82.8	87.7	83.7	68.5	97.1	83.5	72.9	63.9	45.4
Electric Vehicle	+	0.2	1.5	2.1	4.5	9.7	20.7	44.1	94.3	169.0	531.3	1,474.8	2,820.7	3,693.9
SI PHEV - Electricity	+	+	+	+	+	+	+	+	+	21.9	129.4	252.8	413.9	598.4
Fuel Cell Hydrogen	+	+	+	+	+	0.3	0.2	0.5	0.2	0.1	0.1	0.1	0.1	0.1
Light-Duty Trucks	**77.3**	**93.2**	**180.9**	**333.1**	**491.3**	**555.3**	**458.1**	**510.6**	**462.8**	**1,234.4**	**1,366.3**	**2,099.4**	**2,142.1**	**2,285.3**
Ethanol-Flex Fuel ICE	+	0.3	23.4	54.5	62.8	77.0	89.6	102.7	130.9	144.2	191.8	227.2	222.3	238.2
CNG ICE	+	0.1	5.6	14.5	15.0	13.2	10.2	9.7	8.5	9.1	9.4	9.2	8.1	9.2
CNG Bi-fuel	+	0.4	47.2	72.8	68.6	60.9	26.0	21.7	20.3	19.4	15.7	17.1	20.6	26.3
LPG ICE	22.4	26.5	27.6	32.6	28.6	22.8	11.2	12.9	10.3	10.2	6.3	6.7	7.8	9.1
LPG Bi-fuel	55.0	65.1	67.7	67.6	55.0	32.2	25.1	29.2	25.3	13.2	5.2	6.3	23.2	46.2
LNG	+	+	0.1	0.3	0.2	0.2	0.3	0.2	+	+	+	+	+	+
Biodiesel (BD100)	+	+	4.1	85.3	253.9	341.1	287.9	326.6	260.2	1,033.2	1,133.8	1,815.1	1,825.0	1,911.5
Electric Vehicle	+	0.8	5.3	5.6	7.1	7.9	7.7	7.5	7.2	4.8	3.8	17.4	35.0	44.4
Fuel Cell Hydrogen	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Medium Duty Trucks	**273.4**	**267.5**	**260.6**	**317.3**	**523.9**	**626.9**	**567.6**	**597.4**	**448.3**	**1,406.3**	**1,466.0**	**2,325.4**	**2,351.4**	**2,486.1**
CNG ICE	+	+	0.9	3.3	2.3	4.9	6.8	6.1	5.9	8.1	9.5	10.0	11.2	12.3
CNG Bi-fuel	+	0.1	8.3	12.4	10.6	9.6	8.4	7.0	6.7	6.5	7.3	7.6	10.2	11.6
LPG ICE	230.7	225.6	206.0	132.3	69.8	52.1	39.5	35.3	31.1	29.0	27.4	25.2	24.4	24.5
LPG Bi-fuel	42.7	41.7	38.1	35.7	19.2	8.4	13.5	6.8	8.4	7.5	10.0	10.7	13.6	18.6
LNG	+	+	+	+	+	+	+	+	+	+	+	0.1	+	+
Biodiesel (BD100)	+	+	7.3	133.7	422.0	552.0	499.4	542.3	396.2	1,355.2	1,411.8	2,271.9	2,291.8	2,419.1
Heavy-Duty Trucks	**108.3**	**105.9**	**117.4**	**424.2**	**1,033.3**	**1,377.3**	**1,170.4**	**1,218.4**	**1,015.9**	**3,360.1**	**3,361.7**	**5,313.0**	**5,290.0**	**5,554.5**
Neat Ethanol ICE	+	+	+	1.6	1.8	2.2	2.6	3.0	3.7	5.9	9.4	13.0	15.6	19.3
CNG ICE	+	+	0.9	1.9	2.7	2.9	2.7	3.4	3.6	3.6	4.1	5.0	5.5	6.0
LPG ICE	101.7	99.5	90.9	72.6	63.8	54.8	46.8	41.4	34.1	35.9	23.3	23.0	18.6	17.0
LPG Bi-fuel	6.5	6.4	5.8	4.3	3.8	3.7	3.7	4.3	4.5	6.6	5.1	5.4	2.3	+
LNG	+	+	+	0.8	0.9	0.9	1.2	1.3	1.5	1.7	1.7	1.5	2.0	2.0
Biodiesel (BD100)	+	+	19.7	343.0	960.2	1,312.8	1,113.4	1,165.1	968.4	3,306.4	3,318.2	5,265.1	5,246.0	5,510.2
Buses	**20.6**	**39.8**	**146.9**	**518.5**	**624.7**	**623.3**	**654.5**	**684.5**	**695.4**	**779.5**	**769.5**	**832.4**	**844.0**	**816.6**
Neat Methanol ICE	6.5	10.6	+	+	+	+	+	+	+	+	+	+	+	+
Neat Ethanol ICE	+	4.9	0.1	+	+	+	+	+	+	+	0.1	0.1	2.7	2.8
CNG ICE	+	1.1	104.1	413.5	481.7	509.8	546.2	581.7	605.4	637.1	628.3	650.1	650.3	617.8
LPG ICE	13.6	13.2	12.0	9.7	11.0	10.2	11.1	7.5	6.7	4.0	3.9	4.1	4.5	5.2
LNG	0.4	8.9	23.2	61.4	66.8	40.2	39.8	36.0	36.8	39.5	41.1	29.4	38.2	35.4
Biodiesel (BD100)	+	+	0.8	13.2	38.9	53.3	46.6	51.7	38.1	90.1	90.7	143.5	142.8	149.5

Electric	+	1.1	6.8	20.6	26.1	9.6	10.6	7.6	8.3	8.4	5.1	4.9	5.1	5.5
Fuel Cell Hydrogen	+	+	+	+	0.1	0.1	0.1	0.1	0.2	0.3	0.3	0.3	0.4	0.4
Total VMT	**483.6**	**562.4**	**783.9**	**1,788.3**	**2,903.7**	**3,435.2**	**3,111.0**	**3,306.9**	**2,967.0**	**7,355.4**	**8,054.1**	**12,872.8**	**14,414.7**	**15,999.1**

+ Does not exceed 0.05 million vehicle miles traveled

Note: 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 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 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes. In 2016, 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 first incorporated in this year's Inventory and apply to the 2005 to 2015 time period

Source: Derived from Browning (2017).

Table A-100: Age Distribution by Vehicle/Fuel Type for On-Road Vehicles,[a] 2015

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	7.2%	8.2%	6.5%	13.6%	8.8%	6.2%	7.3%
1	7.1%	7.8%	6.0%	13.3%	8.3%	5.7%	7.1%
2	6.8%	7.3%	5.4%	12.8%	7.9%	5.1%	6.7%
3	6.5%	7.0%	4.9%	12.3%	7.5%	4.8%	6.0%
4	4.0%	4.7%	2.8%	7.6%	5.1%	3.0%	4.8%
5	4.5%	4.1%	1.9%	7.3%	3.0%	2.0%	4.3%
6	4.1%	3.0%	1.7%	4.8%	2.6%	2.4%	4.5%
7	5.1%	5.1%	3.2%	0.4%	6.4%	3.6%	7.9%
8	5.6%	5.3%	2.9%	0.3%	5.7%	7.0%	7.1%
9	5.1%	5.3%	4.1%	5.6%	7.1%	6.0%	6.7%
10	5.1%	5.4%	3.3%	3.8%	6.0%	5.5%	5.9%
11	4.7%	5.2%	4.0%	2.3%	5.3%	3.8%	5.0%
12	4.8%	4.7%	3.5%	3.0%	4.7%	3.4%	4.3%
13	4.5%	4.4%	3.5%	3.1%	4.0%	2.7%	3.7%
14	4.0%	3.8%	2.9%	1.9%	4.5%	3.6%	3.2%
15	3.8%	3.5%	5.6%	1.6%	2.3%	5.5%	2.5%
16	2.9%	2.9%	5.4%	0.9%	3.3%	4.4%	1.9%
17	2.3%	2.3%	2.3%	0.8%	1.2%	2.9%	1.6%
18	2.1%	2.0%	4.2%	0.3%	1.5%	2.8%	1.6%
19	1.7%	1.4%	2.5%	0.3%	1.1%	2.5%	1.4%
20	1.7%	1.4%	3.5%	0.2%	0.8%	3.1%	1.0%
21	1.3%	1.1%	2.7%	0.0%	0.5%	2.3%	1.2%
22	1.1%	0.8%	2.2%	0.1%	0.5%	1.7%	1.0%
23	0.9%	0.6%	1.7%	0.2%	0.5%	1.2%	0.8%
24	0.7%	0.5%	1.3%	0.3%	0.3%	1.1%	0.6%
25	0.6%	0.5%	1.9%	0.1%	0.2%	1.4%	0.5%
26	0.5%	0.5%	2.2%	0.1%	0.2%	1.4%	0.4%
27	0.4%	0.4%	1.8%	0.0%	0.2%	1.2%	0.3%
28	0.3%	0.3%	1.7%	0.7%	0.1%	1.0%	0.3%
29	0.3%	0.3%	1.7%	0.4%	0.2%	0.7%	0.3%
30	0.3%	0.2%	2.9%	1.8%	0.2%	1.6%	0.3%
Total	**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), and MC (motorcycles).
Note: This year's Inventory includes updated vehicle population data based on the MOVES 2014a Model.
Source: EPA (2016b).

Table A-101: Annual Average Vehicle Mileage Accumulation per Vehicle[a] (miles)

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC[b]
0	13,712	15,498	19,032	13,712	15,498	41,675	7,577
1	13,452	15,207	19,036	13,452	15,207	41,413	4,046
2	13,170	14,878	19,039	13,170	14,878	41,193	3,061
3	12,870	14,519	19,043	12,870	14,519	41,921	2,531
4	12,553	14,131	16,772	12,553	14,131	46,741	2,190
5	12,220	13,719	14,489	12,220	13,719	45,576	1,947
6	11,875	13,287	13,981	11,875	13,287	47,032	1,765
7	11,520	12,837	14,612	11,520	12,837	33,200	1,622
8	11,156	12,375	12,219	11,156	12,375	43,952	1,500
9	10,785	11,906	12,380	10,785	11,906	36,876	1,402
10	10,410	11,430	10,491	10,410	11,430	34,839	1,318
11	10,033	10,954	10,254	10,033	10,954	28,657	1,243
12	9,656	10,481	9,092	9,656	10,481	27,572	1,182
13	9,282	10,017	8,282	9,282	10,016	23,494	1,121
14	8,912	9,562	7,056	8,912	9,562	21,260	1,068
15	8,547	9,122	7,299	8,547	9,122	19,488	1,023
16	8,192	8,702	6,145	8,192	8,702	16,393	985
17	7,847	8,304	5,709	7,847	8,304	15,976	947
18	7,514	7,934	5,148	7,514	7,934	11,931	909

19	7,197	7,594	4,864	7,197	7,594	12,666	879
20	6,896	7,289	4,825	6,896	7,289	10,576	849
21	6,616	7,022	4,349	6,616	7,022	9,298	826
22	6,355	6,798	4,341	6,355	6,798	8,711	803
23	6,118	6,621	3,652	6,118	6,621	7,984	758
24	5,907	6,494	3,612	5,907	6,494	7,293	712
25	5,723	6,419	3,385	5,723	6,419	6,242	667
26	5,569	6,405	3,189	5,569	6,405	5,319	614
27	5,447	6,405	2,872	5,447	6,405	4,790	568
28	5,359	6,405	2,642	5,359	6,405	4,535	538
29	5,307	6,405	2,438	5,307	6,405	3,807	500
30	5,307	6,405	2,375	5,307	6,405	2,872	462

[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), and MC (motorcycles).
[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 (2016b).

Table A-102: VMT Distribution by Vehicle Age and Vehicle/Fuel Type,[a] 2015

Vehicle Age	LDGV	LDGT	HDGV	LDDV	LDDT	HDDV	MC
0	9.21%	10.49%	11.99%	15.60%	11.00%	9.08%	25.10%
1	8.88%	9.77%	11.07%	15.03%	10.24%	8.29%	13.20%
2	8.31%	9.03%	9.97%	14.07%	9.45%	7.40%	9.32%
3	7.84%	8.42%	9.17%	13.29%	8.81%	7.04%	6.89%
4	4.71%	5.45%	4.58%	7.99%	5.84%	4.91%	4.78%
5	5.14%	4.64%	2.63%	7.49%	3.29%	3.16%	3.84%
6	4.52%	3.35%	2.27%	4.78%	2.84%	3.97%	3.61%
7	5.52%	5.47%	4.56%	0.42%	6.67%	4.19%	5.87%
8	5.79%	5.44%	3.50%	0.28%	5.68%	10.81%	4.83%
9	5.15%	5.20%	5.01%	5.09%	6.84%	7.81%	4.28%
10	4.89%	5.07%	3.35%	3.36%	5.56%	6.75%	3.52%
11	4.34%	4.75%	4.05%	1.93%	4.66%	3.86%	2.82%
12	4.29%	4.07%	3.12%	2.40%	4.00%	3.29%	2.29%
13	3.90%	3.67%	2.83%	2.40%	3.24%	2.25%	1.92%
14	3.29%	3.04%	1.99%	1.40%	3.46%	2.68%	1.55%
15	3.03%	2.62%	4.03%	1.12%	1.71%	3.79%	1.18%
16	2.24%	2.10%	3.24%	0.60%	2.29%	2.53%	0.86%
17	1.71%	1.56%	1.27%	0.54%	0.81%	1.65%	0.71%
18	1.46%	1.28%	2.11%	0.19%	0.96%	1.18%	0.65%
19	1.12%	0.89%	1.18%	0.20%	0.70%	1.12%	0.55%
20	1.07%	0.82%	1.63%	0.14%	0.49%	1.14%	0.40%
21	0.79%	0.67%	1.15%	0.02%	0.27%	0.76%	0.45%
22	0.64%	0.46%	0.92%	0.06%	0.28%	0.52%	0.35%
23	0.50%	0.34%	0.60%	0.08%	0.25%	0.33%	0.28%
24	0.41%	0.28%	0.48%	0.16%	0.14%	0.29%	0.21%
25	0.33%	0.25%	0.61%	0.05%	0.11%	0.31%	0.16%
26	0.26%	0.25%	0.68%	0.03%	0.10%	0.25%	0.11%
27	0.20%	0.21%	0.50%	0.01%	0.08%	0.20%	0.08%
28	0.16%	0.16%	0.43%	0.30%	0.03%	0.16%	0.08%
29	0.13%	0.16%	0.40%	0.16%	0.11%	0.10%	0.06%
30	0.16%	0.11%	0.67%	0.81%	0.08%	0.16%	0.05%
Total	**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), and MC (motorcycles).
Note: Estimated by weighting data in by data in Table A-101. This year's Inventory includes updated vehicle population data based on the MOVES 2014a. Model that affects this distribution.

Table A-103: Fuel Consumption for Off-Road Sources by Fuel Type (million gallons)

Vehicle Type/Year	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aircraft[a]	**19,560**	**18,320**	**20,304**	**19,714**	**18,973**	**18,670**	**17,984**	**16,030**	**15,762**	**15,262**	**14,914**	**15,274**	**15,418**	**16,352**
Aviation Gasoline	374	329	302	294	278	263	235	221	225	225	209	186	181	176
Jet Fuel	19,186	17,991	20,002	19,420	18,695	18,407	17,749	15,809	15,537	15,036	14,705	15,088	15,237	16,176
Commercial Aviation[b]	*11,569*	*12,136*	*14,672*	*13,976*	*14,426*	*14,708*	*13,400*	*12,588*	*11,931*	*12,067*	*11,932*	*12,031*	*12,131*	*12,534*
Ships and Boats	**4,507**	**5,789**	**6,407**	**4,858**	**5,120**	**5,723**	**4,860**	**4,289**	**5,740**	**5,915**	**5,340**	**5,293**	**4,329**	**4,783**
Diesel	1,043	1,546	1,750	1,470	1,409	1,489	1,470	1,480	1,446	1,727	1,475	1,499	1,370	1,967
Gasoline	1,403	1,597	1,629	1,607	1,597	1,587	1,577	1,568	1,556	1,545	1,535	1,528	1,522	1,519
Residual	2,061	2,646	3,028	1,781	2,115	2,647	1,812	1,241	2,738	2,643	2,330	2,265	1,437	1,298
Construction/Mining Equipment[c]	**4,160**	**4,835**	**5,523**	**6,617**	**6,755**	**6,785**	**6,939**	**7,066**	**7,312**	**7,418**	**7,586**	**8,187**	**7,949**	**7,739**
Diesel	3,674	4,387	5,181	5,922	6,069	6,216	6,363	6,511	6,658	6,806	6,954	7,102	7,250	7,372
Gasoline[f]	486	448	342	695	686	569	575	556	655	612	632	1,085	698	367
Agricultural Equipment[d]	**3,134**	**3,698**	**3,929**	**4,776**	**5,011**	**4,926**	**4,582**	**4,708**	**4,807**	**4,998**	**5,157**	**5,021**	**5,094**	**4,693**
Diesel	2,321	2,772	3,277	3,699	3,782	3,865	3,948	4,032	4,115	4,199	4,282	4,366	4,450	4,534
Gasoline[f]	813	927	652	1,078	1,229	1,061	634	676	692	799	875	655	644	159
Rail	**3,461**	**3,864**	**4,106**	**4,446**	**4,665**	**4,539**	**4,216**	**3,535**	**3,807**	**3,999**	**3,921**	**4,025**	**4,175**	**4,000**
Diesel	3,461	3,864	4,106	4,446	4,665	4,539	4,216	3,535	3,807	3,999	3,921	4,025	4,175	4,000
Other[e]	**5,916**	**6,525**	**6,798**	**8,255**	**8,370**	**8,229**	**8,360**	**8,455**	**8,804**	**8,768**	**8,703**	**8,800**	**8,952**	**8,854**
Diesel	1,423	1,720	2,050	2,380	2,446	2,512	2,579	2,645	2,711	2,778	2,844	2,910	2,977	2,960
Gasoline[f]	4,493	4,805	4,748	5,875	5,924	5,717	5,782	5,810	6,093	5,990	5,859	5,890	5,975	5,893
Total	**40,738**	**43,031**	**47,067**	**48,666**	**48,894**	**48,872**	**46,941**	**44,083**	**46,233**	**46,359**	**45,622**	**46,600**	**45,917**	**46,420**

[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.

[f] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications. These method changes created a time-series inconsistency between 2015 and previous years for agricultural, construction, commercial, and industrial non-road mobile sources. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CH_4 and N_2O from Mobile Combustion*.

Note: In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015.

Sources: AAR (2008 through 2016), APTA (2007 through 2016), BEA (1991 through 2016), Benson (2002 through 2004), DHS (2008), DOC (1991 through 2016), DESC (2016), DOE (1993 through 2016), DOT (1991 through 2016), EIA (2002), EIA (2007b), EIA (2016), EIA (2007 through 2016), EIA (1991 through 2016), EPA (2016d), FAA (2017), Gaffney (2007), and Whorton (2006 through 2014).

Table A-104: Control Technology Assignments for Gasoline Passenger Cars (Percent of VMT)

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV	EPA Tier 2
1973-1974	100%	-	-	-	-	-
1975	20%	80%	-	-	-	-
1976-1977	15%	85%	-	-	-	-
1978-1979	10%	90%	-	-	-	-
1980	5%	88%	7%	-	-	-
1981	-	15%	85%	-	-	-
1982	-	14%	86%	-	-	-
1983	-	12%	88%	-	-	-
1984-1993	-	-	100%	-	-	-
1994	-	-	60%	40%	-	-
1995	-	-	20%	80%	-	-
1996	-	-	1%	97%	2%	-
1997	-	-	0.5%	96.5%	3%	-
1998	-	-	<1%	82%	18%	-
1999	-	-	<1%	67%	33%	-
2000	-	-	-	44%	56%	-
2001	-	-	-	3%	97%	-
2002	-	-	-	1%	99%	-
2003	-	-	-	<1%	85%	15%
2004	-	-	-	<1%	24%	76%
2005	-	-	-	-	13%	87%
2006	-	-	-	-	18%	82%
2007	-	-	-	-	4%	96%
2008	-	-	-	-	2%	98%
2009-15	-	-	-	-	-	100%

- 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 (2016e), and EPA (2016f).

Table A-105: Control Technology Assignments for Gasoline Light-Duty Trucks (Percent of VMT)[a]

Model Years	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV[b]	EPA Tier 2
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%	73%

2005	-	-	-	-	17%	83%
2006	-	-	-	-	24%	76%
2007	-	-	-	-	14%	86%
2008-2015	-	-	-	-	-	100%

- 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.
Note: 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 (2016e), and EPA (2016f).

Table A-106: Control Technology Assignments for Gasoline Heavy-Duty Vehicles (Percent of VMT)[a]

Model Years	Uncontrolled	Non-catalyst	Oxidation	EPA Tier 0	EPA Tier 1	LEV[b]	EPA Tier 2
≤1981	100%	-	-	-	-	-	-
1982-1984	95%	-	5%	-	-	-	-
1985-1986	-	95%	5%	-	-	-	-
1987	-	70%	15%	15%	-	-	-
1988-1989	-	60%	25%	15%	-	-	-
1990-1995	-	45%	30%	25%	-	-	-
1996	-	-	25%	10%	65%	-	-
1997	-	-	10%	5%	85%	-	-
1998	-	-	-	-	100%	0%	-
1999	-	-	-	-	98%	2%	-
2000	-	-	-	-	93%	7%	-
2001	-	-	-	-	78%	22%	-
2002	-	-	-	-	94%	6%	-
2003	-	-	-	-	85%	14%	1%
2004	-	-	-	-	0%	33%	67%
2005	-	-	-	-	-	15%	85%
2006	-	-	-	-	-	50%	50%
2007	-	-	-	-	-	0%	100%
2008-2015	-	-	-	-	-	-	100%

- 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.
Note: 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 (2016e), and EPA (2016f).

Table A-107: 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	1996–2015
Diesel Medium- and Heavy-Duty Trucks and Buses	
Uncontrolled	1960–1990
Moderate control	1991–2003
Advanced control	2004–2006
Aftertreatment	2007–2015
Motorcycles	
Uncontrolled	1960–1995
Non-catalyst controls	1996–2015

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

Table A-108: 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 2	0.0036	0.0173
Low Emission Vehicles	0.0150	0.0105
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 2	0.0066	0.0163
Low Emission Vehicles	0.0157	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 2	0.0134	0.0333
Low Emission Vehicles	0.0320	0.0303
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		
Advanced	0.0010	0.0005
Moderate	0.0010	0.0005
Uncontrolled	0.0012	0.0006
Diesel Light-Duty Trucks		
Advanced	0.0015	0.0010
Moderate	0.0014	0.0009
Uncontrolled	0.0017	0.0011
Diesel Medium- and Heavy-Duty Trucks and Buses		
Aftertreatment	0.0048	0.0051
Advanced	0.0048	0.0051
Moderate	0.0048	0.0051
Uncontrolled	0.0048	0.0051
Motorcycles		
Non-Catalyst Control	0.0069	0.0672
Uncontrolled	0.0087	0.0899

[a] The categories "EPA Tier 0" and "EPA Tier 1" were substituted for the early three-way catalyst and advanced three-way catalyst categories, respectively, as defined in the *2006 IPCC Guidelines*. Detailed descriptions of emissions control technologies are provided at the end of this Annex.
Source: ICF (2006b and 2004).

Table A-109: Emission Factors for CH_4 and N_2O for Alternative Fuel Vehicles (g/mi)

	N_2O	CH_4
Light Duty Vehicles		
Methanol	0.067	0.018
CNG	0.050	0.737
LPG	0.067	0.037
Ethanol	0.067	0.055
Biodiesel (BD20)	0.001	0.0005
Medium- and Heavy-Duty Trucks		
Methanol	0.175	0.066

CNG	0.175	1.966
LNG	0.175	1.966
LPG	0.175	0.066
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005
Buses		
Methanol	0.175	0.066
CNG	0.175	1.966
Ethanol	0.175	0.197
Biodiesel (BD20)	0.005	0.005

Source: Developed by ICF (2006a) using ANL (2006) and Lipman and Delucchi (2002).

Table A-110: Emission Factors for CH_4 and N_2O Emissions from Non-Road Mobile Combustion (g/kg fuel)

Vehicle Type/Fuel Type	N_2O	CH_4
Ships and Boats		
Residual	0.16	0.03
Gasoline	0.08	0.23
Diesel	0.14	0.02
Rail		
Diesel	0.08	0.25
Agricultural Equipment[a]		
Gasoline	0.08	0.45
Diesel	0.08	0.45
Construction/Mining Equipment[b]		
Gasoline	0.08	0.18
Diesel	0.08	0.18
Other Non-Road		
All "Other" Categories[c]	0.08	0.18
Aircraft		
Jet Fuel[d]	0.10	0.00
Aviation Gasoline	0.04	2.64

[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.
[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.
[d] 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 in this year's Inventory to reflect the latest emissions testing data.
Source: IPCC (2006) and ICF (2009).

Table A-111: NO_x Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**5,746**	**4,560**	**3,812**	**3,984**	**3,819**	**3,654**	**3,317**	**2,966**	**2,724**	**2,805**	**2,614**	**2,423**	**2,232**	**1,976**
Passenger Cars	3,847	2,752	2,084	2,174	2,083	1,993	1,810	1,618	1,486	1,530	1,426	1,322	1,217	1,078
Light-Duty Trucks	1,364	1,325	1,303	1,378	1,321	1,264	1,147	1,026	942	970	904	838	772	683
Medium- and Heavy-Duty Trucks and Buses	515	469	411	418	401	383	348	311	286	294	274	254	234	207
Motorcycles	20	14	13	15	14	13	12	11	10	10	10	9	8	7
Diesel On-Road	**2,956**	**3,493**	**3,803**	**3,580**	**3,431**	**3,283**	**2,980**	**2,665**	**2,448**	**2,520**	**2,349**	**2,177**	**2,005**	**1,776**
Passenger Cars	39	19	7	6	6	6	5	5	4	4	4	4	4	3
Light-Duty Trucks	20	12	6	6	6	5	5	4	4	4	4	4	3	3
Medium- and Heavy-Duty Trucks and Buses	2,897	3,462	3,791	3,568	3,420	3,272	2,970	2,656	2,439	2,512	2,341	2,169	1,998	1,769
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,160**	**2,483**	**2,584**	**2,731**	**2,490**	**2,249**	**2,226**	**2,166**	**2,118**	**1,968**	**1,908**	**1,848**	**1,788**	**1,665**
Ships and Boats	402	488	506	565	515	465	460	448	438	407	395	382	370	344
Rail	338	433	451	504	460	415	411	400	391	363	352	341	330	307
Aircraft[b]	25	31	40	41	37	34	33	32	32	29	29	28	27	25
Agricultural Equipment[c]	437	478	484	494	450	407	402	392	383	356	345	334	323	301
Construction/Mining Equipment[d]	641	697	697	709	647	584	578	563	550	511	496	480	464	433
Other[e]	318	357	407	418	381	344	341	332	324	301	292	283	274	255
Total	**10,862**	**10,536**	**10,199**	**10,295**	**9,740**	**9,186**	**8,523**	**7,797**	**7,290**	**7,294**	**6,871**	**6,448**	**6,024**	**5,417**

IE (Included Elsewhere)

[a] NO_x emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.

[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.

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

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

[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.

Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-112: CO Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**98,328**	**74,673**	**60,657**	**38,265**	**35,781**	**33,298**	**29,626**	**24,515**	**25,235**	**24,442**	**22,805**	**21,167**	**19,529**	**17,739**
Passenger Cars	60,757	42,065	32,867	21,319	19,936	18,552	16,506	13,659	14,060	13,618	12,706	11,793	10,881	9,883
Light-Duty Trucks	29,237	27,048	24,532	15,230	14,242	13,253	11,792	9,758	10,044	9,729	9,077	8,425	7,773	7,061
Medium- and Heavy-Duty Trucks and Buses	8,093	5,404	3,104	1,627	1,521	1,416	1,259	1,042	1,073	1,039	969	900	830	754
Motorcycles	240	155	154	89	83	77	69	57	58	57	53	49	45	41
Diesel On-Road	**1,696**	**1,424**	**1,088**	**586**	**548**	**510**	**454**	**376**	**387**	**375**	**349**	**324**	**299**	**272**
Passenger Cars	35	18	7	4	4	3	3	3	3	3	2	2	2	2
Light-Duty Trucks	22	16	6	4	3	3	3	2	2	2	2	2	2	2

Medium- and Heavy-Duty Trucks and Buses	1,639	1,391	1,075	579	541	504	448	371	382	370	345	320	295	268
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**19,337**	**21,533**	**21,814**	**19,763**	**18,382**	**17,001**	**16,137**	**14,365**	**13,853**	**13,488**	**12,999**	**12,509**	**12,019**	**11,870**
Ships and Boats	1,559	1,781	1,825	1,626	1,512	1,398	1,327	1,182	1,140	1,109	1,069	1,029	989	976
Rail	85	93	90	80	74	69	65	58	56	54	52	50	48	48
Aircraft[b]	217	224	245	207	193	178	169	151	145	141	136	131	126	124
Agricultural Equipment[c]	581	628	626	551	513	474	450	401	386	376	363	349	335	331
Construction/Mining Equipment[d]	1,090	1,132	1,047	924	860	795	755	672	648	631	608	585	562	555
Other[e]	15,805	17,676	17,981	16,375	15,231	14,087	13,371	11,903	11,479	11,176	10,770	10,364	9,959	9,835
Total	**119,360**	**97,630**	**83,559**	**58,615**	**54,712**	**50,809**	**46,217**	**39,256**	**39,475**	**38,305**	**36,153**	**34,000**	**31,848**	**29,881**

IE (Included Elsewhere)
[a] CO emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[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.
Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series. Totals may not sum due to independent rounding.

Table A-113: NMVOCs Emissions from Mobile Combustion (kt)

Fuel Type/Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Gasoline On-Road	**8,110**	**5,819**	**4,615**	**2,979**	**2,997**	**3,015**	**2,641**	**2,384**	**2,393**	**2,485**	**2,292**	**2,099**	**1,906**	**1,716**
Passenger Cars	5,120	3,394	2,610	1,664	1,674	1,684	1,475	1,332	1,336	1,388	1,280	1,172	1,065	958
Light-Duty Trucks	2,374	2,019	1,750	1,157	1,164	1,171	1,025	926	929	965	890	815	740	666
Medium- and Heavy-Duty Trucks and Buses	575	382	232	143	144	145	127	115	115	120	110	101	92	83
Motorcycles	42	24	23	15	15	15	14	12	12	13	12	11	10	9
Diesel On-Road	**406**	**304**	**216**	**144**	**145**	**146**	**128**	**115**	**116**	**120**	**111**	**102**	**92**	**83**
Passenger Cars	16	8	3	2	2	2	2	2	2	2	2	1	1	1
Light-Duty Trucks	14	9	4	3	3	3	2	2	2	2	2	2	2	1
Medium- and Heavy-Duty Trucks and Buses	377	286	209	140	140	141	124	112	112	116	107	98	89	80
Alternative Fuel On-Road[a]	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
Non-Road	**2,415**	**2,622**	**2,398**	**2,600**	**2,491**	**2,383**	**2,310**	**2,150**	**2,082**	**1,957**	**1,840**	**1,723**	**1,607**	**1,519**
Ships and Boats	608	739	744	798	764	731	709	660	639	600	565	529	493	466
Rail	33	36	35	39	37	35	34	32	31	29	27	26	24	23
Aircraft[b]	28	28	24	21	20	19	19	17	17	16	15	14	13	12
Agricultural Equipment[c]	85	86	76	79	76	73	70	65	63	60	56	52	49	46
Construction/Mining Equipment[d]	149	152	130	137	131	125	121	113	109	103	97	91	84	80
Other[e]	1,512	1,580	1,390	1,527	1,463	1,399	1,356	1,263	1,223	1,149	1,081	1,012	944	892
Total	**10,932**	**8,745**	**7,230**	**5,724**	**5,634**	**5,544**	**5,078**	**4,650**	**4,591**	**4,562**	**4,243**	**3,924**	**3,605**	**3,318**

IE (Included Elsewhere)
[a] NMVOC emissions from alternative fuel on-road vehicles are included under gasoline and diesel on-road.
[b] Aircraft estimates include only emissions related to LTO cycles, and therefore do not include cruise altitude emissions.
[c] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.

[d] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[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.
Notes: The source of this data is the National Emissions Inventory. Updates to estimates from MOVES2014a is a change that affects the emissions time series. Totals may not sum due to independent rounding.

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-104 through Table A-107 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, 1999a) 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 beginning in 1996. 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, and 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.

EPA Tier 0

This emission standard from the Clean Air Act was met through the implementation of early "three-way" catalysts, therefore this technology was used in gasoline passenger cars and light-duty gasoline trucks sold beginning in the early 1980s, and 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 respectively amounted to a 60 and 40 percent reduction 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, and 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 11 emission “Bins,” the three highest of which expire in 2006. These new emission levels represent a 77 to 95 percent reduction in emissions from the EPA Tier 1 standard set in 1994.

Emission reductions were met through the use of more advanced emission control systems and lower sulfur fuels and are 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.

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) and super ultra-low emission vehicles (SULEVs). In this analysis, all categories of LEVs are treated the same due to the fact that there are very 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.

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 (generally 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 GHG 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 generally 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 detail 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 provide all transportation estimates presented throughout the report in one place.

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. In order to calculate these figures, 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. In order to provide comparable information on transportation and mobile sources, Table A-114 provides estimates of CO_2 from these other mobile sources, developed from EPA's NONROAD components of the MOVES2014a 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-103). 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-114, Table A-116, and Table A-117 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 Chapter 3.1 for a discussion of that methodology).

Table A-114: CO_2 Emissions from Non-Transportation Mobile Sources (MMT CO_2 Eq.)

Fuel Type/ Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Agricultural Equipment[a,b]	31.0	36.6	39.3	47.4	49.5	48.7	45.7	46.9	47.8	49.6	51.1	50.0	50.8	47.5
Construction/ Mining Equipment[a,c]	42.0	48.9	56.1	66.8	68.1	68.3	69.8	71.1	73.4	74.5	76.1	81.5	79.7	78.1
Other Sources[a,d]	54.5	59.9	62.6	75.9	77.1	75.7	76.4	77.1	80.0	79.6	79.1	80.1	81.4	80.6
Total	**127.6**	**145.4**	**158.0**	**190.0**	**194.6**	**192.8**	**191.9**	**195.1**	**201.2**	**203.7**	**206.3**	**211.6**	**211.9**	**206.1**

[a] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications. These method changes created a time-series inconsistency in this Inventory between 2015 and previous years for agricultural, construction, commercial, and industrial non-road mobile sources. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1 under *CH_4 and N_2O from Mobile Combustion*.

[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.

[d] "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.

Note: 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 Chapter 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015.

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 (as a result 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 and light-duty trucks; 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-115 below presents these HFC emissions. Table A-116 presents all transportation and mobile source greenhouse gas emissions, including HFC emissions.

Table A-115: HFC Emissions from Transportation Sources (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Mobile AC	+	**18.9**	**53.5**	**65.0**	**65.6**	**66.0**	**66.3**	**65.2**	**61.7**	**55.7**	**49.9**	**44.0**	**40.9**	**38.3**
Passenger Cars	+	11.2	28.1	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3	16.0	14.9
Light-Duty Trucks	+	7.8	25.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7	25.0	23.4
Comfort Cooling for Trains and Buses	+	+	**0.1**	**0.3**	**0.3**	**0.4**	**0.4**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**	**0.5**
School and Tour Buses	+	+	0.1	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Transit Buses	+	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1
Rail	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Refrigerated Transport	+	0.2	0.8	1.8	2.0	2.3	2.6	2.9	3.5	4.1	4.7	5.3	5.8	6.4
Medium- and Heavy-Duty Trucks	+	0.1	0.4	1.2	1.4	1.6	1.7	1.9	2.2	2.5	2.8	3.1	3.4	3.6
Rail	+	0.0	0.3	0.5	0.5	0.6	0.8	0.9	1.2	1.5	1.7	2.0	2.3	2.6
Ships and Boats	+	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	+	**19.1**	**54.5**	**67.1**	**67.9**	**68.7**	**69.3**	**68.5**	**65.6**	**60.2**	**55.1**	**49.8**	**47.2**	**45.1**

+ 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-116 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 2,018.4 MMT CO_2 Eq. in 2015, an increase of 20 percent from 1990.[55] Transportation sources account for 1,810.4 MMT CO_2 Eq. while non-transportation mobile sources account for 208.1MMT 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 the Carbon Dioxide Emissions from Fossil Fuel Combustion section, 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 Substitutes for Ozone Depleting Substances section of the IPPU chapter; and estimates of CO_2 emitted from non-transportation mobile sources reported in Table A-112 above.

Although all emissions reported here are based on estimates reported throughout this Inventory, some additional calculations were performed in order 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 2017 and DESC 2016). 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.[56] 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 and buses 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 2016). Carbon dioxide emissions from non-transportation mobile sources are calculated using data from EPA's NONROAD component of MOVES2014a (EPA 2016d). 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 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 1,810.4 MMT CO_2 Eq. in 2015.

On-road vehicles were responsible for about 75 percent of all transportation and non-transportation mobile greenhouse gas emissions in 2015. Although passenger cars 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. Between 1990 and 2015, greenhouse gas emissions from passenger cars increased by 15 percent, while emissions from light-duty trucks decreased by three percent.[57] Meanwhile, greenhouse gas emissions from medium- and heavy-duty trucks

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[55] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method updates are discussed in the *Planned Improvements* sections of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion* and *CH_4 and N_2O from Mobile Combustion.*

[56] 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 >).

[57] In 2011 FHWA changed how they defined vehicle types for the purposes of reporting VMT for the years 2007–2010. The old approach to vehicle classification was based on body type and split passenger vehicles into "Passenger Cars" and "Other 2 Axle 4-Tire Vehicles". The new approach is a vehicle classification system based on wheelbase. Vehicles with a wheelbase less than or equal to 121 inches are counted as "Light-duty Vehicles –Short Wheelbase". Passenger vehicles with a wheelbase greater than 121 inches are counted as "Light-duty Vehicles - Long Wheelbase". This change in vehicle classification has moved some smaller trucks and sport utility vehicles from the light truck category to the passenger vehicle category in this Inventory. These changes are reflected in a large drop in light-truck emissions between 2006 and 2007. In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series

increased 79 percent between 1990 and 2015, reflecting the increased volume of total freight movement and an increasing share transported by trucks.

Greenhouse gas emissions from aircraft decreased 15 percent between 1990 and 2015. Emissions from military aircraft decreased 58 percent between 1990 and 2015. Commercial aircraft emissions rose 27 percent between 1990 and 2007 then dropped 15 percent from 2007 to 2015, a change of approximately 8 percent between 1990 and 2015.

Non-transportation mobile sources, such as construction/mining equipment, agricultural equipment, and industrial/commercial equipment, emitted approximately 208.1 MMT CO_2 Eq. in 2015. Together, these sources emitted more greenhouse gases than ships and boats, and rail combined. Emissions from non-transportation mobile sources increased rapidly, growing approximately 62 percent between 1990 and 2015.[58] 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-117 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 the vast majority of transportation greenhouse gas emissions (approximately 97 percent in 2015). Emissions of CO_2 from transportation and mobile sources increased by 320.0 MMT CO_2 Eq. between 1990 and 2015.[59] In contrast, the combined emissions of CH_4 and N_2O decreased by 29.7 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 45.1 MMT CO_2 Eq. in 2015 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-118 and Table A-119 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-118. 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-119. 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-116. In addition, estimates of fuel consumption from DOE (1993 through 2016) were used to allocate rail emissions between passenger and freight categories.

In 2015, passenger transportation modes emitted 1,254.1 MMT CO_2 Eq., while freight transportation modes emitted 515.5 MMT CO_2 Eq. Between 1990 and 2015, the percentage growth of greenhouse gas emissions from freight sources was 47 percent, while emissions from passenger sources grew by 9 percent.[61] This difference in growth is due largely to the rapid increase in emissions associated with medium- and heavy-duty trucks.

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inconsistency between 2015 and previous years in this Inventory. The method updates are discussed in the *Planned Improvements* sections of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion* and *CH_4 and N_2O from Mobile Combustion.*

[58] See previous footnote.

[59] See previous footnote.

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

[61] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method updates are discussed in the *Planned Improvements* sections of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion* and *CH_4 and N_2O from Mobile Combustion.*

Table A-116: Total U.S. Greenhouse Gas Emissions from Transportation and Mobile Sources (MMT CO_2 Eq.)

Mode / Vehicle Type / Fuel Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
Transportation Total[a,c]	**1,554.4**	**1,698.4**	**1,927.0**	**2,005.9**	**1,999.4**	**1,999.8**	**1,902.5**	**1,824.1**	**1,832.5**	**1,804.3**	**1,784.7**	**1,794.3**	**1,820.0**	**1,810.4**	**16%[c]**
On-Road Vehicles[c]	1,233.5	1,370.4	1,572.6	1,673.4	1,669.5	1,664.5	1,586.2	1,540.5	1,541.3	1,514.3	1,503.6	1,503.1	1,553.8	1,522.0	23%[c]
Passenger Cars[c]	656.7	646.6	697.2	708.7	682.8	843.3	802.1	792.6	783.4	774.1	767.7	763.0	778.4	758.4	15%[c]
Gasoline[b, c]	648.7	627.6	665.4	672.8	646.9	807.7	767.1	759.1	752.1	746.1	743.0	741.7	758.3	739.2	14%[c]
Diesel[b,c]	7.9	7.8	3.7	4.2	4.1	4.1	3.7	3.6	3.7	4.1	4.1	4.1	4.1	4.3	-46%
AFVs[d]	+	+	+	+	+	+	+	+	+	+	+	+	0.1	0.1	1,057%
HFCs from Mobile AC	+	11.2	28.1	31.7	31.7	31.5	31.2	29.9	27.5	23.9	20.6	17.3	16.0	14.9	NA
Light-Duty Trucks[c]	**335.2**	**436.5**	**514.9**	**552.2**	**564.8**	**367.3**	**348.0**	**351.4**	**348.7**	**331.5**	**325.1**	**322.2**	**343.7**	**325.1**	**-3%[c]**
Gasoline[b,c]	323.5	413.6	469.2	492.7	503.6	318.8	300.4	303.7	301.5	286.4	282.6	282.3	304.2	286.9	-11%[c]
Diesel[b]	11.5	14.9	20.1	25.8	26.7	13.5	12.1	12.0	12.5	13.0	12.9	12.9	13.9	13.9	21%
AFVs[d]	0.2	0.2	0.1	0.4	0.5	0.4	0.5	0.5	0.4	0.4	0.2	0.3	0.6	0.9	362%
HFCs from Mobile AC	+	7.8	25.4	33.3	33.9	34.5	35.1	35.2	34.2	31.7	29.3	26.7	25.0	23.4	NA
Medium- and Heavy-Duty Trucks[c]	**231.4**	**276.2**	**347.7**	**398.9**	**407.8**	**432.1**	**414.7**	**376.3**	**389.7**	**388.4**	**388.8**	**395.8**	**408.3**	**415.0**	**79%[c]**
Gasoline[b, c]	39.5	36.8	37.1	35.8	36.2	47.2	47.4	43.5	43.3	39.7	39.4	40.2	41.4	39.8	1%[c]
Diesel[b]	190.7	238.4	309.5	360.5	369.1	382.5	364.0	329.9	343.1	344.7	344.8	350.4	361.6	369.8	94%
AFVs[d]	1.1	0.9	0.6	1.3	1.1	0.8	1.5	1.0	1.1	1.5	1.8	2.1	1.9	1.8	55%
HFCs from Refrigerated Transport[e]	+	0.1	0.4	1.2	1.4	1.6	1.7	1.9	2.2	2.5	2.8	3.1	3.4	3.6	NA
Buses[c]	**8.5**	**9.2**	**11.0**	**12.0**	**12.2**	**17.6**	**17.1**	**16.0**	**15.9**	**16.7**	**17.8**	**18.0**	**19.5**	**19.8**	**134%[c]**
Gasoline[b,c]	0.4	0.4	0.4	0.4	0.4	0.7	0.7	0.8	0.7	0.7	0.8	0.9	0.9	0.9	156%[c]
Diesel[b]	8.0	8.7	10.2	10.6	10.6	15.5	14.6	13.6	13.5	14.4	15.4	15.5	16.9	17.3	116%
AFVs[d]	0.1	0.1	0.2	0.8	1.0	1.0	1.3	1.1	1.2	1.1	1.1	1.2	1.2	1.1	1,128%
HFCs from Comfort Cooling	+	+	0.1	0.3	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	NA
Motorcycles[c]	**1.8**	**1.8**	**1.9**	**1.7**	**1.9**	**4.3**	**4.4**	**4.2**	**3.7**	**3.6**	**4.2**	**4.0**	**3.9**	**3.7**	**110%[c]**
Gasoline[b, c]	1.8	1.8	1.9	1.7	1.9	4.3	4.4	4.2	3.7	3.6	4.2	4.0	3.9	3.7	110%[c]
Aircraft	**189.2**	**176.7**	**199.4**	**193.6**	**186.3**	**183.4**	**176.7**	**157.4**	**154.8**	**149.9**	**146.5**	**150.1**	**151.5**	**160.7**	**-15%**
General Aviation Aircraft	**42.9**	**35.8**	**35.9**	**40.1**	**30.1**	**24.4**	**30.5**	**21.2**	**26.7**	**22.5**	**19.9**	**23.6**	**19.7**	**25.7**	**-40%**
Jet Fuel[f]	39.8	33.0	33.4	37.6	27.7	22.2	28.5	19.4	24.8	20.6	18.2	22.0	18.2	24.2	-39%
Aviation Gasoline	3.2	2.8	2.6	2.5	2.4	2.2	2.0	1.9	1.9	1.9	1.8	1.6	1.5	1.5	-53%
Commercial Aircraft	**110.9**	**116.3**	**140.6**	**134.0**	**138.3**	**141.0**	**128.4**	**120.6**	**114.4**	**115.7**	**114.3**	**115.4**	**116.3**	**120.1**	**8%**
Jet Fuel[f]	110.9	116.3	140.6	134.0	138.3	141.0	128.4	120.6	114.4	115.7	114.3	115.4	116.3	120.1	8%
Military Aircraft	**35.3**	**24.5**	**22.9**	**19.5**	**18.0**	**18.0**	**17.7**	**15.5**	**13.7**	**11.7**	**12.2**	**11.1**	**15.5**	**14.9**	**-58%**
Jet Fuel[f]	35.3	24.5	22.9	19.5	18.0	18.0	17.7	15.5	13.7	11.7	12.2	11.1	15.5	14.9	-58%
Ships and Boats[g]	**44.9**	**58.5**	**61.3**	**45.0**	**48.2**	**54.8**	**45.4**	**38.8**	**44.9**	**46.5**	**40.2**	**39.5**	**17.6**	**33.1**	**-26%**
Gasoline	12.4	14.1	10.2	14.0	13.8	13.6	13.2	13.0	12.7	12.6	12.5	12.4	1.3	12.3	-1%
Distillate Fuel	9.6	14.9	17.1	11.4	10.8	11.6	11.4	11.5	11.1	14.0	11.4	11.5	10.2	16.2	68%
Residual Fuel[h]	22.9	29.5	33.8	19.6	23.4	29.4	20.7	14.2	20.9	19.8	16.2	15.5	6.0	4.5	-81%
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	NA

Rail	**38.9**	**43.1**	**46.2**	**51.3**	**53.2**	**52.5**	**48.8**	**41.7**	**44.8**	**46.6**	**45.6**	**46.7**	**48.5**	**46.7**	**20%**
Distillate Fuel[i]	35.8	40.0	42.5	46.0	48.1	46.7	43.3	36.3	39.0	40.8	39.9	40.5	42.0	40.3	12%
Electricity	3.1	3.1	3.5	4.8	4.6	5.1	4.7	4.5	4.5	4.3	3.9	4.1	4.1	3.8	23%
Other Emissions from Rail Electricity Use[j]	0.1	0.1	+	0.1	+	0.1	+	+	+	+	+	+	+	+	-100%
HFCs from Comfort Cooling	+	+	+	+	+	+	+	+	+	+	+	+	+	+	NA
HFCs from Refrigerated Transport[e]	+	+	0.3	0.5	0.5	0.6	0.8	0.9	1.2	1.5	1.7	2.0	2.3	2.6	NA
Pipelines[k]	**36.0**	**38.4**	**35.4**	**32.4**	**32.4**	**34.4**	**35.9**	**37.1**	**37.3**	**38.1**	**40.5**	**46.2**	**39.4**	**38.0**	**5%**
Natural Gas	36.0	38.4	35.4	32.4	32.4	34.4	35.9	37.1	37.3	38.1	40.5	46.2	39.4	38.0	5%
Other Transportation	**11.8**	**11.3**	**12.1**	**10.2**	**9.9**	**10.2**	**9.5**	**8.5**	**9.5**	**9.0**	**8.3**	**8.8**	**9.1**	**10.0**	**-16%**
Lubricants	11.8	11.3	12.1	10.2	9.9	10.2	9.5	8.5	9.5	9.0	8.3	8.8	9.1	10.0	-16%
Non-Transportation Mobile[l] Total	**128.8**	**146.7**	**159.5**	**191.8**	**196.4**	**194.6**	**193.7**	**196.9**	**203.1**	**205.7**	**208.3**	**213.6**	**213.9**	**208.1**	**62%[l]**
Agricultural Equipment[l,m]	**31.4**	**37.0**	**39.7**	**47.9**	**50.0**	**49.2**	**46.2**	**47.4**	**48.4**	**50.1**	**51.6**	**50.6**	**51.3**	**48.0**	**53%[l]**
Gasoline[l]	7.3	8.3	5.8	9.6	11.0	9.4	5.6	5.9	6.0	7.0	7.6	5.7	5.6	1.4	-81%[l]
Diesel	24.1	28.7	33.9	38.3	39.1	39.8	40.6	41.5	42.3	43.2	44.0	44.9	45.7	46.6	94%
Construction/ Mining[l] Equipment[l,m]	**42.4**	**49.3**	**56.6**	**67.4**	**68.7**	**68.9**	**70.4**	**71.7**	**74.0**	**75.2**	**76.8**	**82.3**	**80.4**	**78.8**	**86%[l]**
Gasoline[l]	4.4	4.0	3.0	6.2	6.1	5.1	5.1	4.9	5.7	5.3	5.5	9.4	6.1	3.2	-27%[l]
Diesel	38.0	45.4	53.6	61.2	62.6	63.9	65.3	66.9	68.3	69.8	71.3	72.8	74.4	75.6	99%
Other Equipment[l,o]	**55.0**	**60.4**	**63.2**	**76.5**	**77.7**	**76.4**	**77.1**	**77.8**	**80.7**	**80.4**	**79.9**	**80.8**	**82.2**	**81.3**	**48%[l]**
Gasoline[l]	40.3	42.6	42.0	52.0	52.5	50.6	50.6	50.6	52.9	51.9	50.7	50.9	51.7	50.9	26%[l]
Diesel	14.7	17.8	21.2	24.6	25.2	25.8	26.5	27.2	27.8	28.5	29.2	29.9	30.5	30.4	106%
Transportation and Non-Transportation Mobile Total[c,l]	**1,683.1**	**1,845.1**	**2,086.5**	**2,197.7**	**2,195.9**	**2,194.4**	**2,096.3**	**2,021.0**	**2,035.6**	**2,010.0**	**1,993.0**	**2,007.9**	**2,033.9**	**2,018.4**	**20%[c,l]**

+ 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 VM-1 (FHWA 1996 through 2016). Data from Table VM-1 is used to estimate the share of 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 2016). These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.

[c] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1 under *CO_2 from Fossil Fuel Combustion*.

[d] 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 2014 Inventory and apply to the 1990–2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

[e] An updated Vintaging model was used to allocate refrigerated transport emissions to the trucking, rail and marine sectors in this Inventory.

[f] Updates to the jet fuel heat content used in the mobile N_2O emissions estimates for years 1990 through present resulted in small changes to the time series emissions compared to the previous Inventory.

[g] 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.
[h] 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.
[i] Class II and Class II diesel consumption data for 2014 and 2015 is not available yet, therefore 2013 data is used as a proxy.
[j] 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).
[k] 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.
[l] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications. These method changes created a time-series inconsistency in this Inventory between 2015 and previous years for agricultural, construction, commercial, and industrial non-road mobile sources. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CH_4 and N_2O from Mobile Combustion*. 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 Chapter 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).
[m] Includes equipment, such as tractors and combines, as well as fuel consumption from trucks that are used off-road in agriculture.
[n] Includes equipment, such as cranes, dumpers, and excavators, as well as fuel consumption from trucks that are used off-road in construction.
[o] "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 (MOVES2014a) model that is used to estimate on-road gasoline vehicle distribution and mileage across the time series. See Section 3.1 "CH_4 and N_2O from Mobile Combustion" for more detail. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. 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.

Table A-117: Transportation and Mobile Source Emissions by Gas (MMT CO_2 Eq.)

	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
CO_2 [a, b]	1,636.2	1,769.6	1,979.0	2,091.9	2,091.7	2,094.1	1,997.9	1,925.1	1,943.4	1,924.6	1,915.2	1,937.4	1,967.9	1,956.2	20%[a]
N_2O [a]	41.2	51.2	49.3	35.7	33.5	28.9	26.6	25.0	24.1	22.8	20.4	18.5	16.6	15.1	-63%[a]
CH_4 [a]	5.6	5.2	3.7	2.8	2.7	2.5	2.4	2.3	2.3	2.3	2.2	2.1	2.1	2.0	-64%[a]
HFC	+	19.1	54.5	67.1	67.9	68.7	69.3	68.5	65.6	60.2	55.1	49.8	47.2	45.1	NA
Total[a,c]	**1,683.1**	**1,845.0**	**2,086.5**	**2,197.6**	**2,195.8**	**2,194.3**	**2,096.2**	**2,021.0**	**2,035.5**	**2,009.9**	**1,992.9**	**2,007.8**	**2,033.8**	**2,018.4**	**20%[a]**

+ 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] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method updates are discussed in the *Planned Improvements* sections of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion* and *CH_4 and N_2O from Mobile Combustion.*
[b] 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 Chapter 3.1 for the methodology for estimating CO_2 emissions from fossil fuel combustion in this Inventory).
[c] Total excludes other emissions from electricity generation and CH_4 and N_2O emissions from electric rail.
Note: The current Inventory includes updated vehicle population data based on the MOVES 2014a Model.
Note: 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 VM-1 (FHWA 1996 through 2016). Data from Table VM-1 is used to estimate the share of 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 2016). These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.
Note: 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.

Figure A-4: Domestic Greenhouse Gas Emissions by Mode and Vehicle Type, 1990 to 2015 (MMT CO_2 Eq.)

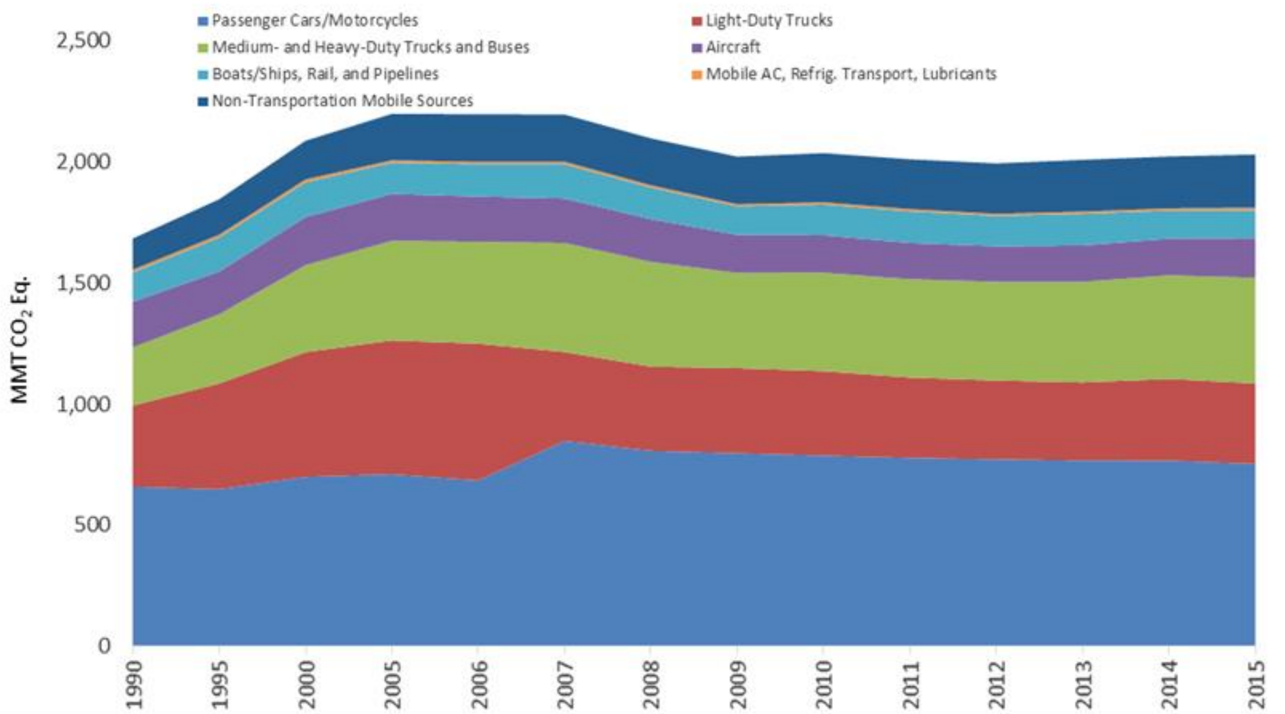

Table A-118: Greenhouse Gas Emissions from Passenger Transportation (MMT CO_2 Eq.)

Vehicle Type	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
On-Road Vehicles[a,b,c]	**1,002.1**	**1,094.1**	**1,224.9**	**1,274.5**	**1,261.7**	**1,232.4**	**1,171.6**	**1,164.3**	**1,151.6**	**1,125.9**	**1,114.8**	**1,107.3**	**1,145.5**	**1,107.1**	**10%[c]**
Passenger Cars	656.7	646.6	697.2	708.7	682.8	843.3	802.1	792.6	783.4	774.1	767.7	763.0	778.4	758.4	15%[c]
Light-Duty Trucks	335.2	436.5	514.9	552.2	564.8	367.3	348.0	351.4	348.7	331.5	325.1	322.2	343.7	325.1	-3%
Buses	8.5	9.2	11.0	12.0	12.2	17.6	17.1	16.0	15.9	16.7	17.8	18.0	19.5	19.8	134%[c]
Motorcycles	1.8	1.8	1.9	1.7	1.9	4.3	4.4	4.2	3.7	3.6	4.2	4.0	3.9	3.7	110%[c]
Aircraft	**134.6**	**132.0**	**152.2**	**152.7**	**146.6**	**144.9**	**140.9**	**125.2**	**124.8**	**122.1**	**118.5**	**123.1**	**119.7**	**129.3**	**-4%**
General Aviation	42.9	35.8	35.9	40.1	30.1	24.4	30.5	21.2	26.7	22.5	19.9	23.6	19.7	25.7	-40%
Commercial Aircraft	91.7	96.2	116.3	112.6	116.5	120.4	110.4	103.9	98.0	99.6	98.6	99.5	100.0	103.6	13%
Recreational Boats	**14.3**	**16.4**	**13.0**	**17.2**	**17.1**	**17.0**	**16.6**	**16.5**	**16.3**	**16.2**	**16.2**	**16.3**	**1.3**	**12.3**	**-14%**
Passenger Rail	**4.4**	**4.5**	**5.2**	**6.2**	**6.0**	**6.6**	**6.2**	**6.1**	**6.2**	**5.9**	**5.5**	**5.8**	**5.7**	**5.4**	**24%**
Total[c]	**1,155.4**	**1,247.0**	**1,395.3**	**1,450.6**	**1,431.4**	**1,400.8**	**1,335.4**	**1,312.0**	**1,298.8**	**1,270.2**	**1,255.0**	**1,252.4**	**1,272.2**	**1,254.1**	**9%[c]**

[a] The current Inventory includes updated vehicle population data based on the MOVES 2014a 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 VM-1 (FHWA 1996 through 2016). Data from Table VM-1 is used to estimate the share of 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 2016). These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data are used as a proxy.

[c] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion*.

Notes: Data from DOE (1993 through 2016) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's Inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. 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 2014 Inventory and apply to the 1990 through 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

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.

Table A-119: Greenhouse Gas Emissions from Domestic Freight Transportation (MMT CO_2 Eq.)

By Mode	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Percent Change 1990-2015
Trucking[a,b,c]	231.4	276.3	347.9	398.9	407.8	432.1	414.7	376.3	389.7	388.4	388.8	395.8	408.3	415.0	79%[c]
Freight Rail	34.5	38.6	40.9	45.0	47.1	45.8	42.6	35.6	38.6	40.7	40.0	40.9	42.8	41.3	20%
Ships and Non-Recreational Boats	30.6	42.1	48.1	27.9	31.1	37.9	28.8	22.3	28.6	30.3	24.0	27.8	6.3	4.8	-84%
Pipelines[d]	36.0	38.4	35.4	32.4	32.4	34.4	35.9	37.1	37.3	38.1	40.5	46.2	39.4	38.0	5%
Commercial Aircraft	19.2	20.1	24.3	21.4	21.8	20.5	18.0	16.7	16.3	16.0	15.8	15.9	16.2	16.5	-14%
Total[c]	**351.7**	**415.5**	**496.7**	**525.5**	**540.1**	**570.7**	**539.9**	**487.9**	**510.4**	**513.4**	**509.1**	**526.6**	**513.1**	**515.5**	**47%[c]**

[a] The current Inventory includes updated vehicle population data based on the MOVES 2014a 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 VM-1 (FHWA 1996 through 2016). Data from Table VM-1 is used to estimate the share of 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 2016). These fuel consumption and mileage estimates are combined with estimates of fuel shares by vehicle type from DOE's TEDB Annex Tables A.1 through A.6 (DOE 1993 through 2016). TEDB data for 2015 has not been published yet, therefore 2014 data is as a proxy.

[c] In 2016, FHWA changed its methods for estimating the share of gasoline used in on-road and non-road applications, which created a time-series inconsistency between 2015 and previous years in this Inventory. The method changes resulted in a decrease in the estimated motor gasoline consumption for the transportation sector and a subsequent increase in the commercial and industrial sectors of this Inventory for 2015. The method updates are discussed further in the *Planned Improvements* section of Chapter 3.1. under *CO_2 from Fossil Fuel Combustion*.

[d] Pipelines reflect CO_2 emissions from natural gas powered pipelines transporting natural gas.

Notes: Data from DOE (1993 through 2015) were used to disaggregate emissions from rail and buses. Emissions from HFCs have been included in these estimates. In 2015, EPA incorporated the NONROAD2008 model into MOVES2014a. This year's inventory uses the NONROAD component of MOVES2014a for years 1999 through 2015. 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 2014 Inventory and apply to the 1990 to 2015 time period. This resulted in large reductions in AFV VMT, thus leading to a shift in VMT to conventional on-road vehicle classes.

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.

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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 2015 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* (IPCC 2006).

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 2015 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 Tier 3B 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 and 2015 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 the additional 1991 to1999 emissions estimates, which were established using previously available trends.

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 2000 to 2015 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 estimate is approximately 8 percent lower than the 2015 CO_2 emissions estimate. It is important to note that the distance flown increased by more than 45 percent over this 25-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.[62]

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 (Santoni et al. 2011). As a result, the U.S. EPA 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.*"[63] 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 less 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.

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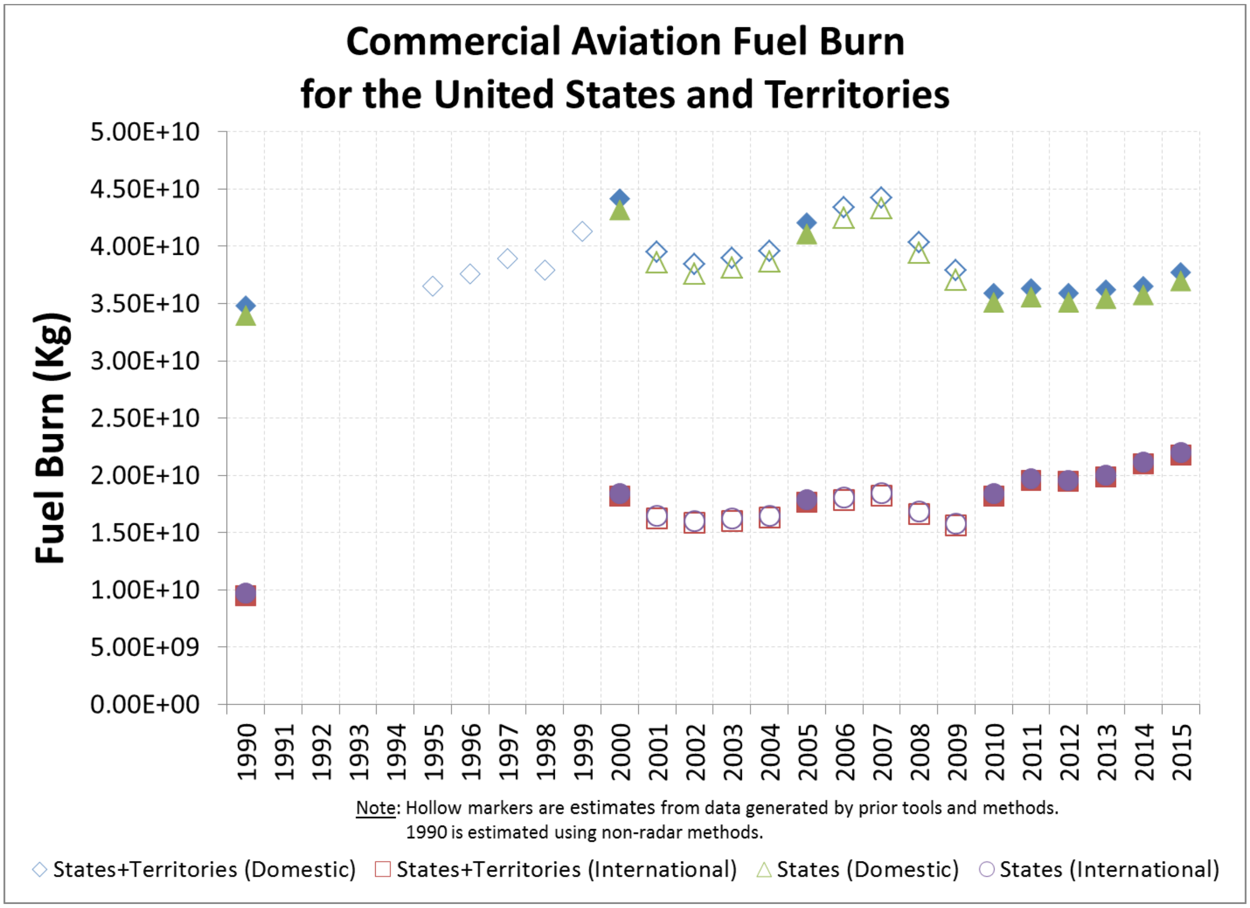
[62] Additional information on the AEDT modeling process is available at:
<http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/>.

[63] 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 <http://www.epa.gov/otaq/aviation.html>.

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



Note: Hollow markers are estimates from data generated by prior tools and methods. 1990 is estimated using non-radar methods.

Table A-120: Commercial Aviation Fuel Burn for the United States and Territories

Year	Region	Distance Flown (nmi)	Fuel Burn (M Gallon)	Fuel Burn (Tbtu)	Fuel Burn (Kg)	CO_2 (MMT)
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[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,136	1,638	36,528,990,675	115.2
1996[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,492	1,686	37,600,624,534	118.6
1997[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,937	1,747	38,940,896,854	122.9
1998[a]	Domestic U.S. 50 States and U.S. Territories	NA	12,601	1,701	37,930,582,643	119.7
1999[a]	Domestic U.S. 50 States and U.S. Territories	NA	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[a]	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[a]	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 [a]	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 [a]	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 [a]	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 [a]	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 [a]	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 [a]	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

NA (Not Applicable)

[a] Estimates for these years were derived from previously reported tools and methods

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Santoni, G., B. Lee, E. Wood, S. Herndon, R. Miake-Lye, S Wofsy, J. McManus, D. Nelson, M. Zahniser (2011) Aircraft emissions of methane and nitrous oxide during the alternative aviation fuel experiment. Environ Sci Technol. 2011 Aug 15; 45(16):7075-82.

3.4. Methodology for Estimating CH_4 Emissions from Coal Mining

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 from 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 emissions 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 2016).[64] Based on the four 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 2015, the average daily CH_4 emissions were multiplied by the number of days corresponding to the number of quarters the mine vent was operating. For example, if the mine vent was operational in one out of the four quarters, the average daily CH_4 emissions were multiplied by 92 days. Total ventilation emissions for a particular year were estimated by summing emissions from individual mines.

Since 2011, the nation's "gassiest" underground coal mines—those that liberate more than 36,500,000 actual cubic feet of CH_4 per year (about 14,700 MT CO_2 Eq.)—have been required to report to EPA's GHGRP (EPA 2016).[65] Mines that report to EPA's GHGRP must report quarterly measurements of CH_4 emissions from ventilation systems to EPA; 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.[66]

Since 2013, ventilation emission estimates have been calculated based on both EPA's GHGRP[67] data submitted by underground mines, and on quarterly measurement data obtained directly from MSHA for the remaining mines. The quarterly measurements are used to determine the average daily emissions rate for the reporting year quarter. The CH_4 liberated from ventilation systems was estimated by summing the emissions from the EPA's GHGRP mines and emissions based on MSHA quarterly measurements for the remaining mines not reporting to EPA's GHGRP.

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[64] 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.

[65] Underground coal mines report to EPA under Subpart FF of EPA's GHGRP. In 2015, 123 underground coal mines reported to the program.

[66] MSHA records coal mine CH_4 readings with concentrations of greater than 50 ppm (parts per million) CH_4. Readings below this threshold are considered non-detectable.

[67] 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-121: 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 Emissions Factors Used Instead of Mine-Specific Data
1992	1990 Emissions 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)

[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-six mines employed degasification systems in 2015, and the CH_4 liberated through these systems was reported to the EPA's GHGRP (EPA 2016). Sixteen of these mines reported CH_4 recovery and use projects, and the other ten 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 to estimate CH_4 liberated from degasification systems at 21 of the 26 mines that used degasification systems in 2015.

Degasification volumes for the life of any pre-mining wells are attributed to the mine as emissions in the year in which the well is mined through.[68] 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 5 mines with degasification systems that include pre-mining wells, EPA's GHGRP information was supplemented with historical data from state gas well production databases (DMME 2016; GSA 2016; WVGES 2016), as well as with mine-specific information regarding the dates on which pre-mining wells are mined through (JWR 2010; El Paso 2009). For pre-mining wells, the cumulative CH_4 production from the well is totaled using gas sales data, and considered liberated from the mine's degasification system the year in which the well is mined through.

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

EPA's GHGRP reports 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 unavailable, estimates of CH_4 liberated are based on historical CH_4 liberation rates.

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

Of the 16 active coal mines with operational CH_4 recovery and use projects in 2015, 14 sold the recovered CH_4 to a pipeline, including one that also used CH_4 to fuel a thermal coal dryer. Uses at other mines include electrical power generation (one mine) and heating mine ventilation air (one mine).

Ten of the 16 mines deployed degasification systems in 2015; for those mines, estimates of CH_4 recovered from the systems were exclusively based on GHGRP data. 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.

Of the 16 mines with methane recovery in 2015, four intersected pre-mining wells in 2015. EPA's GHGRP and supplemental data were used to estimate CH_4 recovered and used at two of these mines, while supplemental data alone were used at the other two mines, that reported as a single entity to EPA's GHGRP. Supplemental information was used for these four mines because estimating CH_4 recovery and use from pre-mining wells requires additional data (not reported under subpart FF of EPA's GHGRP; see discussion in step 1.2 above) to account for the emissions avoided. The supplemental data came from state gas production databases (GSA 2016; WVGES 2015), as well as mine-specific information on the timing of mined-through pre-mining wells (JWR 2010; El Paso 2009). For pre-mining wells, the cumulative CH_4 production from the wells was totaled using gas sales data, and considered to be CH_4 recovered and used from the mine's degasification system the year in which the well is mined through.

For one mine, due to a lack of mine-provided information used in prior years and a GHGRP reporting discrepancy, the CH_4 liberated was based on an estimate from historical mine-provided CH_4 recovery and use rates and state gas sales records (DMME 2016). In 2015 the availability of the Virginia Division of Gas and Oil Data Information System made it possible to estimate recovered degasification emissions for this mine based on published well production.

EPA's GHGRP reports with CH_4 recovered and used from degasification systems are reviewed for errors in reporting. For some mines, GHGRP data are corrected for the inventory based on expert judgment (see further discussion in Step 1.2). In 2015, GHGRP information was not used to estimate CH_4 recovered and used at two mines because of a lack of mine-provided information used in prior years and GHGRP reporting discrepancies.

In 2015, one mine destroyed a portion of its CH_4 emissions from ventilation systems using thermal oxidation technology. The amount of CH_4 recovered and destroyed by the project was determined through publicly available emission reduction project information (ACR 2016).

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

Mine-specific data were not available for estimating CH_4 emissions from surface coal mines or for post-mining activities. For surface mines, basin-specific coal production obtained from the Energy Information Administration's *Annual Coal Report* was 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 (see King 1994; Saghafi 2013). For post-mining activities, basin-specific coal production was 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 emissions 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 was to define the geographic resolution of the analysis and to collect coal production data at that level of resolution. The analysis was conducted by coal basin as defined in Table A-122, which presents coal basin definitions by basin and by state.

The Energy Information Administration's *Annual Coal Report* (EIA 2016) includes state- and county-specific underground and surface coal production by year. To calculate production by basin, the state level data were grouped into coal basins using the basin definitions listed in Table A-122. For two states—West Virginia and Kentucky—county-level production data were used for the basin assignments because coal production occurred in geologically distinct coal basins within these states. Table A-123 presents the coal production data aggregated by basin.

Step 2.2: Estimate Emissions 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 U.S. (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-124 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 was calculated by multiplying the coal production in each basin by the appropriate emission factors.

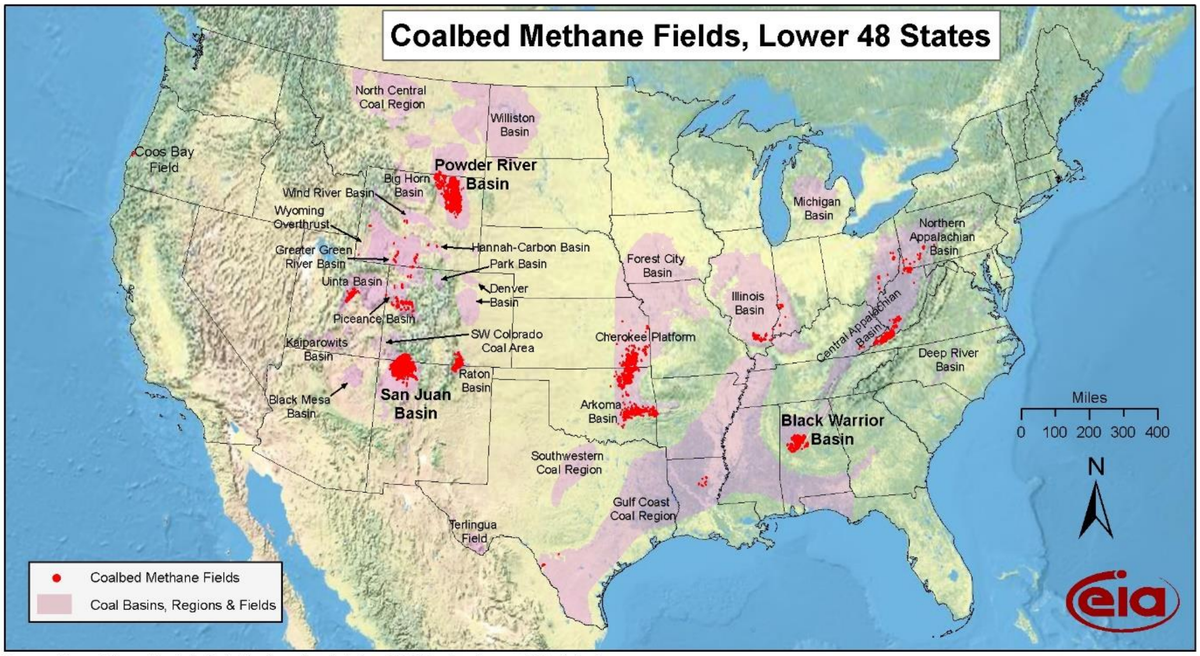
Table A-122 lists each of the major coal mine basins in the United States and the states in which they are located. As shown in Figure A-6, several coal basins span several states. Table A-123 shows annual underground, surface, and total coal production (in short tons) for each coal basin. Table A-124 shows the surface, post-surface, and post-underground emission factors used for estimating CH_4 emissions for each of the categories. Table A-125 presents annual estimates of CH_4 emissions for ventilation and degasification systems, and CH_4 used and emitted by underground coal mines. Table A-126 presents annual estimates of total CH_4 emissions from underground, post-underground, surface, and post-surface activities. Table A-127 provides the total net CH_4 emissions by state.

Table A-122: 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-123: Annual Coal Production (Thousand Short Tons)

Basin	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Underground Coal Production	**423,556**	**368,611**	**357,074**	**332,061**	**337,155**	**345,607**	**342,387**	**341,216**	**354,705**	**306,820**
N. Appalachia	103,865	111,151	105,228	99,629	103,109	105,752	103,408	104,198	116,700	103,578
Cent. Appalachia	198,412	123,083	114,998	98,689	96,354	94,034	78,067	70,440	64,219	53,230
Warrior	17,531	13,295	12,281	11,505	12,513	10,879	12,570	13,391	12,516	9,897
Illinois	69,167	59,180	64,609	67,186	72,178	81,089	92,500	98,331	105,211	96,361
S. West/Rockies	32,754	60,865	55,781	50,416	44,368	45,139	45,052	41,232	44,302	33,762
N. Great Plains	1,722	572	3,669	4,248	8,208	8,179	10,345	13,126	11,272	9,510
West Interior	105	465	508	388	425	535	445	498	485	482
Northwest	0	0	0	0	0	0	0	0	0	0
Surface Coal Production	**602,753**	**762,191**	**813,321**	**740,175**	**764,709**	**754,871**	**672,748**	**640,740**	**643,721**	**588,774**
N. Appalachia	60,761	28,873	30,413	26,552	26,082	26,382	21,411	19,339	17,300	13,491
Cent. Appalachia	94,343	112,222	118,962	97,778	89,788	90,778	69,721	57,173	52,399	37,278
Warrior	11,413	11,599	11,172	10,731	11,406	10,939	9,705	8,695	7,584	6,437
Illinois	72,000	33,702	34,266	34,837	32,911	34,943	34,771	33,798	31,969	27,360
S. West/Rockies	43,863	42,756	34,283	32,167	28,889	31,432	30,475	28,968	27,564	26,020
N. Great Plains	249,356	474,056	538,387	496,290	507,995	502,734	455,320	444,740	458,112	436,928
West Interior	64,310	52,263	44,361	39,960	46,136	55,514	49,293	46,477	47,201	40,083
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550	1,502	1,177
Total Coal Production	**1,026,309**	**1,130,802**	**1,170,395**	**1,072,236**	**1,101,864**	**1,100,478**	**1,015,135**	**981,956**	**998,426**	**895,594**
N. Appalachia	164,626	140,024	135,641	126,181	129,191	132,134	124,819	123,537	134,000	117,069
Cent. Appalachia	292,755	235,305	233,960	196,467	186,142	184,812	147,788	127,613	116,618	90,508
Warrior	28,944	24,894	23,453	22,236	23,919	21,818	22,275	22,086	20,100	16,334
Illinois	141,167	92,882	98,875	102,023	105,089	116,032	127,271	132,129	137,180	123,721
S. West/Rockies	76,617	103,621	90,064	82,583	73,257	76,571	75,527	70,200	71,956	59,782
N. Great Plains	251,078	474,628	542,056	500,538	516,203	510,913	465,665	457,866	469,384	446,438
West Interior	64,415	52,728	44,869	40,348	46,561	56,049	49,738	46,975	47,686	40,565
Northwest	6,707	6,720	1,477	1,860	2,151	2,149	2,052	1,550	1,502	1,177

Note: Totals may not sum due to independent rounding.
Source for 1990–2015 data: EIA (1990 through 2015), *Annual Coal Report*. Table 1. U.S. Department of Energy.
Source for 2015 data: spreadsheet for the 2015 *Annual Coal Report*.

Table A-124: 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
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	1.8	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-125: Underground Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Ventilation Output	112	75	100	114	117	97	90	89	89	84

Adjustment Factor for Mine Data [a]	98%	98%	99%	99%	99%	99%	99%	100%	100%	100%
Adjusted Ventilation Output	114	77	101	115	118	98	91	89	89	84
Degasification System Liberated	54	48	49	49	58	48	45	45	42	41
Total Underground Liberated	168	124	150	163	177	147	137	134	131	126
Recovered & Used	(14)	(37)	(40)	(40)	(49)	(42)	(38)	(38)	(35)	(33)
Total	**154**	**87**	**110**	**123**	**128**	**104**	**98**	**96**	**96**	**93**

[a] Refer to Table A-121.

Note: Totals may not sum due to independent rounding. Parenthesis indicate negative values.

Table A-126: Total Coal Mining CH_4 Emissions (Billion Cubic Feet)

Activity	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Underground Mining	154	87	110	123	128	104	98	96	96	93
Surface Mining	22	25	27	24	24	24	21	20	20	18
Post-Mining (Underground)	19	16	15	14	14	14	14	14	14	12
Post-Mining (Surface)	5	5	6	5	5	5	5	4	4	4
Total	**200**	**132**	**157**	**166**	**171**	**148**	**138**	**134**	**135**	**126**

Note: Totals may not sum due to independent rounding.

Table A-127: Total Coal Mining CH_4 Emissions by State (Million Cubic Feet)

State	1990	2005	2008	2009	2010	2011	2012	2013	2014	2015
Alabama	32,097	15,789	20,992	22,119	21,377	18,530	18,129	17,486	16,301	12,675
Alaska	50	42	43	54	63	63	60	45	44	34
Arizona	151	161	107	100	103	108	100	101	107	91
Arkansas	5	+	237	119	130	348	391	214	176	559
California	1	0	0	0	0	0	0	0	0	0
Colorado	10,187	13,441	12,871	13,999	16,470	11,187	9,305	4,838	4,038	3,248
Illinois	10,180	6,488	7,568	7,231	8,622	7,579	9,763	8,920	9,217	10,547
Indiana	2,232	3,303	5,047	5,763	5,938	6,203	7,374	6,427	7,159	6,891
Iowa	24	0	0	0	0	0	0	0	0	0
Kansas	45	11	14	12	8	2	1	1	4	12
Kentucky	10,018	6,898	9,986	12,035	12,303	10,592	7,993	8,098	8,219	6,377
Louisiana	64	84	77	73	79	168	80	56	52	69
Maryland	474	361	263	219	238	263	197	166	169	170
Mississippi	0	199	159	193	224	154	165	200	209	176
Missouri	166	3	15	28	29	29	26	26	23	9
Montana	1,373	1,468	1,629	1,417	1,495	1,445	1,160	1,269	1,379	1,353
New Mexico	363	2,926	3,411	3,836	3,956	4,187	2,148	2,845	2,219	2,648
North Dakota	299	306	303	306	296	289	281	282	298	294
Ohio	4,406	3,120	3,686	4,443	3,614	3,909	3,389	3,182	3,267	2,718
Oklahoma	226	825	932	624	436	360	499	282	112	735
Pennsylvania	21,864	17,904	20,684	22,939	23,372	17,708	17,773	20,953	19,803	19,587
Tennessee	276	115	86	69	67	60	35	31	22	40
Texas	1,119	922	783	704	823	922	887	854	876	721
Utah	3,587	4,787	5,524	5,449	5,628	3,651	3,624	2,733	1,605	1,737
Virginia	46,041	8,649	9,223	8,042	9,061	8,526	6,516	8,141	6,980	6,386
Washington	146	154	0	0	0	0	0	0	0	0
West Virginia	48,335	29,745	36,421	40,452	40,638	35,709	33,608	32,998	38,023	35,784
Wyoming	6,671	14,745	16,959	15,627	16,032	15,916	14,507	14,025	14,339	13,624
Total	**200,399**	**132,481**	**157,112**	**165,854**	**171,000**	**147,908**	**138,012**	**134,173**	**134,643**	**126,483**

+ 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 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 and CO_2 Emissions from Petroleum Systems

As described in the main body text on Petroleum Systems, the Inventory methodology involves the calculation of emissions for 65 activities that emit CH_4 and 35 activities that emit non-combustion CO_2 from petroleum systems 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.

Tables referenced in Annex 3.5 are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg.

Most of the activities are part of crude oil production field operations, which account for 97.9 percent of total oil industry CH_4 emissions. Crude transportation and refining accounted for the remaining CH_4 emissions of approximately 0.5 and 1.6 percent, respectively. Non-combustion CO_2 emissions were analyzed for production operations and asphalt blowing, flaring, and process vents in refining operations. Non-combustion CO_2 emissions from transportation operations are not included because they are negligible. The following steps were taken to estimate CH_4 and CO_2 emissions from petroleum systems.

Methane Emission Factors

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 early years of the time series.

In recent Inventories, EPA has revised the emission estimation methodology for many sources in Petroleum Systems. New data from studies and EPA's GHGRP (EPA 2016a,b) 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 the refining segment, EPA has directly used the GHGRP data for all emission sources for recent years (2011 forward) and developed source level throughput-based emission factors from GHGRP data to estimate emissions in earlier time series years (1990 through 2010). For some sources, EPA continues to apply the historical emission factors for all time series years.

Many key sources in Petroleum Systems currently use emission factors that account for control technologies and emission reduction practices when paired with related activity data (see below section "Activity Data"). This approach allows for net emissions to be calculated directly. 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 oil well completions with hydraulic fracturing, the controlled and uncontrolled emission factors were developed using data analyzed for the 2015 NSPS OOOOa proposal (EPA 2015a). For pneumatic controllers, separate estimates are developed for low bleed, high bleed, and intermittent controllers. For chemical injection pumps, the estimate is calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours.

For petroleum refining activities, as described above, 2010 to 2015 emissions were directly obtained from EPA's GHGRP (EPA 2016b). All refineries have been required to report CH_4 and CO_2 emissions for all major activities since 2010. The national totals of these emissions for each activity were used for the 2010 to 2015 emissions. The national emission totals for each activity were divided by refinery feed rates for those four Inventory years 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 2015c).

Offshore emissions from shallow water and deep water oil platforms are taken from analysis of the *2011 Gulf-wide Emission Inventory Study* (EPA 2015b; BOEM 2014). The emission factors were assumed to be representative of emissions from each source type over the period 1990 through 2014, and are used for each year throughout this period.

In general, 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. The standard approach used to estimate CO_2 emission factors was to use the CH_4 emissions factors and multiply them 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. The exceptions are the emissions factor for storage tanks, which are estimated using API E&P Tank Calc simulation runs of tank emissions for crude oil of different gravities less than 45 API degrees; emission factors for shallow water and deep water platforms, which are estimated from analysis of the *2011 Gulf-wide Emission Inventory Study* (BOEM 2014); and the emissions estimates for refineries, which are estimated using the data from U.S. EPA's GHGRP.

Table 3.5-2 below shows CH_4 emissions for all sources in Petroleum Systems, for all time series years. Table 3.5-3 shows the average emission factors for all sources in Petroleum Systems, for all time series years. These average emission factors are calculated by dividing net emissions by activity.

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

1990-2015 Inventory updates to emission factors

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in an April 2017 memorandum addressing the natural gas and petroleum production segment (see "Revisions to Natural Gas and Petroleum Production Emissions,") (EPA 2017a), as well as the "Recalculations Discussion" section of the main body text.

For the production segment, oil tank control category-specific emission factors based on GHGRP data and associated gas venting and flaring emission factors based on GHGRP data are used for the full time series.

Activity Data

Table 3.5-5 shows the activity data for all sources in Petroleum Systems, for all time series years. 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, 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, the number of platforms in shallow water and the number of platforms in deep water are used as activity data and are taken from Bureau of Ocean Energy Management (BOEM) (formerly Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE)) datasets (BOEM 2011a,b,c).

Additional detail on the basis for activity data used across the time series is provided in Table 3.5-6.

Methodology for well counts and events

EPA used DI Desktop, a production database maintained by DrillingInfo, Inc. (DrillingInfo 2016), covering U.S. oil and natural gas wells to populate activity data for oil wells with and without hydraulic fracturing, and oil well completions with hydraulic fracturing. EPA queried DI Desktop 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. 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. Oil wells with hydraulic fracturing were assumed to be the subset of the oil wells that were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in DI Desktop referenced against a formation type crosswalk developed by EIA (EIA 2012a).

For hydraulically fractured oil well completions, EPA developed activity data specific to each year of the time series using the date of completion or first reported production available from a data set licensed by DrillingInfo, Inc. For more information on the DrillingInfo data processing, please see Annex 3.6 Methodology for Estimating CH_4 and CO_2 from Natural Gas Systems.

Methodology for transportation segment

The activity data for the total crude transported in the transportation segment is not available. In this case, all the crude oil that was transported was assumed to go to refineries. Therefore, the activity data for the refining sector (i.e., refinery feed in 1000 bbl/year) was used also for the transportation sector. In the few cases where no data were located, oil industry data based on expert judgment was used. In the case of non-combustion CO_2 emission sources, the activity factors are the same as for CH_4 emission sources. In some instances, where 2014 data are not yet available 2013 or prior data has been used as proxy.

1990-2015 Inventory updates to activity data

Summary information for activity data for sources with revisions in this year's Inventory is below. The details are presented in an April 2017 memorandum addressing the natural gas and petroleum production segment (see "Revisions to Natural Gas and Petroleum Production Emissions,") (EPA 2017a), as well as the "Recalculations Discussion" section of the main body text.

For the production segment, oil tank throughput for years 2011 to 2015 was allocated to tank control categories based on 2015 GHGRP data. For year 1990, throughput was allocated between large and small tanks according to the fraction observed in GHGRP data for year 2015, and the previous Inventory assumption of 0 percent control on tanks was applied for 1990. Linear interpolation from the throughput allocations in year 1990 was used to assign activity data (throughput) by category for years 1991 through 2010.

For associated gas venting and flaring, the fraction of wells that either vent or flare associated gas each year was developed from 2015 GHGRP data. Then, that fraction of wells is split into wells that vent and wells that flare based on year-specific GHGRP data for 2011 to 2015; the 2011 split between venting and flaring wells is applied to all prior years.

Additionally in the production segment, GHGRP-based activity factors (i.e., counts per oil well) were calculated from 2015 GHGRP data and applied for the years 2011 to 2015 for pneumatic controllers, chemical injection pumps, separators, heater-treaters, and headers. The year-specific bleed type split (i.e., continuous high bleed, continuous low bleed, and intermittent bleed) was also developed for pneumatic controllers from 2011 to 2015 GHGRP data.

Methane and Carbon Dioxide Emissions by Emission Source for Each Year

Annual CH_4 emissions and CO_2 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 and CO_2 emissions, respectively. As various updates to emission factors have resulted in calculation of net emissions (already taking into account any reduced emissions) for sources in petroleum production, EPA no longer takes into account Gas STAR reductions in emission calculations, as had been done for previous Inventories. Net emissions at a segment level are shown in Table 3.5-2.

The same procedure for estimating CH_4 emissions applies for estimating non-energy related CO_2 emissions. CO_2 emissions by segment and source are summarized in Table 3.5-7 below. In this year's Inventory, EPA has held constant the CO_2 values from the previous GHG Inventory as it assesses improvements to the CO_2 estimates. See Planned Improvements in the main body text on Natural Gas Systems.

Refer to https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg for the following data tables, in Excel 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: Effective CH_4 Emission Factors (kg/unit activity) for Petroleum Systems Sources, for All Years
- Table 3.5-4: CH_4 Emission Factors for Petroleum Systems, Data Sources/Methodology
- Table 3.5-5: Activity Data for Petroleum Systems Sources, for All Years
- Table 3.5-6: Activity Data for Petroleum Systems, Data Sources/Methodology
- Table 3.5-7: CO_2 Emissions (kt) for Petroleum Systems, by Segment and Source, for All Years

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3.6. Methodology for Estimating CH_4 and CO_2 Emissions from Natural Gas Systems

As described in the main body text on Natural Gas Systems, the Inventory methodology involves the calculation of CH_4 and CO_2 emissions for over 100 emissions sources, and then the summation of emissions for each natural gas sector stage. 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.

Tables referenced in Annex 3.6 are available at https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg.

Methane Emission Factors

Table 3.6-2 shows the average emissions per unit for all sources in Natural Gas Systems, for all time series years. 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 (EPA/GRI 1996), the EPA's Greenhouse Gas Reporting Program (GHGRP), 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.

In recent Inventories, EPA has revised the emission estimation methodology for many sources in Natural Gas Systems. New data from studies and EPA's GHGRP (EPA 2016a) allows for the use of emission factors 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 through 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").

Many key sources in the production segment currently use emission factors that account for control technologies and emission reduction practices when paired with related activity data (see below section "Activity Data"). 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 liquids unloading, separate emissions estimates were developed for wells with plunger lifts and wells without plunger lifts. Likewise, for condensate 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. Chemical injection pumps estimates are calculated with an emission factor developed with GHGRP data, which is based on the previous GRI/EPA factor but takes into account operating hours. 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.

Table 3.6-1 below shows CH_4 emissions for all sources in Natural Gas Systems, for all time series years. Table 3.6-2 below shows the effective emission factors 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 emission factors used across the time series is provided in Table 3.6-6.

1990-2015 Inventory updates to emission factors

Summary information for emission factors for sources with revisions in this year's Inventory is below. The details are presented in three memoranda addressing the production, processing, and storage segments (see "Revisions to Natural Gas and Petroleum Production Emissions," "Revisions to Natural Gas Processing Emissions," and "Incorporating an Estimate for the Aliso Canyon Leak,") (EPA 2017a, b, and c), as well as the "Recalculations Discussion" section of the main body text.

For the production segment, condensate storage tanks control category-specific emission factors and liquids unloading category-specific emission factors based on GHGRP data are used for the full time series. Gathering and boosting episodic event emissions are represented with a new emission factor based on Marchese et al., (2015) for the full time series.

For the processing segment, emission factors were developed from GHGRP data for plant fugitives, compressors, dehydrators, flares, and blowdowns; and used for 2011 to 2015. In order to create time-series consistency for emission factors between earlier years' estimates (1990 to 1992) that generally rely on data from GRI/EPA 1996 and the most recent years' estimates (2011 to 2015) that were calculated using data from EPA's GHGRP, linear interpolation between the data endpoints of 1992 (GRI/EPA) and 2011 (GHGRP) was used for calculations.

For the storage segment, the emission estimate for year 2015 incorporated emissions data for the Aliso Canyon leak.

Activity Data

Table 3.6-7 shows the activity data for all sources in Natural Gas Systems, for all time series years. For a few sources, recent direct activity data were not available. For these sources, either 2014 data were used as proxy for 2015 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.

Additional detail on the basis for activity data used across the time series is provided in Table 3.6-8.

Methodology for well counts and events

EPA used DI Desktop, a production database maintained by DrillingInfo, Inc. (DrillingInfo 2016), covering U.S. oil and natural gas wells to populate activity data for non-associated gas wells with and without hydraulic fracturing, and completions with hydraulic fracturing. EPA queried DI Desktop 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 within DI Desktop 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. Gas wells with hydraulic fracturing were assumed to be the subset of the non-associated gas wells that were horizontally drilled and/or located in an unconventional formation (i.e., shale, tight sands, or coalbed). Unconventional formations were identified based on well basin, reservoir, and field data reported in DI Desktop 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 1990 through 2010, 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 DrillingInfo data. For 2011 through 2015, EPA used GHGRP data for the total number of well completions and workovers. The GHGRP data represent a subset of total national completions and workovers due to the reporting threshold and therefore using this data without scaling it up to national level could result in an underestimate. However, because EPA's GHGRP counts of completions and workovers were higher than national counts of completions and workovers, obtained using DI Desktop data, EPA directly used the GHGRP data for completions and workovers for 2011 through 2015.

EPA calculated the percentage of gas well completions and workovers with hydraulic fracturing in the each of the four control categories using 2011 through 2015 Subpart W data. EPA assumed no REC use from 1990 through 2000, used GHGRP RECs percentage for 2011 through 2015, 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 through 2015, EPA used the GHGRP data on flaring.

1990-2015 Inventory updates to activity data

Summary information for activity data for sources with revisions in this year's Inventory is below. The details are presented in two memoranda addressing the production and processing segments (see "Revisions to Natural Gas and

Petroleum Production Emissions" and "Revisions to Natural Gas Processing Emissions") (EPA 2017a and b), as well as the "Recalculations Discussion" section of the main body text.

For the production segment, condensate storage tank throughput was allocated to tank control categories based on 2015 GHGRP data for years 2011 forward. For year 1990, throughput was allocated between large and small tanks according to the fraction observed in GHGRP data for year 2015, and the existing Inventory assumption of 50 percent control on large tanks was applied for 1990, assuming that any controlled tanks had flares (as opposed to VRU); small tanks were assumed to be uncontrolled in 1990. Linear interpolation from the throughput allocations in year 1990 was used to assign activity data (throughput) by category for years 1991 through 2010.

For liquids unloading, activity data (fraction of wells conducting liquids unloading, and split between plunger and non-plunger lift) were developed from GHGRP data for recent time series years. The existing activity basis (API/ANGA (2012)) was used to estimate the fraction of wells conducting liquids unloading. EPA interpolated between 1990 (assuming all wells in 1990 that conducted liquids unloading vented without plunger lifts) to the activity category allocations in based on subpart W in year 2011 to populate activity data for years 1991 through 2010.

Additionally, in the production segment, GHGRP-based activity factors (i.e., counts per gas well) were calculated from 2015 GHGRP data and applied for the years 2011 to 2015 for in-line heaters, separators, dehydrators, compressors, meters/piping, pneumatic pumps, and pneumatic controllers. The year-specific bleed type split (i.e., continuous high bleed, continuous low bleed, and intermittent bleed was also developed for pneumatic controllers from 2011 to 2015 GHGRP data).

Activity data for gathering and boosting episodic event emissions is the count of gathering and boosting stations by year.

For the processing segment, the new emission factors developed from GHGRP data for plant fugitives, dehydrators, flares, and blowdowns are applied at the plant-level, while the compressor factors are applied at the compressor-level. The data source for national plant counts (Oil and Gas Journal) remains unchanged from previous Inventories.

Reductions Data

As described under "Emission Factors" above, some sources in Natural Gas Systems rely on 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 for activities such as replacing gas engines with electric compressor drivers, installing automated air-to-fuel ratio controls for engines, and implementing gas recovery for pipeline pigging operations.

There are significant Gas STAR reductions in the production segment that are not classified as applicable to specific emission sources. As many sources in production are now calculated with net factor approaches, to address potential double-counting of reductions, a scaling factor was applied to the "other voluntary reductions" to reduce this reported amount based an estimate of the fraction of those reductions that occur in the sources that are now calculated using net emissions approaches. This fraction was developed by dividing the net emissions from sources with net approaches, by the total production segment emissions (without deducting the Gas STAR reductions). The result for 2015, is that around 70 percent of the reductions were estimated to occur in sources for which net emissions are now calculated, which yields an adjusted "other reductions" estimate of 5 MMT CO_2 Eq.

<u>Federal regulations</u>

Regulatory actions reducing emissions in the current Inventory include National Emission Standards for Hazardous Air Pollutants (NESHAP) regulations and the 2012 New Source Performance Standards (NSPS) subpart OOOO for oil and gas . In regards 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.

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. Previous Inventories also took into account NESHAP driven reductions from storage tanks and from dehydrators in the processing segment; these sources are now estimated with net emission methodologies that take into account controls implemented due to regulations.

The Inventory reflects the NSPS subpart OOOO 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.

Methane Emissions by Emission Source for Each Year

Annual CH_4 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 emissions. As a final step, any relevant reductions data from each segment is summed for each year and deducted from the total emissions to estimate net CH_4 emissions for the Inventory. Potential emissions, reductions, and net emissions at a segment level are shown in Table 3.6-1.

CO_2 Emissions

The same procedure for estimating CH_4 emissions applies for estimating non-energy related CO_2 emissions, except the emission estimates are not adjusted for reductions due to the Natural Gas STAR program or regulations. CO_2 emissions by segment and source are summarized in Table 3.6-10 below. In this year's Inventory, EPA has held constant the CO_2 values from the previous GHG Inventory (developed using the methodology as described in this section) as it assesses improvements to the CO_2 estimates. See Planned Improvements in the main body text on Natural Gas Systems.

Produced natural gas contains, in some cases, as much as 8 percent CO_2. The same vented and fugitive natural gas that led to CH_4 emissions also contains a certain volume of CO_2. Accordingly, the CO_2 emissions for each sector can be estimated using the same activity data for these vented and fugitive sources. The emission factors used to estimate CH_4 were also used to calculate non-combustion CO_2 emissions. The Gas Technology Institute's (GTI, formerly GRI) Unconventional Natural Gas and Gas Composition Databases (GTI 2001) were used to adapt the CH_4 emission factors into non-combustion related CO_2 emission factors. For the CO_2 content used to develop CO_2 emission factors from CH_4 potential factors, see Table 3.6-11.

In the processing sector, the CO_2 content of the natural gas remains the same as the CO_2 content in the production sector for the equipment upstream of the acid gas removal unit because produced natural gas is usually only minimally treated after being produced and then transported to natural gas processing plants via gathering pipelines. The CO_2 content in gas for the remaining equipment that is downstream of the acid gas removal is the same as in pipeline quality gas. The EPA/GRI study estimates the average CH_4 content of natural gas in the processing sector to be 87 percent CH_4. The processing sector CO_2 emission factors were developed using CH_4 emission factors proportioned to reflect the CO_2 content of either produced natural gas or pipeline quality gas using the same methodology as the production sector.

For the transmission sector, CO_2 content in natural gas transmission pipelines was estimated for the top 20 transmission pipeline companies in the United States (separate analyses identified the top 20 companies based on gas throughput and total pipeline miles). The weighted average CO_2 content in the transmission pipeline quality gas in both cases—total gas throughput and total miles of pipeline—was estimated to be about 1 percent. To estimate the CO_2 emissions for the transmission sector, the CH_4 emission factors were proportioned from the 93.4 percent CH_4 reported in EPA/GRI (1996) to reflect the 1 percent CO_2 content found in transmission quality natural gas.

The natural gas in the distribution sector of the system has the same characteristics as the natural gas in the transmission sector. The CH_4 content (93.4 percent) and CO_2 content (1 percent) are identical to transmission segment contents due to the absence of any further treatment between sector boundaries. Thus, the CH_4 emissions factors were converted to CO_2 emission factors using the same methodology as discussed for the transmission sector.

Three exceptions to this methodology are CO_2 emissions from flares, CO_2 from acid gas removal units, and CO_2 from condensate tanks. In the case of flare emissions, a direct CO_2 emission factor from EIA (1996) was used. This emission factor was applied to the portion of offshore gas that is not vented and all of the gas reported as vented and flared onshore by EIA, including associated gas. The amount of CO_2 emissions from an acid gas unit in a processing plant is equal to the difference in CO_2 concentrations between produced natural gas and pipeline quality gas applied to the throughput of the plant. This methodology was applied to the national gas throughput using national average CO_2 concentrations in produced gas (3.45 percent) and transmission quality gas (1 percent). Data were unavailable to use annual values for CO_2 concentration. For condensate tanks, a series of E&P Tank (EPA 1999) simulations provide the total CO_2 vented per barrel of condensate throughput from fixed roof tank flash gas for condensate gravities of API 45 degree and higher. The ratios of emissions to throughput were used to estimate the CO_2 emission factor for condensate passing through fixed roof tanks.

Refer to https://www.epa.gov/ghgemissions/natural-gas-and-petroleum-systems-ghg-inventory-additional-information-1990-2015-ghg for the following data tables, in Excel format:

- Table 3.6-1: CH_4 Emissions (kt) for Natural Gas Systems, by Segment and Source, for All Years
- 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
- Table3.6-9: 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: U.S. Production Sector CO_2 Content in Natural Gas by NEMS Region and Formation Type for all years

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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 incineration of waste include CO_2 generated by the incineration of plastics, synthetic rubber and synthetic fibers in municipal solid waste (MSW), and incineration of tires (which are composed in part of synthetic rubber and C black) in a variety of other combustion facilities (e.g., cement kilns). Incineration of waste also results in emissions of CH_4 and N_2O. The emission estimates are calculated for all four sources on a mass-basis based on the data available. The methodology for calculating emissions from each of these waste incineration sources is described in this Annex.

CO_2 from Plastics Incineration

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, 2016) the flows of plastics in the U.S. waste stream are reported for seven resin categories. For 2015, the quantity generated, recovered, and discarded for each resin is shown in Table A-128. The data set for 1990 through 2015 is incomplete, and several assumptions were employed to bridge the data gaps. The EPA reports do not provide estimates for individual materials landfilled and incinerated, although they do provide such an estimate for the waste stream as a whole. To estimate the quantity of plastics landfilled and incinerated, total discards were apportioned based on the proportions of landfilling and incineration for the entire U.S. waste stream for each year in the time series according to *Biocycle's State of Garbage in America* (van Haaren et al. 2010), and Shin (2014). For those years when distribution by resin category was not reported (1990 through 1994), total values were apportioned according to 1995 (the closest year) distribution ratios. Generation and recovery figures for 2002 and 2004 were linearly interpolated between surrounding years' data.

Table A-128: 2015 Plastics in the Municipal Solid Waste Stream by Resin (kt)

Waste Pathway	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Generation	4,600	5,289	762	6,995	6,450	2,114	3,955	**30,164**
Recovery	880	553	0	408	54	27	953	**2,876**
Discard	3,720	4,736	762	6,586	6,396	2,087	3,003	**27,289**
Landfill	3,437	4,376	704	6,086	5,910	1,928	2,775	**25,215**
Combustion	283	360	58	501	486	159	228	**2,074**
Recovery[a]	19%	10%	0%	6%	1%	1%	24%	**10%**
Discard[a]	81%	90%	100%	94%	99%	99%	76%	**90%**
Landfill[a]	75%	83%	92%	87%	92%	91%	70%	**84%**
Combustion[a]	6%	7%	8%	7%	8%	8%	6%	**7%**

[a] As a percent of waste generation.

Note: Totals may not sum due to independent rounding. Abbreviations: PET (polyethylene terephthalate), HDPE (high density polyethylene), PVC (polyvinyl chloride), LDPE/LLDPE (linear low density polyethylene), PP (polypropylene), PS (polystyrene).

Fossil fuel-based CO_2 emissions were calculated as the product of plastic combusted, C content, and fraction oxidized (see Table A-129). The C content of each of the six types of plastics is listed, with the value for "other plastics" assumed equal to the weighted average of the six categories. The fraction oxidized was assumed to be 98 percent.

Table A-129: 2015 Plastics Incinerated (kt), Carbon Content (%), Fraction Oxidized (%) and Carbon Incinerated (kt)

Factor	PET	HDPE	PVC	LDPE/ LLDPE	PP	PS	Other	Total
Quantity Combusted	283	360	58	501	486	159	228	**2,074**
Carbon Content of Resin	63%	86%	38%	86%	86%	92%	66%	**-**
Fraction Oxidized	98%	98%	98%	98%	98%	98%	98%	**-**
Carbon in Resin Combusted	173	302	22	420	408	143	147	**1,617**
Emissions (MMT CO_2 Eq.)	**0.6**	**1.1**	**0.1**	**1.5**	**1.5**	**0.5**	**0.5**	**5.9**

[a] Weighted average of other plastics produced.

Note: Totals may not sum due to independent rounding.

CO_2 from Incineration of Synthetic Rubber and Carbon Black in Tires

Emissions from tire incineration require two pieces of information: the amount of tires incinerated and the C content of the tires. "2014 U.S. Scrap Tire Management Summary" (RMA 2016) reports that 1,923 thousand of the 3,551 thousand tons of scrap tires generated in 2015 (approximately 54 percent of generation) were used for fuel purposes. Using

RMA'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.[69] Table A-130 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 incinerated by the total C content of the synthetic rubber, C black portions of scrap tires, and then by a 98 percent oxidation factor, yielded CO_2 emissions, as shown in Table A-131. 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-128 (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 2015 were taken from RMA 2006, RMA 2009, RMA 2011; RMA 2014a; RMA2016; where data were not reported, they were linearly interpolated between bracketing years' data or, for the ends of time series, set equal to the closest year with reported data.

In 2009, RMA 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; RMA 2002 through 2006, 2014b, 2016).

Table A-130: 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-131: Scrap Tire Constituents and CO_2 Emissions from Scrap Tire Incineration in 2015

Material	Weight of Material (MMT)	Fraction Oxidized	Carbon Content	Emissions (MMT CO_2 Eq.)
Synthetic Rubber	0.3	98%	90%	1.2
Carbon Black	0.4	98%	100%	1.4
Total	**0.8**	**NA**	**NA**	**2.7**

NA (Not Applicable)

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

CO_2 from Incineration of Synthetic Rubber in Municipal Solid Waste

Similar to the methodology for scrap tires, CO_2 emissions from synthetic rubber in MSW were estimated by multiplying the amount of rubber incinerated by an average rubber C content. The amount of rubber discarded in the MSW stream was estimated from generation and recycling data[70] provided 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, 2016), and unpublished backup data (Schneider 2007). The reports divide rubber found in MSW into three product categories: other durables (not including tires), non-durables (which includes clothing and footwear and other non-durables), and containers and packaging. EPA (2016) did not report rubber found in the product category "containers and packaging;" however, containers and packaging from miscellaneous material types were reported for 2009 through 2015. As a result, EPA assumes that rubber containers and packaging are reported under the "miscellaneous" category; and therefore, the quantity reported for 2009 through 2015 were set equal to the quantity reported for 2008. Since there was negligible recovery for these product types, all the waste generated is considered to be discarded. Similar to the plastics method, discards were apportioned into landfilling and incineration based on their relative proportions, for each year, for the entire U.S. waste stream. The report aggregates rubber and leather in the MSW stream; an assumed synthetic rubber content of 70 percent was assigned to each product type, as shown in Table A-132.[71] A C content of 85 percent was assigned to synthetic rubber for all product types (based on the weighted average C content of rubber consumed for non-tire uses), and a 98 percent fraction oxidized was assumed.

Table A-132: Rubber and Leather in Municipal Solid Waste in 2014

Product Type	Incinerated (kt)	Synthetic Rubber (%)	Carbon Content (%)	Fraction Oxidized (%)	Emissions (MMT CO_2 Eq.)
Durables (not Tires)	**259**	**70%**	**85%**	**98%**	**0.8**
Non-Durables	**79**	**-**	**-**	**-**	**0.2**
Clothing and Footwear	60	70%	85%	98%	0.2
Other Non-Durables	19	70%	85%	98%	0.1
Containers and Packaging	**2**	**70%**	**85%**	**98%**	**0.0**
Total	**341**	**-**	**-**	**-**	**1.1**

- Not Applicable

CO_2 from Incineration of Synthetic Fibers

Carbon dioxide emissions from synthetic fibers were estimated as the product of the amount of synthetic fiber discarded annually and the average C content of synthetic fiber. Fiber in the MSW stream was estimated from data provided in the *Municipal Solid Waste Generation, Recycling, and Disposal in the United States: Facts and Figures* reports (EPA 1999 through 2003, 2005 through 2014) and *Advancing Sustainable Materials Management: Facts and Figures – Assessing Trends in Material Generation, Recycling and Disposal in the United States* (EPA 2015, 2016) for textiles. Production data for the synthetic fibers was based on data from the American Chemical Society (FEB 2009). The amount of synthetic fiber in MSW was estimated by subtracting (a) the amount recovered from (b) the waste generated (see Table A-133). As with the other materials in the MSW stream, discards were apportioned based on the annually variable proportions of landfilling and incineration for the entire U.S. waste stream, as found in van Haaren et al. (2010), and Shin (2014). It was assumed that approximately 55 percent of the fiber was synthetic in origin, based on information received from the Fiber Economics Bureau (DeZan 2000). The average C content of 71 percent was assigned to synthetic fiber using the production-weighted average of the C contents of the four major fiber types (polyester, nylon, olefin, and acrylic) based on 2015 fiber production (see Table A-134). The equation relating CO_2 emissions to the amount of textiles combusted is shown below.

$$\begin{gathered}\text{CO}_2\text{ Emissions from the Incineration of Synthetic Fibers} = \text{Annual Textile Incineration (kt)} \times \\ \text{(Percent of Total Fiber that is Synthetic)} \times \text{(Average C Content of Synthetic Fiber)} \times \\ (44\text{ g CO}_2/12\text{ g C})\end{gathered}$$

[70] Discards = Generation minus recycling.

[71] As a sustainably harvested biogenic material, the incineration of leather is assumed to have no net CO_2 emissions.

Table A-133: Synthetic Textiles in MSW (kt)

Year	Generation	Recovery	Discards	Incineration
1990	2,884	328	2,557	332
1995	3,674	447	3,227	442
1996	3,832	472	3,361	467
1997	4,090	526	3,564	458
1998	4,269	556	3,713	407
1999	4,498	611	3,887	406
2000	4,706	655	4,051	417
2001	4,870	715	4,155	432
2002	5,123	750	4,373	459
2003	5,297	774	4,522	472
2004	5,451	884	4,567	473
2005	5,714	913	4,800	480
2006	5,893	933	4,959	479
2007	6,041	953	5,088	470
2008	6,305	968	5,337	470
2009	6,424	978	5,446	458
2010	6,508	998	5,510	441
2011	6,513	1,003	5,510	419
2012	7,114	1,117	5,997	456
2013	7,496	894	6,602	502
2014	8,052	1,301	6,751	513
2015	8,052	1,301	6,751	513

Table A-134: Synthetic Fiber Production in 2015

Fiber	Production (MMT)	Carbon Content
Polyester	1.2	63%
Nylon	0.5	64%
Olefin	1.0	86%
Acrylic	-	68%
Total	**2.8**	**71%**

CH_4 and N_2O from Incineration of Waste

Estimates of N_2O emissions from the incineration 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, 2016) and unpublished backup data (Schneider 2007). According to this methodology, emissions of N_2O from waste incineration are the product of the mass of waste incinerated, an emission factor of N_2O emitted per unit mass of waste incinerated, and an N_2O emissions control removal efficiency. The mass of waste incinerated was derived from the results of the biannual national survey of Municipal Solid Waste (MSW) Generation and Disposition in the U.S., published in *BioCycle* (van Haaren et al. 2010), and Shin (2014). For waste incineration in the United States, 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 incinerators in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009).

Estimates of CH_4 emissions from the incineration 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 incineration are the product of the mass of waste incinerated and an emission factor of CH_4 emitted per unit mass of waste incinerated. Similar to the N_2O emissions methodology, the mass of waste incinerated was derived from the information published in *BioCycle* (van Haaren et al. 2010) for 1990 through 2008. Data for 2011 were derived from information in Shin (2014). For waste incineration in the United States, an emission factor of 0.20 kg CH_4/kt MSW was used based on the *2006 IPCC Guidelines* and assuming that all MSW incinerators in the United States use continuously-fed stoker technology (Bahor 2009; ERC 2009). No information was available on the mass of waste incinerated for 2012 through 2015, so these values were assumed to be equal to the 2011 value.

Despite the differences in methodology and data sources, the two series of references (EPA 2014; van Haaren, Rob, Themelis, N., and Goldstein, N. 2010) provide estimates of total solid waste incinerated that are relatively consistent (see Table A-135).

Table A-135: U.S. Municipal Solid Waste Incinerated, as Reported by EPA and BioCycle (Metric Tons)

Year	EPA	BioCycle
1990	28,939,680	30,632,057
1995	32,241,888	29,639,040
2000	30,599,856	25,974,978
2001	30,481,920	25,942,036[a]
2002	30,255,120	25,802,917
2003	30,028,320	25,930,542[b]
2004	28,585,872	26,037,823
2005	28,685,664	25,973,520[c]
2006	28,985,040	25,853,401
2007	29,003,184	24,788,539[d]
2008	28,622,160	23,674,017
2009	26,317,872	22,714,122[e]
2010	26,544,672	21,741,734[e]
2011	26,544,672	20,756,870
2012	26,544,672	20,756,870[f]
2013	29,629,152	20,756,870[f]
2014	30,136,361	20,756,870[f]
2015	30,136,361[g]	20,756,870[f]

[a] Interpolated between 2000 and 2002 values.
[b] Interpolated between 2002 and 2004 values.
[c] Interpolated between 2004 and 2006 values.
[d] Interpolated between 2006 and 2008 values
[e] Interpolated between 2011 and 2008 values
[f] Set equal to the 2011 value
[g] Set equal to the 2014 value.

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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 2015 fuel sales in the Continental United States (CONUS).[72] 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 JP-8 between Aviation and Land-based Vehicles

As a result of DoD[73] and NATO[74] policies on implementing the Single Fuel For the Battlefield concept, DoD activities have been increasingly replacing diesel fuel with JP8 (a type of jet fuel) in compression ignition and turbine engines of land-based equipment. DoD is replacing JP-8 with commercial specification Jet A fuel with additives (JAA) for non-naval aviation and ground assets. The transition is scheduled to be completed in 2016. Based on this concept and examination of all data describing jet fuel used in land-based vehicles, it was determined that a portion of JP8 consumption should be attributed to ground vehicle use. Based on available Military Service data and expert judgment, a small fraction of the total JP8 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 JP8 use reported for aviation was reduced and the total fuel use for land-based equipment increased. DoD's total fuel use did not change.

Table A-136 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 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.

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[72] FAS contains data for 1995 through 2015, 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.

[73] DoD Directive 4140.25-M-V1, Fuel Standardization and Cataloging, 2013; DoD Directive 4140.25, DoD Management Policy for Energy Commodities and Related Services, 2004.

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

- 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.[75]

Table A-137 and Table A-138 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 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-137 and Table A-138, below. CO_2 emissions from aviation bunkers and distillate marine bunkers are presented in Table A-141, and are based on emissions from fuels tallied in Table A-137 and Table A-138.

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[75] 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-136: Transportation Fuels from Domestic Fuel Deliveries[a] (Million Gallons)

Vehicle Type/Fuel	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aviation	**4,598.4**	**3,099.9**	**2,664.4**	**2,900.6**	**2,609.8**	**2,615.0**	**2,703.1**	**2,338.1**	**2,092.0**	**2,081.0**	**2,067.8**	**1,814.5**	**1,663.9**	**1,405.0**	**1,449.7**	**1,336.4**	**1,796.2**	**1,773.8**
Total Jet Fuels	4,598.4	3,099.9	2,664.4	2,900.6	2,609.6	2,614.9	2,703.1	2,338.0	2,091.9	2,080.9	2,067.7	1,814.3	1,663.7	1,404.8	1,449.5	1,336.2	1,795.9	1,773.6
JP8	*285.7*	*2,182.8*	*2,122.7*	*2,326.2*	*2,091.4*	*2,094.3*	*2,126.2*	*1,838.8*	*1,709.3*	*1,618.5*	*1,616.2*	*1,358.2*	*1,100.1*	*882.8*	*865.2*	*718.0*	*546.6*	*126.6*
JP5	*1,025.4*	*691.2*	*472.1*	*503.2*	*442.2*	*409.1*	*433.7*	*421.6*	*325.5*	*376.1*	*362.2*	*361.2*	*399.3*	*372.3*	*362.5*	*316.4*	*311.0*	*316.4*
Other Jet Fuels	*3,287.3*	*225.9*	*69.6*	*71.2*	*76.1*	*111.4*	*143.2*	*77.6*	*57.0*	*86.3*	*89.2*	*94.8*	*164.3*	*149.7*	*221.8*	*301.7*	*938.3*	*1,330.6*
Aviation Gasoline	+	+	+	+	0.1	0.1	+	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.2	0.3	0.3
Marine	**686.8**	**438.9**	**454.4**	**418.4**	**455.8**	**609.1**	**704.5**	**604.9**	**531.6**	**572.8**	**563.4**	**485.8**	**578.8**	**489.9**	**490.4**	**390.4**	**427.9**	**421.7**
Middle Distillate (MGO)	+	+	48.3	33.0	41.2	88.1	71.2	54.0	45.8	45.7	55.2	56.8	48.4	37.3	52.9	40.9	62.0	56.0
Naval Distillate (F76)	686.8	438.9	398.0	369.1	395.1	460.9	583.5	525.9	453.6	516.0	483.4	399.0	513.7	440.0	428.4	345.7	362.7	363.3
Intermediate Fuel Oil (IFO)[b]	+	+	8.1	16.3	19.5	60.2	49.9	25.0	32.2	11.1	24.9	30.0	16.7	12.5	9.1	3.8	3.2	2.4
Other[c]	**717.1**	**310.9**	**248.2**	**109.8**	**211.1**	**221.2**	**170.9**	**205.6**	**107.3**	**169.0**	**173.6**	**206.8**	**224.0**	**208.6**	**193.8**	**180.6**	**190.7**	**181.1**
Diesel	93.0	119.9	126.6	26.6	57.7	60.8	46.4	56.8	30.6	47.3	49.1	58.3	64.1	60.9	57.9	54.9	57.5	54.8
Gasoline	624.1	191.1	74.8	24.7	27.5	26.5	19.4	24.3	11.7	19.2	19.7	25.2	25.5	22.0	19.6	16.9	16.5	16.2
Jet Fuel[d]	+	+	46.7	58.4	125.9	133.9	105.1	124.4	65.0	102.6	104.8	123.3	134.4	125.6	116.2	108.8	116.7	110.1
Total (Including Bunkers)	**6,002.4**	**3,849.8**	**3,367.0**	**3,428.8**	**3,276.7**	**3,445.3**	**3,578.5**	**3,148.6**	**2,730.9**	**2,822.8**	**2,804.9**	**2,507.1**	**2,466.7**	**2,103.5**	**2,133.9**	**1,907.5**	**2,414.9**	**2,376.6**

+ 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.

Note: Totals may not sum due to independent rounding.

Table A-137: Total U.S. Military Aviation Bunker Fuel (Million Gallons)

Fuel Type/Service	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jet Fuels																		
JP8	**56.7**	**300.4**	**307.6**	**341.2**	**309.5**	**305.1**	**309.8**	**285.6**	**262.5**	**249.1**	**229.4**	**211.4**	**182.5**	**143.4**	**141.2**	**122.0**	**71.8**	**13.1**
Navy	56.7	38.3	53.4	73.8	86.6	76.3	79.2	70.9	64.7	62.7	59.2	55.4	60.8	47.1	50.4	48.9	19.8	0.8
Air Force	+	262.2	254.2	267.4	222.9	228.7	230.6	214.7	197.8	186.5	170.3	156.0	121.7	96.2	90.8	73.0	52.0	12.3
JP5	**370.5**	**249.8**	**160.3**	**169.7**	**158.3**	**146.1**	**157.9**	**160.6**	**125.0**	**144.5**	**139.2**	**137.0**	**152.5**	**144.9**	**141.2**	**124.9**	**121.9**	**124.1**
Navy	365.3	246.3	155.6	163.7	153.0	141.3	153.8	156.9	122.8	141.8	136.5	133.5	149.7	143.0	139.5	123.6	120.2	122.6
Air Force	5.3	3.5	4.7	6.1	5.3	4.9	4.1	3.7	2.3	2.7	2.6	3.5	2.8	1.8	1.7	1.3	1.6	1.5
JP4	**420.8**	**21.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	420.8	21.5	+	+	+	+	+	+	+	+	+	+	0.1	+	+	+	+	+
JAA	**13.7**	**9.2**	**12.5**	**12.6**	**13.7**	**21.7**	**30.0**	**15.5**	**11.7**	**15.6**	**16.8**	**18.1**	**31.4**	**31.1**	**38.6**	**46.5**	**124.5**	**189.8**
Navy	8.5	5.7	7.9	8.0	9.8	15.5	21.5	11.6	9.1	11.7	12.5	12.3	13.7	14.6	14.8	13.4	32.2	62.1
Air Force	5.3	3.5	4.5	4.6	3.8	6.2	8.6	3.9	2.6	3.9	4.3	5.9	17.7	16.5	23.8	33.1	92.3	127.7
JA1	**+**	**+**	**+**	**0.1**	**0.6**	**0.2**	**0.5**	**0.5**	**0.4**	**1.1**	**1.0**	**0.6**	**0.3**	**-+**	**-+**	**0.6**	**0.3**	**0.3**
Navy	+	+	+	+	+	+	+	+	+	0.1	0.1	0.1	0.1	-+	-+	0.6	-+	+
Air Force	+	+	+	0.1	0.6	0.2	0.5	0.5	0.4	1.0	0.8	0.5	0.1	-+	-+	+	0.3	0.3
JAB	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**	**+**
Navy	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Air Force	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Navy Subtotal	**430.5**	**290.2**	**216.9**	**245.5**	**249.4**	**233.1**	**254.4**	**239.4**	**196.6**	**216.3**	**208.3**	**201.3**	**224.4**	**204.3**	**204.5**	**186.5**	**172.3**	**185.5**
Air Force Subtotal	**431.3**	**290.7**	**263.5**	**278.1**	**232.7**	**239.9**	**243.7**	**222.9**	**203.1**	**194.0**	**178.1**	**165.9**	**142.4**	**114.5**	**116.3**	**107.4**	**146.2**	**141.9**
Total	**861.8**	**580.9**	**480.4**	**523.6**	**482.1**	**473.0**	**498.1**	**462.3**	**399.7**	**410.3**	**386.3**	**367.2**	**366.7**	**318.8**	**320.8**	**293.9**	**318.5**	**327.4**

+ Does not exceed 0.05 million gallons.
Note: Totals may not sum due to independent rounding. The negative values in this table represent returned products.

Table A-138: Total U.S. DoD Maritime Bunker Fuel (Million Gallons)

Marine Distillates	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Navy – MGO	0.0	0.0	23.8	22.5	27.1	63.7	56.2	38.0	33.0	31.6	40.9	39.9	32.9	25.5	36.5	32.3	43.3	37.8
Navy – F76	522.4	333.8	298.6	282.6	305.6	347.8	434.4	413.1	355.9	404.1	376.9	311.4	402.2	346.6	337.9	273.1	286.2	286.7
Navy – IFO	0.0	0.0	6.4	12.9	15.4	47.5	39.4	19.7	25.4	8.8	19.0	23.1	12.9	9.5	6.1	3.0	1.5	1.9
Total	**522.4**	**333.8**	**328.8**	**318.0**	**348.2**	**459.0**	**530.0**	**470.7**	**414.3**	**444.4**	**436.7**	**374.4**	**448.0**	**381.5**	**380.6**	**308.5**	**331.0**	**326.3**

+ Does not exceed 0.05 million gallons.
Note: Totals may not sum due to independent rounding.

Table A-139: 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)	20.17	1.00
Marine (Residual)	20.48	1.00

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

Table A-140: Annual Variable Carbon Content Coefficient for Jet Fuel (MMT Carbon/QBtu)

Fuel	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
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	19.70	19.70	19.70	19.70	19.70	19.70

Source: EPA (2010)

Table A-141: Total U.S. DoD CO_2 Emissions from Bunker Fuels (MMT CO_2 Eq.)

Mode	1990	1995	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Aviation	8.1	5.5	4.7	5.1	4.7	4.6	4.8	4.5	3.9	4.0	3.8	3.6	3.6	3.1	3.1	2.9	3.1	3.2
Marine	5.4	3.4	3.4	3.3	3.6	4.7	5.4	4.8	4.2	4.6	4.5	3.8	4.6	3.9	3.9	3.2	3.4	3.3
Total	**13.4**	**9.0**	**8.0**	**8.3**	**8.3**	**9.3**	**10.3**	**9.3**	**8.1**	**8.5**	**8.2**	**7.4**	**8.2**	**7.0**	**7.0**	**6.0**	**6.5**	**6.6**

Note: Totals may not sum due to independent rounding.

References

DLA Energy (2017) Unpublished data from the Defense Fuels Automated Management System (DFAMS). Defense Energy Support Center, Defense Logistics Agency, U.S. Department of Defense. Washington, D.C.

IPCC (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change. H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.9. Methodology for Estimating HFC and PFC Emissions from Substitution of Ozone Depleting Substances

Emissions of HFCs and PFCs from the substitution of ozone depleting substances (ODS) are developed using a country-specific modeling approach. The Vintaging Model 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) and perfluorocarbons (PFCs), 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 end-use sectors: refrigeration and air-conditioning, foams, aerosols, solvents, and fire-extinguishing. Within these sectors, there are 65 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.

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 two categories: emissions during equipment lifetime, which arise from annual leakage and service losses, and disposal emissions, which occur at the time of discard. Two separate steps are required to calculate the lifetime emissions from 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 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.

Step 1: 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:

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

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 2: 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. 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:

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

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 3: Calculate total emissions

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

$$E_j = Es_j + Ed_j$$

where:

E	=	Total Emissions. Emissions from refrigeration and air conditioning equipment in year *j*.
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-142, 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.

Table A-142: Refrigeration and Air-Conditioning Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
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%	
									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%	R-450A	2017	2017	1%	1.4%

Initial Market Segment	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
									R-513A	2017	2017	1%	
									R-450A	2018	2024	49%	
									R-513A	2018	2024	49%	
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				1.3%
					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				1.3%
					R-410A	2001	2005	18%	None				
					R-410A	2006	2009	8%	None				
					R-410A	2009	2010	71%	None				
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	25%	None								2.1%
	R-404A	1993	1995	75%									
Industrial Process Refrigeration													
CFC-11	HCFC-123	1992	1994	70%	Unknown								3.2%
	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%

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[1]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[1]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[1]	Tertiary Substitute: Maximum Market Penetration	Growth Rate
					R-404A	1995	2010	50%	None				
					R-410A	1999	2010	20%	None				
					R-507	1995	2010	15%	None				
	HCFC-123	1992	1994	35%	Unknown								
	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				
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 (School and Tour Buses)													
CFC-12	HCFC-22	1994	1995	0.5%	HFC-134a	2006	2007	100%	None				0.3%
	HFC-134a	1194	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[2]	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%	

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[1]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[1]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[1]	Tertiary Substitute: Maximum Market Penetration	Growth Rate
									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				
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				

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
					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				
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				
Residential Unitary Air Conditioners													
HCFC-22	HCFC-22	2006	2006	70%	R-410A	2007	2010	29%	None				1.3%
					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[3]	DX	2000	2006	67.5%	DX	2006	2015	35%	None				1.7%
					DR[4]	2000	2015	23%	None				
					SLS[5]	2000	2015	15%	None				
	DR	2001	2006	22.5%	None								
	SLS	2001	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[6]					R-407A	2011	2015	63.3%	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: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
	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%	
									CO_2	2016	2016	11%	
									Non-ODP/GWP	2016	2016	17.3%	
									CO_2	2014	2019	7%	
									Non-ODP/GWP	2014	2019	13%	
									R-450A	2016	2020	23%	
									R-513A	2016	2020	23%	
					HFC-134a	2000	2009	9%	CO_2	2014	2019	10%	
									Non-ODP/GWP	2014	2019	20%	
									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				
Retail Food (Vending Machines)													
CFC-12	HFC-134a	1995	1998	90%	CO_2	2012	2012	1%	None				-0.03%
					CO_2	2013	2017	39%	None				
					Propane	2014	2014	1%	None				
					Propane	2015	2015	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				
Transport Refrigeration (Road Transport)													
CFC-12	HFC-134a	1993	1995	10%	None								5.5%
	R-404A	1993	1995	60%	None								
	HCFC-22	1993	1995	30%	R-410A	2000	2003	5%	CO_2	2017	2021	5%	

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
					R-404A	2006	2010	95%	CO_2	2017	2021	5%	
Transport Refrigeration (Intermodal Containers)													
CFC-12	HFC-134a	1993	1993	60%	CO_2	2017	2021	5%	None				7.3%
	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-404	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%	None								0.3%
	HFC-134A	2005	2005	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								
	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								

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[1]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[1]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[1]	Tertiary Substitute: Maximum Market Penetration	Growth Rate
Window Units													
HCFC-22	R-410A	2008	2009	10%	None								4.0%
	R-410A	2009	2010	90%	None								

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] 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-143 presents the average equipment lifetimes and annual HFC emission rates (for servicing, leaks, and disposal) for each end-use assumed by the Vintaging Model.

Table A-143: Refrigeration and Air-Conditioning Lifetime Assumptions

End-Use	Lifetime (Years)	HFC Emission Rates (Servicing and Leaks) (%)	HFC Emission Rates (Disposal) (%)
Centrifugal Chillers	20 – 27	2.0 – 10.9	10
Cold Storage	20 – 25	15.0	10
Commercial Unitary A/C	15	7.9 – 8.6	30 – 40
Dehumidifiers	11	0.5	50
Ice Makers	8	3.0	49
Industrial Process Refrigeration	25	3.6 – 12.3	10
Mobile Air Conditioners	5 –16	2.3 – 18.0	43 – 50
Positive Displacement Chillers	20	0.5 – 1.5	10
PTAC/PTHP	12	3.9	40
Retail Food	10 – 20	1.0 – 25	10 – 35
Refrigerated Appliances	14	0.6	42
Residential Unitary A/C	15	11.8	40
Transport Refrigeration	9 – 40	19.4 – 36.4	10 – 65
Water & Ground Source Heat Pumps	20	3.9	43
Window Units	12	0.6	50

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. Two types of aerosol products are modeled: metered dose inhalers (MDI) and consumer 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 continued to use CFCs 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.

All HFCs and PFCs 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.

$$E_j = Qc_j$$

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-144.

Table A-144: Aerosol Product Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
MDIs									
CFC Mix[2]	HFC-134a	1997	1997	6%	None				0.8%
	Non-ODP/GWP	1998	2007	7%	None				
	CFC Mix[a]	2000	2000	87%	HFC-134a	2002	2002	34%	
					HFC-134a	2003	2009	47%	
					HFC-227ea	2006	2009	5%	
					HFC-134a	2010	2011	6%	
					HFC-227ea	2010	2011	1%	
					HFC-134a	2011	2012	3%	
					HFC-227ea	2011	2012	0.3%	
					HFC-134a	2014	2014	3%	
					HFC-227ea	2014	2014	0.3%	
Consumer Aerosols (Non-MDIs)									
NA[3]	HFC-152a	1990	1991	50%	None				2.0%
	HFC-134a	1995	1995	50%	HFC-152a	1997	1998	44%	
					HFC-152a	2001	2005	36%	
					HFO-1234ze(E)	2016	2018	7%	

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.
[2] 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.
[3] 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. The following equation calculates emissions from solvent applications.

$$E_j = l \times Qc_j$$

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-145.

Table A-145: Solvent Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Growth Rate
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
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	1996	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	1996	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				
	PFC/PFPE	1995	1996	0.1%	Non-ODP/GWP	2000	2003	90%	
					Non-ODP/GWP	2005	2009	10%	
CFC-113	Non-ODP/GWP	1995	1996	96%	None				2.0%
	HCFC-225ca/cb	1995	1996	1%	Unknown				
	HFE-7100	1995	1996	3%	None				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.

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 of course 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 12-year lifetime and flooding applications have a 20-year lifetime.

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

where:

E = Emissions. Total emissions of a specific chemical in year j for streaming 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-146.

Table A-146: Fire Extinguishing Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Growth Rate
Initial Market Segment	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	
Flooding Agents									
Halon-1301	Halon-1301[2]	1994	1994	4%	Unknown				2.2%
	HFC-23	1994	1999	0.2%	None				
	HFC-227ea	1994	1999	18%	FK-5-1-12	2003	2010	10%	
					HFC-125	2001	2008	10%	
	Non-ODP/GWP	1994	1994	46%	FK-5-1-12	2003	2010	7%	
	Non-ODP/GWP	1995	2034	10%	None				
	Non-ODP/GWP	1998	2027	10%	None				
	C_4F_{10}	1994	1999	1%	FK-5-1-12	2003	2003	100%	
	HFC-125	1997	2006	11%	None				
Streaming Agents									
Halon-1211	Halon-1211*	1992	1992	5%	Unknown				3.0%
	HFC-236fa	1997	1999	3%	None				
	Halotron	1994	1995	0.1%	None				
	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				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.

[2] 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.

$$Em_j = lm \times Qc_j$$

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.

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

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.

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

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, the only foam type assumed to have post-disposal emissions is polyurethane foam used as domestic refrigerator and freezer insulation, which is expected to continue to emit for 26 years post-disposal, calculated as presented in the following equation.

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

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.

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

where:

E_j	=	Total Emissions. Total emissions of a specific chemical in year *j*, by weight.
Em	=	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-147. The emission profiles of these thirteen foam types are shown in Table A-148.

Table A-147: Foam Blowing Market Transition Assumptions

Initial Market Segment	Primary Substitute: Name of Substitute	Primary Substitute: Start Date	Primary Substitute: Date of Full Penetration in New Equipment[1]	Primary Substitute: Maximum Market Penetration	Secondary Substitute: Name of Substitute	Secondary Substitute: Start Date	Secondary Substitute: Date of Full Penetration in New Equipment[1]	Secondary Substitute: Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Tertiary Substitute: Start Date	Tertiary Substitute: Date of Full Penetration in New Equipment[1]	Tertiary Substitute: Maximum Market Penetration	Growth Rate
Commercial Refrigeration Foam													
CFC-11	HCFC-141b	1989	1996	40%	HFC-245fa	2002	2003	80%	HCFO-1233zd(E)	2015	2020	70%	6.0%
									Non-ODP/GWP	2015	2020	30%	
					Non-ODP/GWP	2002	2003	20%	None				
	HCFC-142b	1989	1996	8%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	HCFO-1233zd(E)	2015	2020	70%	
									Non-ODP/GWP	2015	2020	30%	
	HCFC-22	1989	1996	52%	Non-ODP/GWP	2009	2010	80%	None				
					HFC-245fa	2009	2010	20%	HCFO-1233zd(E)	2015	2020	70%	
									Non-ODP/GWP	2015	2020	30%	
Flexible PU Foam: Integral Skin Foam													
CFC-11	HCFC-141b	1989	1990	100%	HFC-134a	1993	1996	25%	CO_2	2015	2017	50%	2.0%
									HCFO-1233zd(E)	2015	2017	50%	
					HFC-134a	1994	1996	25%	CO_2	2015	2017	50%	
									HCFO-1233zd(E)	2015	2017	50%	
					CO_2	1993	1996	25%	None				
					CO_2	1994	1996	25%	None				
Flexible PU Foam: Slabstock Foam, Moulded Foam													
CFC-11	Non-ODP/GWP	1992	1992	100%	None								2.0%
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	95%	None				6.0%
					HC/HFC-245fa Blend	2000	2003	5%	Non-ODP/GWP	2017	2017	100%	
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				

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
					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%
					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[2]	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: Spray Foam													
CFC-11	HCFC-141b	1989	1996	100%	HFC-245fa	2002	2003	30%	HCFO-1233zd(E)	2016	2020	100%	6.0%
					HFC-245fa/CO_2 Blend	2002	2003	60%	None				
					Non-ODP/GWP	2001	2003	10%	None				
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				

Initial Market Segment	Primary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Secondary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Tertiary Substitute: Name of Substitute	Start Date	Date of Full Penetration in New Equipment[1]	Maximum Market Penetration	Growth Rate
	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				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.

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

Table A-148: Emission Profile for the Foam End-Uses

Foam End-Use	Loss at Manufacturing (%)	Annual Leakage Rate (%)	Leakage Lifetime (years)	Loss at Disposal (%)	Total[a] (%)
Flexible PU Foam: Slabstock Foam, Moulded Foam	100	0	1	0	100
Commercial Refrigeration	4	0.25	15	92.25	100
Rigid PU: Spray Foam	15	1.5	50	10.0	100
Rigid PU: Slabstock and Other	32.5	0.875	15	54.375	100
Phenolic Foam	28	0.875	32	44.0	100
Polyolefin Foam	40	3	20	0	100
Rigid PU: One Component Foam	95	2.5	2	0	100
XPS: Sheet Foam[a]	50	25	2	0	100
XPS: Boardstock Foam	25	0.75	25	56.25	100
Flexible PU Foam: Integral Skin Foam	95	2.5	2	0	100
Rigid PU: Domestic Refrigerator and Freezer Insulation[a]	3.75-6.5	0.25-0.5	14	39.9-37.2	47.15
PU and PIR Rigid: Boardstock	6	1	25	69.0	100
PU Sandwich Panels: Continuous and Discontinuous	8.5-11.25	0.5	50	63.75-66.5	100

PIR (Polyisocyanurate)
PU (Polyurethane)
XPS (Extruded Polystyrene)
[a] In general, total emissions from foam end-uses are assumed to be 100 percent. In the Rigid PU Domestic Refrigerator and Freezer Insulation end-use, the source of emission rates and lifetimes did not yield 100 percent emission; the remainder is anticipated to be emitted at a rate of 2.0%/year 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 dilutent 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.

$$E_j = Qc_j$$

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-149.

Table A-149: Sterilization Market Transition Assumptions

	Primary Substitute				Secondary Substitute				Tertiary Substitute				Growth Rate
Initial Market Segment	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	Name of Substitute	Start Date	Date of Full Penetration in New Equipment	Maximum Market Penetration	
12/88	EtO	1994	1995	95%	None								2.0%
	Non-ODP/GWP	1994	1995	1%	None								
	HCFC/EtO Blends	1993	1994	4%	Non-ODP/GWP	2010	2010	100%	None				

[1] Transitions between the start year and date of full penetration in new equipment are assumed to be linear.

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:

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

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-150 provides the bank for ODS and ODS substitutes by chemical grouping in metric tons (MT) for 1990 to 2015.

Table A-150: Banks of ODS and ODS Substitutes, 1990-2015 (MT)

Year	CFC	HCFC	HFC
1990	683,218	281,698	872
1995	760,787	508,167	49,281
2000	635,772	938,108	182,151
2001	607,568	1,007,660	210,081
2002	583,423	1,061,037	237,950
2003	559,499	1,097,836	271,580
2004	535,143	1,135,490	306,730
2005	505,684	1,176,739	344,095
2006	475,707	1,213,944	387,333
2007	448,358	1,242,230	431,796
2008	426,222	1,259,372	472,808
2009	413,431	1,251,425	518,528
2010	376,199	1,214,311	583,367
2011	339,448	1,166,817	647,323
2012	302,837	1,118,161	718,147
2013	267,100	1,064,634	790,647
2014	231,330	1,009,540	863,106
2015	195,498	955,581	931,347

References

IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. The National Greenhouse Gas Inventories Programme, The Intergovernmental Panel on Climate Change, H.S. Eggleston, L. Buendia, K. Miwa, T Ngara, and K. Tanabe (eds.). Hayama, Kanagawa, Japan.

3.10. Methodology for Estimating CH_4 Emissions from Enteric Fermentation

Methane emissions from enteric fermentation were estimated for seven livestock categories: cattle, horses, sheep, swine, goats, American bison, and the non-horse equines (mules and asses). Emissions from cattle represent the majority of U.S. emissions from enteric fermentation; consequently, a more detailed IPCC Tier 2 methodology was used to estimate emissions from cattle. The IPCC Tier 1 methodology was used to estimate emissions for the other types of livestock, including horses, goats, sheep, swine, American bison, and mules and asses (IPCC 2006).

Estimate Methane Emissions from Cattle

This section describes the process used to estimate CH_4 emissions from enteric fermentation from cattle using the Cattle Enteric Fermentation Model (CEFM). The CEFM was developed based on recommendations provided in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (IPCC 2006) and uses information on population, energy requirements, digestible energy, and CH_4 conversion rates to estimate CH_4 emissions.[76] The emission methodology consists of the following three steps: (1) characterize the cattle population to account for animal population categories with different emission profiles; (2) characterize cattle diets to generate information needed to estimate emission factors; and (3) estimate emissions using these data and the IPCC Tier 2 equations.

Step 1: Characterize U.S. Cattle Population

The CEFM's state-level cattle population estimates are based on data obtained from the U.S. Department of Agriculture's (USDA) National Agricultural Statistics Service Quick Stats database (USDA 2016). State-level cattle population estimates are shown by animal type for 2015 in Table A-151. A national-level summary of the annual average populations upon which all livestock-related emissions are based is provided in Table A-152. Cattle populations used in the Enteric Fermentation source category were estimated using the cattle transition matrix in the CEFM, which uses January 1 USDA population estimates and weight data to simulate the population of U.S. cattle from birth to slaughter, and results in an estimate of the number of animals in a particular cattle grouping while taking into account the monthly rate of weight gain, the average weight of the animals, and the death and calving rates. The use of supplemental USDA data and the cattle transition matrix in the CEFM results in cattle population estimates for this sector differing slightly from the January 1 or July 1 USDA point estimates and the cattle population data obtained from the Food and Agriculture Organization of the United Nations (FAO).

Table A-151: 2015 Cattle Population Estimates from the CEFM Transition Matrix, by Animal Type and State (1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Repl. Heif. 7-11 Months	Dairy Repl. Heif. 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Repl. Heif. 7-11 Months	Beef Repl. Heif. 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	4	8	1	2	45	336	652	27	63	24	16	5
Alaska	0	0	0	0	2	2	4	0	1	0	0	0
Arizona	100	195	20	46	20	90	175	8	19	132	11	254
Arkansas	4	7	1	3	55	445	863	36	84	63	27	11
California	911	1,780	232	541	70	304	590	31	73	265	73	438
Colorado	74	145	30	70	55	374	725	41	96	375	244	927
Conn.	10	19	2	6	1	3	5	1	1	1	0	0
Delaware	3	5	1	2	0	1	3	0	0	1	0	0
Florida	63	124	11	25	60	467	906	31	73	12	16	3
Georgia	41	81	8	19	28	247	479	22	51	22	16	4
Hawaii	1	2	0	1	4	35	69	3	6	4	3	1
Idaho	296	579	96	225	40	238	461	29	67	135	88	241
Illinois	48	94	16	37	25	189	366	15	36	101	51	234
Indiana	93	181	24	56	17	103	199	12	28	56	23	101
Iowa	107	210	39	91	60	464	900	44	101	620	328	1,210
Kansas	73	143	27	63	95	736	1,427	70	163	909	692	2,149
Kentucky	32	63	14	32	65	514	997	34	79	96	55	15
Louisiana	7	14	2	4	30	240	466	18	42	12	12	3
Maine	15	30	5	11	2	6	11	1	3	2	1	0

[76] Additional information on the Cattle Enteric Fermentation Model can be found in ICF (2006).

Maryland	25	49	8	18	4	22	42	2	5	7	5	10
Mass.	6	13	2	5	1	3	6	0	1	1	1	0
Michigan	206	403	50	117	15	55	107	6	13	82	18	156
Minn.	235	460	84	197	35	175	340	22	51	240	83	379
Miss.	6	12	2	4	38	241	468	23	55	27	17	6
Missouri	46	89	18	42	110	955	1,851	83	194	192	117	70
Montana	7	14	2	5	100	772	1,496	105	245	84	103	42
Nebraska	28	54	6	14	95	906	1,756	102	236	1,121	666	2,484
Nevada	14	28	3	6	12	109	212	9	21	21	15	4
N. Hamp.	7	14	2	4	1	2	3	0	1	0	0	0
N. Jersey	4	7	1	3	1	4	8	0	1	1	0	0
N. Mexico	165	323	33	77	35	210	407	21	48	46	36	10
New York	315	615	105	246	15	54	105	10	23	17	23	25
N. Car.	24	47	5	13	29	187	363	17	39	17	14	4
N. Dakota	8	16	2	4	50	461	894	41	95	103	96	42
Ohio	137	268	38	88	25	145	282	12	28	94	26	166
Oklahoma	20	40	8	18	140	970	1,880	102	236	418	190	262
Oregon	64	125	18	42	40	271	525	27	62	79	55	82
Penn	271	530	92	214	25	77	150	13	31	70	29	93
R.Island	0	1	0	0	0	1	2	0	0	0	0	0
S. Car.	8	15	2	4	14	88	170	7	17	4	6	1
S. Dakota	51	99	20	46	100	831	1,611	98	228	327	255	379
Tenn.	24	47	8	18	60	450	873	34	79	58	34	9
Texas	241	470	75	176	320	2,131	4,130	181	422	1,212	723	2,474
Utah	49	96	14	34	22	167	324	19	44	38	33	24
Vermont	68	132	17	39	3	6	12	1	2	2	3	1
Virginia	48	93	13	30	40	329	637	27	62	75	22	20
Wash.	142	277	41	96	18	102	198	13	30	84	70	205
W. Virg.	5	9	1	3	13	95	185	8	19	21	10	4
Wisconsin	653	1,275	220	513	35	142	275	18	42	180	23	257
Wyoming	3	6	2	4	40	358	694	47	109	65	74	74

Table A-152: Cattle Population Estimates from the CEFM Transition Matrix for 1990–2015 (1,000 head)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Dairy									
Dairy Calves (0–6 months)	5,369	5,091	4,951	4,628	4,709	4,770	4,758	4,727	4,764
Dairy Cows	10,015	9,482	9,183	9,004	9,156	9,236	9,221	9,208	9,307
Dairy Replacements 7–11 months	1,214	1,216	1,196	1,257	1,362	1,348	1,341	1,356	1,417
Dairy Replacements 12–23 months	2,915	2,892	2,812	2,905	3,215	3,233	3,185	3,190	3,310
Beef									
Beef Calves (0–6 months)	16,909	18,177	17,431	16,918	15,817	15,288	14,859	14,946	15,117
Bulls	2,160	2,385	2,293	2,214	2,165	2,100	2,074	2,038	2,109
Beef Cows	32,455	35,190	33,575	32,674	30,913	30,282	29,631	29,085	29,302
Beef Replacements 7–11 months	1,269	1,493	1,313	1,363	1,232	1,263	1,291	1,342	1,473
Beef Replacements 12–23 months	2,967	3,637	3,097	3,171	2,889	2,968	3,041	3,113	3,422
Steer Stockers	10,321	11,716	8,724	8,185	7,568	7,173	7,457	7,411	7,517
Heifer Stockers	5,946	6,699	5,371	5,015	4,752	4,456	4,455	4,384	4,402
Feedlot Cattle	9,549	11,064	13,006	12,652	13,601	13,328	13,267	13,222	12,883

The population transition matrix in the CEFM simulates the U.S. cattle population over time and provides an estimate of the population age and weight structure by cattle type on a monthly basis.[77] Since cattle often do not remain in a single population type for an entire year (e.g., calves become stockers, stockers become feedlot animals), and emission profiles vary both between and within each cattle type, these monthly age groups are tracked in the enteric fermentation model to obtain more accurate emission estimates than would be available from annual point estimates of population (such as available from USDA statistics) and weight for each cattle type.

[77] Mature animal populations are not assumed to have significant monthly fluctuations, and therefore the populations utilized are the January estimates downloaded from USDA (2016).

The transition matrix tracks both dairy and beef populations, and divides the populations into males and females, and subdivides the population further into specific cattle groupings for calves, replacements, stockers, feedlot, and mature animals. The matrix is based primarily on two types of data: population statistics and weight statistics (including target weights, slaughter weights, and weight gain). Using the weight data, the transition matrix simulates the growth of animals over time by month. The matrix also relies on supplementary data, such as feedlot placement statistics, slaughter statistics, death rates, and calving rates, described in further detail below.

The basic method for tracking population of animals per category is based on the number of births (or graduates) into the monthly age group minus those animals that die or are slaughtered and those that graduate to the next category (such as stockers to feedlot placements).

Each stage in the cattle lifecycle was modeled to simulate the cattle population from birth to slaughter. This level of detail accounts for the variability in CH_4 emissions associated with each life stage. Given that a stage can last less than one year (e.g., calves are usually weaned between 4 and 6 months of age), each is modeled on a per-month basis. The type of cattle also influences CH_4 emissions (e.g., beef versus dairy). Consequently, there is an independent transition matrix for each of three separate lifecycle phases, 1) calves, 2) replacements and stockers, and 3) feedlot animals. In addition, the number of mature cows and bulls are tabulated for both dairy and beef stock. The transition matrix estimates total monthly populations for all cattle subtypes. These populations are then reallocated to the state level based on the percent of the cattle type reported in each state in the January 1 USDA data. Each lifecycle is discussed separately below, and the categories tracked are listed in Table A-153.

Table A-153: Cattle Population Categories Used for Estimating CH_4 Emissions

Dairy Cattle	Beef Cattle
Calves	Calves
Heifer Replacements	Heifer Replacements
Cows	Heifer and Steer Stockers
	Animals in Feedlots (Heifers & Steer)
	Cows
	Bulls[a]

[a] Bulls (beef and dairy) are accounted for in a single category.

The key variables tracked for each of these cattle population categories are as follows:

Calves. Although enteric emissions are only calculated for 4- to 6-month old calves, it is necessary to calculate populations from birth as emissions from manure management require total calf populations and the estimates of populations for older cattle rely on the available supply of calves from birth. The number of animals born on a monthly basis was used to initiate monthly cohorts and to determine population age structure. The number of calves born each month was obtained by multiplying annual births by the percentage of births per month. Annual birth information for each year was taken from USDA (2016). For dairy cows, the number of births is assumed to be distributed equally throughout the year (approximately 8.3 percent per month) while beef births are distributed according to Table A-154, based on approximations from the National Animal Health Monitoring System (NAHMS) (USDA/APHIS/VS 1998, 1994, 1993). To determine whether calves were born to dairy or beef cows, the dairy cow calving rate (USDA/APHIS/VS 2002, USDA/APHIS/VS 1996) was multiplied by the total dairy cow population to determine the number of births attributable to dairy cows, with the remainder assumed to be attributable to beef cows. Total annual calf births are obtained from USDA, and distributed into monthly cohorts by cattle type (beef or dairy). Calf growth is modeled by month, based on estimated monthly weight gain for each cohort (approximately 61 pounds per month). The total calf population is modified through time to account for veal calf slaughter at 4 months and a calf death loss of 0.35 percent annually (distributed across age cohorts up to 6 months of age). An example of a transition matrix for calves is shown in

Table **A-155**. Note that 1- to 6-month old calves in January of each year have been tracked through the model based on births and death loss from the previous year.

Table A-154: Estimated Beef Cow Births by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
7%	15%	28%	22%	9%	3%	2%	2%	3%	4%	3%	3%

Table A-155: Example of Monthly Average Populations from Calf Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6	1,138	1,131	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522
5	1,131	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153
4	1,389	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144

3	1,612	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402
2	1,554	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625
1	1,538	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625	1,565
0	2,431	4,488	7,755	6,298	2,971	1,522	1,153	1,144	1,402	1,625	1,565	1,547

Note: The cohort starting at age 0 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss, and between months 4 and 5, a more significant loss is seen than in other months due to estimated veal slaughter.

Replacements and Stockers. At 7 months of age, calves "graduate" and are separated into the applicable cattle types: replacements (cattle raised to give birth), or stockers (cattle held for conditioning and growing on grass or other forage diets). First the number of replacements required for beef and dairy cattle are calculated based on estimated death losses and population changes between beginning and end of year population estimates. Based on the USDA estimates for "replacement beef heifers" and "replacement dairy heifers," the transition matrix for the replacements is back-calculated from the known animal totals from USDA, and the number of calves needed to fill that requirement for each month is subtracted from the known supply of female calves. All female calves remaining after those needed for beef and dairy replacements are removed and become "stockers" that can be placed in feedlots (along with all male calves). During the stocker phase, animals are subtracted out of the transition matrix for placement into feedlots based on feedlot placement statistics from USDA (2016).

The data and calculations that occur for the stocker category include matrices that estimate the population of backgrounding heifers and steer, as well as a matrix for total combined stockers. The matrices start with the beginning of year populations in January and model the progression of each cohort. The age structure of the January population is based on estimated births by month from the previous two years, although in order to balance the population properly, an adjustment is added that slightly reduces population percentages in the older populations. The populations are modified through addition of graduating calves (added in month 7, bottom row of Table A-156) and subtraction through death loss and animals placed in feedlots. Eventually, an entire cohort population of stockers may reach zero, indicating that the complete cohort has been transitioned into feedlots. An example of the transition matrix for stockers is shown in Table A-156.

Table A-156: Example of Monthly Average Populations from Stocker Transition Matrix (1,000 head)

Age (month)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
23	185	180	104	37	15	9	8	8	6	3	1	0
22	320	146	49	19	12	9	9	9	6	3	17	181
21	260	69	25	14	11	11	11	8	6	68	218	313
20	123	35	19	14	14	13	10	8	133	331	387	254
19	63	27	19	17	16	13	10	196	472	615	318	120
18	48	27	23	20	16	13	241	610	900	514	149	61
17	47	33	27	19	15	295	709	1,179	759	237	129	47
16	58	38	26	19	363	828	1,380	1,000	348	340	47	46
15	67	36	25	452	977	1,619	1,172	456	603	47	46	57
14	65	36	599	1,172	1,921	1,378	534	862	47	46	57	66
13	64	845	1,478	2,309	1,639	629	1,117	47	46	57	66	63
12	982	1,602	2,556	1,858	755	1,512	214	46	57	66	63	63
11	1,814	2,770	2,056	855	1,872	277	138	76	89	81	80	1,016
10	3,133	2,255	945	2,241	385	189	184	231	209	185	1,135	2,445
9	2,545	1,062	2,502	484	335	341	420	372	371	1,292	2,786	5,299
8	1,200	2,951	664	482	557	759	658	649	1,503	3,247	5,984	4,877
7	3,381	800	794	956	1,160	1,109	1,100	1,876	3,666	6,504	5,243	2,353

Note: The cohort starting at age 7 months on January 1 is tracked in order to illustrate how a single cohort moves through the transition matrix. Each month, the cohort reflects the decreases in population due to the estimated 0.35 percent annual death loss and loss due to placement in feedlots (the latter resulting in the majority of the loss from the matrix).

In order to ensure a balanced population of both stockers and placements, additional data tables are utilized in the stocker matrix calculations. The tables summarize the placement data by weight class and month, and is based on the total number of animals within the population that are available to be placed in feedlots and the actual feedlot placement statistics provided by USDA (2016). In cases where there are discrepancies between the USDA estimated placements by weight class and the calculated animals available by weight, the model pulls available stockers from one higher weight category if available. If there are still not enough animals to fulfill requirements the model pulls animals from one lower weight category. In the current time series, this method was able to ensure that total placement data matched USDA estimates, and no shortfalls have occurred.

In addition, average weights were tracked for each monthly age group using starting weight and monthly weight gain estimates. Weight gain (i.e., pounds per month) was estimated based on weight gain needed to reach a set target weight, divided by the number of months remaining before target weight was achieved. Birth weight was assumed to be 88 pounds for both beef and dairy animals. Weaning weights were estimated at 515 pounds. Other reported target weights were available for 12-, 15-, 24-, and 36-month-old animals, depending on the animal type. Beef cow mature weight was taken from measurements provided by a major British Bos taurus breed (Enns 2008) and increased during the time series through 2007.[78] Bull mature weight was calculated as 1.5 times the beef cow mature weight (Doren et al. 1989). Beef replacement weight was calculated as 70 percent of mature weight at 15 months and 85 percent of mature weight at 24 months. As dairy weights are not a trait that is typically tracked, mature weight for dairy cows was estimated at 1,500 pounds for all years, based on a personal communication with Kris Johnson (2010) and an estimate from Holstein Association USA (2010).[79] Dairy replacement weight at 15 months was assumed to be 875 pounds and 1,300 pounds at 24 months. Live slaughter weights were estimated from dressed slaughter weight (USDA 2016) divided by 0.63. This ratio represents the dressed weight (i.e., weight of the carcass after removal of the internal organs), to the live weight (i.e., weight taken immediately before slaughter). The annual typical animal mass for each livestock type are presented in Table A-157.

Weight gain for stocker animals was based on monthly gain estimates from Johnson (1999) for 1989, and from average daily estimates from Lippke et al. (2000), Pinchack et al. (2004), Platter et al. (2003), and Skogerboe et al. (2000) for 2000. Interim years were calculated linearly, as shown in Table A-158, and weight gain was held constant starting in 2000. Table A-158 provides weight gains that vary by year in the CEFM.

Table A-157: Typical Animal Mass (lbs)

Year/Cattle Type	Calves	Dairy Cows[a]	Dairy Replacements[b]	Beef Cows[a]	Bulls[a]	Beef Replacements[b]	Steer Stockers[b]	Heifer Stockers[b]	Steer Feedlot[b]	Heifer Feedlot[b]
1990	269	1,500	899	1,221	1,832	819	691	651	923	845
1991	270	1,500	897	1,225	1,838	821	694	656	933	855
1992	269	1,500	897	1,263	1,895	840	714	673	936	864
1993	270	1,500	898	1,280	1,920	852	721	683	929	863
1994	270	1,500	897	1,280	1,920	853	720	688	943	875
1995	270	1,500	897	1,282	1,923	857	735	700	947	879
1996	269	1,500	898	1,285	1,928	858	739	707	939	878
1997	270	1,500	899	1,286	1,929	860	736	707	938	876
1998	270	1,500	896	1,296	1,944	865	736	709	956	892
1999	270	1,500	899	1,292	1,938	861	730	708	959	894
2000	270	1,500	896	1,272	1,908	849	719	702	960	898
2001	270	1,500	897	1,272	1,908	850	725	707	963	900
2002	270	1,500	896	1,276	1,914	851	725	707	981	915
2003	270	1,500	899	1,308	1,962	871	718	701	972	904
2004	270	1,500	896	1,323	1,985	877	719	702	966	904
2005	270	1,500	894	1,327	1,991	879	717	706	974	917
2006	270	1,500	897	1,341	2,012	889	724	712	983	925
2007	270	1,500	896	1,348	2,022	894	720	706	991	928
2008	270	1,500	897	1,348	2,022	894	720	704	999	938
2009	270	1,500	895	1,348	2,022	894	730	715	1007	947
2010	270	1,500	897	1,348	2,022	896	726	713	996	937
2011	270	1,500	897	1,348	2,022	891	721	712	989	932
2012	270	1,500	899	1,348	2,022	892	714	706	1003	945
2013	270	1,500	898	1,348	2,022	892	718	709	1016	958
2014	270	1,500	895	1,348	2,022	888	722	714	1022	962
2015	270	1,500	896	1,348	2,022	891	717	713	1037	982

[a] Input into the model.
[b] Annual average calculated in model based on age distribution.

78 Mature beef weight is held constant after 2007 but future inventory submissions will incorporate known trends through 2007 and extrapolate to future years, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

79 Mature dairy weight is based solely on Holstein weight, so could be higher than the national average. Future Inventory submissions will consider other dairy breeds, as noted in the Planned Improvements section of 5.1 Enteric Fermentation.

Table A-158: Weight Gains that Vary by Year (lbs)

Year/Cattle Type	Steer Stockers to 12 months(lbs/day)	Steer Stockers to 24 months (lbs/day)	Heifer Stockers to 12 months(lbs/day)	Heifer Stockers to 24 months(lbs/day)
1990	1.53	1.23	1.23	1.08
1991	1.56	1.29	1.29	1.15
1992	1.59	1.35	1.35	1.23
1993	1.62	1.41	1.41	1.30
1994	1.65	1.47	1.47	1.38
1995	1.68	1.53	1.53	1.45
1996	1.71	1.59	1.59	1.53
1997	1.74	1.65	1.65	1.60
1998	1.77	1.71	1.71	1.68
1999	1.80	1.77	1.77	1.75
2000–onwards	1.83	1.83	1.83	1.83

Sources: Enns (2008), Johnson (1999), Lippke et al. (2000), NRC (1999), Pinchack et al. (2004), Platter et al. (2003), Skogerboe et al. (2000).

Feedlot Animals. Feedlot placement statistics from USDA provide data on the placement of animals from the stocker population into feedlots on a monthly basis by weight class. The model uses these data to shift a sufficient number of animals from the stocker cohorts into the feedlot populations to match the reported placement data. After animals are placed in feedlots they progress through two steps. First, animals spend 25 days on a step-up diet to become acclimated to the new feed type (e.g., more grain than forage, along with new dietary supplements), during this time weight gain is estimated to be 2.7 to 3 pounds per day (Johnson 1999). Animals are then switched to a finishing diet (concentrated, high energy) for a period of time before they are slaughtered. Weight gain during finishing diets is estimated to be 2.9 to 3.3 pounds per day (Johnson 1999). The length of time an animal spends in a feedlot depends on the start weight (i.e., placement weight), the rate of weight gain during the start-up and finishing phase of diet, and the target weight (as determined by weights at slaughter). Additionally, animals remaining in feedlots at the end of the year are tracked for inclusion in the following year's emission and population counts. For 1990 to 1995, only the total placement data were available, therefore placements for each weight category (categories displayed in Table A-159) for those years are based on the average of monthly placements from the 1996 to 1998 reported figures. Placement data is available by weight class for all years from 1996 onward. Table A-159 provides a summary of the reported feedlot placement statistics for 2015.

Table A-159: Feedlot Placements in the United States for 2015 (Number of animals placed/1,000 Head)

Weight Placed When:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 600 lbs	410	330	365	320	360	350	365	395	405	645	470	375
600 – 700 lbs	340	265	275	240	260	250	235	215	290	530	387	355
700 – 800 lbs	474	396	449	348	389	336	327	362	416	431	310	357
> 800 lbs	565	560	720	640	710	545	620	660	830	680	435	440
Total	**1,789**	**1,551**	**1,809**	**1,548**	**1,719**	**1,481**	**1,547**	**1,632**	**1,941**	**2,286**	**1,602**	**1,527**

Note: Totals may not sum due to independent rounding.
Source: USDA (2016).

Mature Animals. Energy requirements and hence, composition of diets, level of intake, and emissions for particular animals, are greatly influenced by whether the animal is pregnant or lactating. Information is therefore needed on the percentage of all mature animals that are pregnant each month, as well as milk production, to estimate CH_4 emissions. A weighted average percent of pregnant cows each month was estimated using information on births by month and average pregnancy term. For beef cattle, a weighted average total milk production per animal per month was estimated using information on typical lactation cycles and amounts (NRC 1999), and data on births by month. This process results in a range of weighted monthly lactation estimates expressed as pounds per animal per month. The monthly estimates for daily milk production by beef cows are shown in Table A-160. Annual estimates for dairy cows were taken from USDA milk production statistics. Dairy lactation estimates for 1990 through 2015 are shown in Table A-161. Beef and dairy cow and bull populations are assumed to remain relatively static throughout the year, as large fluctuations in population size are assumed to not occur. These estimates are taken from the USDA beginning and end of year population datasets.

Table A-160: Estimates of Average Monthly Milk Production by Beef Cows (lbs/cow)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Beef Cow Milk Production (lbs/ head)	3.3	5.1	8.7	12.0	13.6	13.3	11.7	9.3	6.9	4.4	3.0	2.8

Table A-161: Dairy Lactation Rates by State (lbs/ year/cow)

State/Year	1990	1995	2000	2005	2011	2012	2013	2014	2015
Alabama	12,214	14,176	13,920	14,000	14,300	13,000	13,000	13,625	12,625
Alaska	13,300	17,000	14,500	12,273	13,800	14,250	10,667	11,667	11,667
Arizona	17,500	19,735	21,820	22,679	23,473	23,979	23,626	24,368	24,477
Arkansas	11,841	12,150	12,436	13,545	11,917	13,300	11,667	13,714	13,000
California	18,456	19,573	21,130	21,404	23,438	23,457	23,178	23,786	23,002
Colorado	17,182	18,687	21,618	22,577	23,430	24,158	24,292	24,951	25,685
Connecticut	15,606	16,438	17,778	19,200	19,000	19,889	20,556	20,158	20,842
Delaware	13,667	14,500	14,747	16,622	18,300	19,542	19,521	20,104	19,700
Florida	14,033	14,698	15,688	16,591	19,067	19,024	19,374	20,390	20,656
Georgia	12,973	15,550	16,284	17,259	18,354	19,138	19,600	20,877	21,651
Hawaii	13,604	13,654	14,358	12,889	14,421	14,200	13,409	13,591	15,909
Idaho	16,475	18,147	20,816	22,332	22,926	23,376	23,440	24,127	24,126
Illinois	14,707	15,887	17,450	18,827	18,510	19,061	19,063	19,681	20,128
Indiana	14,590	15,375	16,568	20,295	20,657	21,440	21,761	21,865	22,143
Iowa	15,118	16,124	18,298	20,641	21,191	22,015	22,149	22,449	22,943
Kansas	12,576	14,390	16,923	20,505	21,016	21,683	21,881	22,085	22,231
Kentucky	10,947	12,469	12,841	12,896	14,342	15,135	15,070	15,905	17,607
Louisiana	11,605	11,908	12,034	12,400	12,889	13,059	12,875	13,600	13,429
Maine	14,619	16,025	17,128	18,030	18,688	18,576	19,548	19,967	19,800
Maryland	13,461	14,725	16,083	16,099	18,654	19,196	19,440	19,740	20,061
Massachusetts	14,871	16,000	17,091	17,059	16,923	18,250	17,692	17,923	18,083
Michigan	15,394	17,071	19,017	21,635	23,164	23,976	24,116	24,638	25,130
Minnesota	14,127	15,894	17,777	18,091	18,996	19,512	19,694	19,841	20,578
Mississippi	12,081	12,909	15,028	15,280	14,571	14,214	13,286	14,462	15,000
Missouri	13,632	14,158	14,662	16,026	14,611	14,979	14,663	15,539	15,511
Montana	13,542	15,000	17,789	19,579	20,571	21,357	21,286	21,500	21,357
Nebraska	13,866	14,797	16,513	17,950	20,579	21,179	21,574	22,130	22,930
Nevada	16,400	18,128	19,000	21,680	22,966	22,931	22,034	23,793	23,069
New Hampshire	15,100	16,300	17,333	18,875	20,429	19,643	20,923	20,143	20,143
New Jersey	13,538	13,913	15,250	16,000	16,875	18,571	18,143	18,143	18,143
New Mexico	18,815	18,969	20,944	21,192	24,854	24,694	24,944	25,093	24,245
New York	14,658	16,501	17,378	18,639	21,046	21,623	22,070	22,325	22,816
North Carolina	15,220	16,314	16,746	18,741	20,089	20,435	20,326	20,891	20,979
North Dakota	12,624	13,094	14,292	14,182	18,158	19,278	18,944	20,250	20,750
Ohio	13,767	15,917	17,027	17,567	19,194	19,833	20,178	20,318	20,573
Oklahoma	12,327	13,611	14,440	16,480	17,415	17,896	17,311	18,150	18,462
Oregon	16,273	17,289	18,222	18,876	20,488	20,431	20,439	20,565	20,408
Pennsylvania	14,726	16,492	18,081	18,722	19,495	19,549	19,797	20,121	20,387
Rhode Island	14,250	14,773	15,667	17,000	17,909	16,636	19,000	19,000	17,667
South Carolina	12,771	14,481	16,087	16,000	17,438	17,250	16,500	16,438	17,400
South Dakota	12,257	13,398	15,516	17,741	20,582	21,391	21,521	21,753	22,255
Tennessee	11,825	13,740	14,789	15,743	16,200	16,100	15,938	16,196	16,489
Texas	14,350	15,244	16,503	19,646	22,232	22,009	21,991	22,268	22,235
Utah	15,838	16,739	17,573	18,875	22,161	22,863	22,432	22,989	23,146
Vermont	14,528	16,210	17,199	18,469	18,940	19,316	19,448	20,197	20,197
Virginia	14,213	15,116	15,833	16,990	17,906	17,990	18,337	19,129	19,462
Washington	18,532	20,091	22,644	23,270	23,727	23,794	23,820	24,088	23,848
West Virginia	11,250	12,667	15,588	14,923	15,700	15,400	15,200	15,556	15,667
Wisconsin	13,973	15,397	17,306	18,500	20,599	21,436	21,693	21,869	22,697
Wyoming	12,337	13,197	13,571	14,878	20,517	20,650	21,367	21,583	22,567

Source: USDA (2016).

Step 2: Characterize U.S. Cattle Population Diets

To support development of digestible energy (DE, the percent of gross energy intake digested by the animal) and CH_4 conversion rate (Y_m, the fraction of gross energy converted to CH_4) values for each of the cattle population categories, data were collected on diets considered representative of different regions. For both grazing animals and animals being fed mixed rations, representative regional diets were estimated using information collected from state livestock specialists, the USDA, expert opinion, and other literature sources. The designated regions for this analysis for dairy cattle for all years and foraging beef cattle from 1990 through 2006 are shown in Table A-162. For foraging beef cattle from 2007 onwards, the regional designations were revised based on data available from the NAHMS 2007–2008 survey on cow-calf system management practices (USDA:APHIS:VS 2010) and are shown in and Table A-163. The data for each of the diets (e.g., proportions of different feed constituents, such as hay or grains) were used to determine feed chemical composition for use in estimating DE and Y_m for each animal type.

Table A-162: Regions used for Characterizing the Diets of Dairy Cattle (all years) and Foraging Cattle from 1990–2006

West	California	Northern Great Plains	Midwestern	Northeast	Southcentral	Southeast
Alaska	California	Colorado	Illinois	Connecticut	Arkansas	Alabama
Arizona		Kansas	Indiana	Delaware	Louisiana	Florida
Hawaii		Montana	Iowa	Maine	Oklahoma	Georgia
Idaho		Nebraska	Michigan	Maryland	Texas	Kentucky
Nevada		North Dakota	Minnesota	Massachusetts		Mississippi
New Mexico		South Dakota	Missouri	New Hampshire		North Carolina
Oregon		Wyoming	Ohio	New Jersey		South Carolina
Utah			Wisconsin	New York		Tennessee
Washington				Pennsylvania		Virginia
				Rhode Island		
				Vermont		
				West Virginia		

Source: USDA (1996).

Table A-163: Regions used for Characterizing the Diets of Foraging Cattle from 2007–2015

West	Central	Northeast	Southeast
Alaska	Illinois	Connecticut	Alabama
Arizona	Indiana	Delaware	**Arkansas**
California	Iowa	Maine	Florida
Colorado	**Kansas**	Maryland	Georgia
Hawaii	Michigan	Massachusetts	Kentucky
Idaho	Minnesota	New Hampshire	**Louisiana**
Montana	Missouri	New Jersey	Mississippi
Nevada	**Nebraska**	New York	North Carolina
New Mexico	**North Dakota**	Pennsylvania	**Oklahoma**
Oregon	Ohio	Rhode Island	South Carolina
Utah	**South Dakota**	Vermont	Tennessee
Washington	Wisconsin	West Virginia	**Texas**
Wyoming			Virginia

Note: States in **bold** represent a change in region from the 1990–2006 assessment.
Source: Based on data from USDA:APHIS:VS (2010).

DE and Y_m vary by diet and animal type. The IPCC recommends Y_m values of 3.0$\pm$1.0 percent for feedlot cattle and 6.5$\pm$1.0 percent for all other cattle (IPCC 2006). Given the availability of detailed diet information for different regions and animal types in the United States, DE and Y_m values unique to the United States were developed for dairy and beef cattle. Digestible energy and Y_m values were estimated across the time series for each cattle population category based on physiological modeling, published values, and/or expert opinion.

For dairy cows, ruminant digestion models were used to estimate Y_m. The three major categories of input required by the models are animal description (e.g., cattle type, mature weight), animal performance (e.g., initial and final weight, age at start of period), and feed characteristics (e.g., chemical composition, habitat, grain or forage). Data used to simulate ruminant digestion is provided for a particular animal that is then used to represent a group of animals with similar characteristics. The Y_m values were estimated for 1990 using the Donovan and Baldwin model (1999), which represents physiological processes in the ruminant animals, as well as diet characteristics from USDA (1996). The Donovan and Baldwin model is able to account for differing diets (i.e., grain-based or forage-based), so that Y_m values for the variable feeding characteristics within the U.S. cattle population can be estimated. Subsequently, a literature review of dairy diets was conducted and nearly 250 diets were analyzed from 1990 through 2009 across 23 states—the review indicated highly variable diets, both temporally and spatially. Kebreab et al. (2008) conducted an evaluation of models and found that the COWPOLL model was the best model for estimating Y_m for dairy, so COWPOLL was used to determine the Y_m value associated with each of the evaluated diets. The statistical analysis of the resulting Y_m estimates showed a downward trend in predicting Y_m, which inventory team experts modeled using the following best-fit non-liner curve:

$$Y_m = 4.52e^{\left(\frac{1.22}{Year-1980}\right)}$$

The team determined that the most comprehensive approach to estimating annual, region-specific Y_m values was to use the 1990 baseline Y_m values derived from Donovan and Baldwin and then scale these Y_m values for each year beyond 1990 with a factor based on this function. The scaling factor is the ratio of the Y_m value for the year in question to the 1990 baseline Y_m value. The scaling factor for each year was multiplied by the baseline Ym value. The resulting Y_m equation (incorporating both Donovan and Baldwin (1999) and COWPOLL) is shown below (and described in ERG 2016):

$$Y_m = Y_m(1990)EXP\left(\frac{1.22}{(Year-1980)}\right) / EXP\left(\frac{1.22}{(1990-1980)}\right)$$

DE values for dairy cows were estimated from the literature search based on the annual trends observed in the data collection effort. The regional variability observed in the literature search was not statistically significant, and therefore DE was not varied by region, but did vary over time, and was grouped by the following years 1990–1993, 1994–1998, 1999–2003, 2004–2006, 2007, and 2008 onwards.

Considerably less data was available for dairy heifers and dairy calves. Therefore, for dairy heifers assumptions were based on the relationship of the collected data in the literature on dairy heifers to the data on dairy cow diets. From this relationship, DE was estimated as the mature cow DE minus three percent, and Y_m was estimated as that of the mature dairy cow plus 0.1 percent.

To calculate the DE values for grazing beef cattle, diet composition assumptions were used to estimate weighted DE values for a combination of forage and supplemental diets. The forage portion makes up an estimated 85 to 95 percent of grazing beef cattle diets, and there is considerable variation of both forage type and quality across the United States. Currently there is no comprehensive survey of this data, so for this analysis two regional DE values were developed to account for the generally lower forage quality in the "West" region of the United States versus all other regions in Table A-162 (California, Northern Great Plains, Midwestern, Northeast, Southcentral, Southeast) and Table A-163 (Central, Northeast, and Southeast). For all non-western grazing cattle, the forage DE was an average of the estimated seasonal values for grass pasture diets for a calculated DE of 64.2 percent. For foraging cattle in the west, the forage DE was calculated as the seasonal average for grass pasture, meadow and range diets, for a calculated DE of 61.3 percent. The assumed specific components of each of the broad forage types, along with their corresponding DE value and the calculated regional DE values can be found in Table A-164. In addition, beef cattle are assumed to be fed a supplemental diet, consequently, two sets of supplemental diets were developed, one for 1990 through 2006 (Donovan 1999) and one for 2007 onwards (Preston 2010, Archibeque 2011, USDA:APHIS:VS 2010) as shown in Table A-165 and Table A-166 along with the percent of each total diet that is assumed to be made up of the supplemental portion. By weighting the calculated DE values from the forage and supplemental diets, the DE values for the composite diet were calculated.[80] These values are used for steer and heifer stockers and beef replacements. Finally, for mature beef cows and bulls, the DE value was adjusted downward by two percent to reflect the lower digestibility diets of mature cattle based on Johnson (2002). Y_m values for all grazing beef cattle were set at 6.5 percent based on Johnson (2002). The Y_m values and the resulting final weighted DE values by region for 2007 onwards are shown in Table A-167.

For feedlot animals, DE and Y_m are adjusted over time as diet compositions in actual feedlots are adjusted based on new and improved nutritional information and availability of feed types. Feedlot diets are assumed to not differ significantly by state, and therefore only a single set of national diet values is utilized for each year. The DE and Y_m values for 1990 were estimated by Dr. Don Johnson (1999). In the CEFM, the DE values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000. DE and Y_m values from 2000 through the current year were estimated using the MOLLY model as described in Kebreab et al. (2008), based on a series of average diet feed compositions from Galyean and Gleghorn (2001) for 2000 through 2006 and Vasconcelos and Galyean (2007) for 2007 onwards. In addition, feedlot animals are assumed to spend the first 25 days in the feedlot on a "step-up" diet to become accustomed to the higher quality feedlot diets. The step-up DE and Y_m are calculated as the average of all state forage and feedlot diet DE and Y_m values.

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[80] For example, the West has a forage DE of 61.3 which makes up 90 percent of the diet and a supplemented diet DE of 67.4 percent was used for 10 percent of the diet, for a total weighted DE of 61.9 percent, as shown in Table A-167.

For calves aged 4 through 6 months, a gradual weaning from milk is simulated, with calf diets at 4 months assumed to be 25 percent forage, increasing to 50 percent forage at age 5 months, and 75 percent forage at age 6 months. The portion of the diet allocated to milk results in zero emissions, as recommended by the IPCC (2006). For calves, the DE for the remainder of the diet is assumed to be similar to that of slightly older replacement heifers (both beef and dairy are calculated separately). The Y_m for beef calves is also assumed to be similar to that of beef replacement heifers (6.5 percent), as literature does not provide an alternative Y_m for use in beef calves. For dairy calves, the Y_m is assumed to be 7.8 percent at 4 months, 8.03 percent at 5 months, and 8.27 percent at 6 months based on estimates provided by Soliva (2006) for Y_m at 4 and 7 months of age and a linear interpolation for 5 and 6 months.

Table A-168 shows the regional DE and Y_m for U.S. cattle in each region for 2015.

Table A-164: Feed Components and Digestible Energy Values Incorporated into Forage Diet Composition Estimates

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Bahiagrass Paspalum notatum, fresh	61.38			x							
Bermudagrass Cynodon dactylon, fresh	66.29		x								
Bremudagrass, Coastal Cynodon dactylon, fresh	65.53		x								
Bluegrass, Canada Poa compressa, fresh, early vegetative	73.99	x									
Bluegrass, Kentucky Poa pratensis, fresh, early vegetative	75.62	x									
Bluegrass, Kentucky Poa pratensis, fresh, mature	59.00		x	x							
Bluestem Andropagon spp, fresh, early vegetative	73.17				x						
Bluestem Andropagon spp, fresh, mature	56.82					x	x	x	x		x
Brome Bromus spp, fresh, early vegetative	78.57	x									
Brome, Smooth Bromus inermis, fresh, early vegetative	75.71	x									
Brome, Smooth Bromus inermis, fresh, mature	57.58		x	x					x		
Buffalograss, Buchloe dactyloides, fresh	64.02				x	x					
Clover, Alsike Trifolium hybridum, fresh, early vegetative	70.62	x									
Clover, Ladino Trifolium repens, fresh, early vegetative	73.22	x									
Clover, Red Trifolium pratense, fresh, early bloom	71.27	x									
Clover, Red Trifolium pratense, fresh, full bloom	67.44		x		x						
Corn, Dent Yellow Zea mays indentata, aerial part without ears, without husks, sun-cured, (stover)(straw)	55.28			x							
Dropseed, Sand Sporobolus cryptandrus, fresh, stem cured	64.69				x	x	x			x	
Fescue Festuca spp, hay, sun-cured, early vegetative	67.39	x									
Fescue Festuca spp, hay, sun-cured, early bloom	53.57			x							
Grama Bouteloua spp, fresh, early vegetative	67.02	x									
Grama Bouteloua spp, fresh, mature	63.38		x	x						x	
Millet, Foxtail Setaria italica, fresh	68.20	x			x						
Napiergrass Pennisetum purpureum, fresh, late bloom	57.24		x	x							
Needleandthread Stipa comata, fresh, stem cured	60.36					x	x	x			
Orchardgrass Dactylis glomerata, fresh, early vegetative	75.54	x									
Orchardgrass Dactylis glomerata, fresh, midbloom	60.13		x								
Pearlmillet Pennisetum glaucum, fresh	68.04	x									
Prairie plants, Midwest, hay, sun-cured	55.53			x							x
Rape Brassica napus, fresh, early bloom	80.88	x									
Rye Secale cereale, fresh	71.83	x									
Ryegrass, Perennial Lolium perenne, fresh	73.68	x									
Saltgrass Distichlis spp, fresh, post ripe	58.06		x	x							

Forage Type	DE (% of GE)	Grass pasture - Spring	Grass pasture - Summer	Grass pasture - Fall	Range June	Range July	Range August	Range September	Range Winter	Meadow - Spring	Meadow - Fall
Sorghum, Sudangrass Sorghum bicolor sudanense, fresh, early vegetative	73.27	x									
Squirreltail Stanion spp, fresh, stem-cured	62.00		x			x					
Summercypress, Gray Kochia vestita, fresh, stem-cured	65.11			x	x	x					
Timothy Phleum pratense, fresh, late vegetative	73.12	x									
Timothy Phleum pratense, fresh, midbloom	66.87		x								
Trefoil, Birdsfoot Lotus corniculatus, fresh	69.07	x									
Vetch Vicia spp, hay, sun-cured	59.44			x							
Wheat Triticum aestivum, straw	45.77			x							
Wheatgrass, Crested Agropyron desertorum, fresh, early vegetative	79.78	x									
Wheatgrass, Crested Agropyron desertorum, fresh, full bloom	65.89		x			x					
Wheatgrass, Crested Agropyron desertorum, fresh, post ripe	52.99			x					x		x
Winterfat, Common Eurotia lanata, fresh, stem-cured	40.89								x		
Weighted Average DE		**72.99**	**62.45**	**57.26**	**67.11**	**62.70**	**60.62**	**58.59**	**52.07**	**64.03**	**55.11**
Forage Diet for West	**61.3**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**	**10%**
Forage Diet for All Other Regions	**64.2**	**33.3%**	**33.3%**	**33.3%**	**-**	**-**	**-**	**-**	**-**	**-**	**-**

Sources: Preston (2010) and Archibeque (2011).
Note that forages marked with an x indicate that the DE from that specific forage type is included in the general forage type for that column (e.g., grass pasture, range, meadow or meadow by month or season).

Table A-165: DE Values with Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 1990–2006

Feed	Source of DE (NRC 1984)	Unweighted DE (% of GE)	California*	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	30%	29%	12%	30%	
Barley		85.08	10%	15%					
Bermuda	Table 8, feed #030	66.29							35%
Bermuda Hay	Table 8, feed #031	50.79				40%			
Corn	Table 8, feed #089	88.85	10%	10%	25%	11%	13%	13%	
Corn Silage	Table 8, feed #095	72.88			25%		20%	20%	
Cotton Seed Meal						7%			
Grass Hay	Table 8, feed #126, 170, 274	58.37		40%				30%	
Orchard	Table 8, feed #147	60.13							40%
Soybean Meal Supplement		77.15		5%	5%				5%
Sorghum	Table 8, feed #211	84.23							20%
Soybean Hulls		66.86						7%	
Timothy Hay	Table 8, feed #244	60.51					50%		
Whole Cotton Seed		75.75	5%				5%		
Wheat Middlings	Table 8, feed #257	68.09			15%	13%			
Wheat	Table 8, feed #259	87.95	10%						
Weighted Supplement DE (%)			**70.1**	**67.4**	**73.0**	**62.0**	**67.6**	**66.9**	**68.0**
Percent of Diet that is Supplement			**5%**	**10%**	**15%**	**10%**	**15%**	**10%**	**5%**

Source of representative regional diets: Donovan (1999).
* Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.

Table A-166: DE Values and Representative Regional Diets for the Supplemental Diet of Grazing Beef Cattle for 2007–2015

Feed	Source of DE (NRC1984)	Unweighted DE (% of GE)	West[a]	Central[a]	Northeast[a]	Southeast[a]
Alfalfa Hay	Table 8, feed #006	61.79	65%	30%	12%	
Bermuda	Table 8, feed #030	66.29				20%
Bermuda Hay	Table 8, feed #031	50.79				20%
Corn	Table 8, feed #089	88.85	10%	15%	13%	10%
Corn Silage	Table 8, feed #095	72.88		35%	20%	
Grass Hay	Table 8, feed #126, 170, 274	58.37	10%			
Orchard	Table 8, feed #147	60.13				30%
Protein supplement (West)	Table 8, feed #082, 134, 225 [b]	81.01	10%			
Protein Supplement (Central and Northeast)	Table 8, feed #082, 134, 225 [b]	80.76		10%	10%	
Protein Supplement (Southeast)	Table 8, feed #082, 134, 101 [b]	77.89				10%
Sorghum	Table 8, feed #211	84.23		5%		10%
Timothy Hay	Table 8, feed #244	60.51			45%	
Wheat Middlings	Table 8, feed #257	68.09		5%		
Wheat	Table 8, feed #259	87.95	5%			
Weighted Supplement DE			**67.4**	**73.1**	**68.9**	**66.6**
Percent of Diet that is Supplement			**10%**	**15%**	**5%**	**15%**

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above.
[b] Not in equal proportions.
Sources of representative regional diets: Donovan (1999), Preston (2010), Archibeque (2011), and USDA:APHIS:VS (2010).

Table A-167: Foraging Animal DE (% of GE) and Y_m Values for Each Region and Animal Type for 2007–2015

Animal Type	Data	West[a]	Central	Northeast	Southeast
Beef Repl. Heifers	DE[b]	61.9	65.6	64.5	64.6
	Y_m[c]	6.5%	6.5%	6.5%	6.5%
Beef Calves (4–6 mo)	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Steer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Heifer Stockers	DE	61.9	65.6	64.5	64.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Beef Cows	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%
Bulls	DE	59.9	63.6	62.5	62.6
	Y_m	6.5%	6.5%	6.5%	6.5%

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied by the regions shown in the table above. To see the regional designation per state, please see Table A-163.
[b] DE is the digestible energy in units of percent of GE (MJ/Day).
[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Table A-168: Regional DE (% of GE) and Y_m Rates for Dairy and Feedlot Cattle by Animal Type for 2015

Animal Type	Data	California[a]	West	Northern Great Plains	Southcentral	Northeast	Midwest	Southeast
Dairy Repl. Heifers	DE[b]	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym[c]	6.0%	6.0%	5.7%	6.5%	6.4%	5.7%	7.0%
Dairy Calves (4–6 mo)	DE	63.7	63.7	63.7	63.7	63.7	63.7	63.7
	Ym	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%	6.5%
Dairy Cows	DE	66.7	66.7	66.7	66.7	66.7	66.7	66.7
	Ym	5.9%	5.9%	5.6%	6.4%	6.3%	5.6%	6.9%
Steer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%
Heifer Feedlot	DE	82.5	82.5	82.5	82.5	82.5	82.5	82.5
	Ym	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%	3.9%

[a] Note that emissions are currently calculated on a state-by-state basis, but diets are applied in Table A-162 by the regions shown in the table above. To see the regional designation for foraging cattle per state, please see Table A-162.
[b] DE is the digestible energy in units of percent of GE (MJ/Day).
[c] Y_m is the methane conversion rate, the fraction of GE in feed converted to methane.

Step 3: Estimate CH_4 Emissions from Cattle

Emissions by state were estimated in three steps: a) determine gross energy (GE) intake using the Tier 2 IPCC (2006) equations, b) determine an emission factor using the GE values, Y_m and a conversion factor, and c) sum the daily emissions for each animal type. Finally, the state emissions were aggregated to obtain the national emissions estimate. The necessary data values for each state and animal type include:

- Body Weight (kg)
- Weight Gain (kg/day)
- Net Energy for Activity (C_a, MJ/day)[81]
- Standard Reference Weight (kg)[82]
- Milk Production (kg/day)
- Milk Fat (percent of fat in milk = 4)
- Pregnancy (percent of population that is pregnant)
- DE (percent of GE intake digestible)
- Y_m (the fraction of GE converted to CH_4)
- Population

Step 3a: Determine Gross Energy, GE

As shown in the following equation, GE is derived based on the net energy estimates and the feed characteristics. Only variables relevant to each animal category are used (e.g., estimates for feedlot animals do not require the NE_l factor). All net energy equations are provided in IPCC (2006). Calculated GE values for 2015 are shown by state and animal type in Table A-169.

$$GE = \left[\frac{\left(\frac{NE_m + NE_a + NE_l + NE_{work} + NE_p}{REM} \right) + \left(\frac{NE_g}{REG} \right)}{\frac{DE\%}{100}} \right]$$

where,

GE = Gross energy (MJ/day)
NE_m = Net energy required by the animal for maintenance (MJ/day)
NE_a = Net energy for animal activity (MJ/day)
NE_l = Net energy for lactation (MJ/day)
NE_{work} = Net energy for work (MJ/day)
NE_p = Net energy required for pregnancy (MJ/day)
REM = Ratio of net energy available in a diet for maintenance to digestible energy consumed
NE_g = Net energy needed for growth (MJ/day)
REG = Ratio of net energy available for growth in a diet to digestible energy consumed
DE = Digestible energy expressed as a percent of gross energy (percent)

Table A-169: Calculated Annual GE by Animal Type and State, for 2015 (MJ/1,000 head)

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	35	902	41	146	3,749	3,017	52,535	1,385	3,732	1,188	801	227

[81] Zero for feedlot conditions, 0.17 for high quality confined pasture conditions, and 0.36 for extensive open range or hilly terrain grazing conditions. C_a factor for dairy cows is weighted to account for the fraction of the population in the region that grazes during the year (IPCC 2006).

[82] Standard Reference Weight is the mature weight of a female animal of the animal type being estimated, used in the model to account for breed potential.

Alaska	1	32	1	5	213	21	370	12	32	8	3	1
Arizona	852	30,695	897	3,164	1,779	874	15,053	453	1,216	7,034	604	11,759
Arkansas	31	781	55	195	4,582	3,993	69,536	1,854	4,998	3,090	1,362	513
California	7,779	267,829	10,630	37,484	6,226	2,947	50,750	1,734	4,648	14,069	4,026	19,832
Colorado	634	23,528	1,381	4,868	4,892	3,621	62,362	2,267	6,078	19,952	13,517	43,396
Conn.	83	2,713	110	389	42	23	404	31	84	48	13	7
Delaware	22	691	35	122	33	12	202	9	23	52	19	8
Florida	542	17,979	483	1,704	4,999	4,192	73,000	1,607	4,331	594	801	156
Georgia	354	12,068	373	1,314	2,333	2,216	38,595	1,113	2,999	1,070	801	212
Hawaii	10	271	14	49	356	344	5,918	147	393	230	144	40
Idaho	2,530	90,326	4,418	15,578	3,558	2,302	39,654	1,600	4,290	7,162	4,889	11,432
Illinois	411	13,154	718	2,531	2,036	1,650	28,830	771	2,081	4,867	2,577	10,732
Indiana	791	26,794	1,104	3,894	1,385	897	15,675	602	1,626	2,688	1,145	4,666
Iowa	918	31,762	1,795	6,328	4,887	4,057	70,894	2,168	5,854	29,897	16,397	56,928
Kansas	625	21,219	1,242	4,381	7,738	6,432	112,406	3,493	9,431	43,803	34,617	101,724
Kentucky	275	8,363	621	2,191	5,415	4,613	80,333	1,731	4,664	4,753	2,803	700
Louisiana	61	1,586	69	243	2,499	2,156	37,548	915	2,466	570	614	133
Maine	131	4,159	221	779	125	51	889	56	150	107	67	20
Maryland	214	6,844	345	1,217	334	195	3,394	112	301	358	241	467
Mass.	55	1,647	97	341	84	26	444	25	67	48	27	8
Michigan	1,761	64,494	2,305	8,130	1,222	482	8,428	277	748	3,940	911	7,466
Minn.	2,010	65,205	3,865	13,631	2,851	1,533	26,782	1,084	2,927	11,588	4,164	17,965
Miss.	52	1,467	83	292	3,166	2,165	37,709	1,199	3,232	1,331	881	252
Missouri	389	10,804	828	2,921	8,959	8,343	145,805	4,156	11,220	9,270	5,856	3,266
Montana	61	2,028	97	341	8,894	7,472	128,681	5,801	15,552	4,476	5,695	1,866
Nebraska	236	8,165	276	974	7,738	7,915	138,321	5,059	13,659	54,000	33,315	118,056
Nevada	122	4,249	124	438	1,067	1,059	18,236	493	1,323	1,126	834	187
N. Hamp.	61	1,960	76	268	42	14	242	12	33	24	13	4
N. Jersey	31	924	52	185	84	35	606	16	43	48	24	8
N. Mexico	1,412	50,542	1,519	5,355	3,113	2,033	35,009	1,134	3,039	2,430	2,013	467
New York	2,688	92,703	4,832	17,038	1,253	487	8,484	508	1,370	834	1,178	1,213
N. Car.	205	6,876	248	876	2,416	1,680	29,249	865	2,332	856	721	178
N. Dakota	70	2,279	83	292	4,072	4,030	70,421	2,036	5,496	4,983	4,815	2,053
Ohio	1,171	37,983	1,726	6,085	2,036	1,271	22,213	602	1,626	4,519	1,301	7,933
Oklahoma	175	5,340	345	1,217	11,664	8,698	151,480	5,192	13,993	20,677	9,745	12,366
Oregon	546	17,633	828	2,921	3,558	2,622	45,159	1,467	3,933	4,221	3,020	3,966
Penn.	2,316	74,719	4,211	14,848	2,089	696	12,120	682	1,838	3,457	1,473	4,200
R. Island	4	117	7	24	8	7	121	6	17	12	5	2
S. Car.	66	1,979	69	243	1,166	787	13,698	371	1,000	214	320	59
S. Dakota	433	14,700	897	3,164	8,145	7,262	126,900	4,879	13,171	15,760	12,754	17,965
Tenn.	205	6,028	345	1,217	4,999	4,039	70,341	1,731	4,664	2,852	1,735	524
Texas	2,054	69,866	3,451	12,170	26,661	19,109	332,772	9,272	24,988	59,892	37,111	117,123
Utah	420	14,598	663	2,337	1,957	1,618	27,869	1,040	2,789	1,995	1,841	1,120
Vermont	577	18,509	773	2,726	251	56	970	50	134	95	134	25
Virginia	406	13,038	594	2,093	3,333	2,947	51,326	1,360	3,665	3,684	1,121	933
Wash.	1,211	42,903	1,877	6,621	1,601	989	17,031	720	1,931	4,476	3,883	9,799
W. Virg.	39	1,098	55	195	1,086	859	14,948	409	1,108	1,049	536	187
Wisconsin	5,572	191,584	10,078	35,537	2,851	1,240	21,662	903	2,439	8,691	1,171	12,132
Wyoming	26	898	69	243	3,558	3,466	59,696	2,574	6,900	3,453	4,084	3,500

Step 3b: Determine Emission Factor

The daily emission factor (DayEmit) was determined using the GE value and the methane conversion factor (Y_m) for each category. This relationship is shown in the following equation:

$$DayEmit = \frac{GE \times \mathrm{Y_m}}{55.65}$$

where,

DayEmit = Emission factor (kg CH_4/head/day)

GE = Gross energy intake (MJ/head/day)
Y_m = CH_4 conversion rate, which is the fraction of GE in feed converted to CH_4 (%)
55.65 = A factor for the energy content of methane (MJ/kg CH_4)

The daily emission factors were estimated for each animal type and state. Calculated annual national emission factors are shown by animal type in Table A-170. State-level emission factors are shown by animal type for 2015 in Table A-171.

Table A-170: Calculated Annual National Emission Factors for Cattle by Animal Type, for 2015 (kg CH_4/head/year)

Cattle Type	1990	1995	2000	2005	2010	2011	2012	2013	2014	2015
Dairy										
Calves	12	12	12	12	12	12	12	12	12	12
Cows	124	125	132	133	142	142	144	144	145	146
Replacements 7–11 months	48	46	46	45	46	46	46	46	46	46
Replacements 12–23 months	73	69	70	67	69	69	69	69	69	69
Beef										
Calves	11	11	11	11	11	11	11	11	11	11
Bulls	91	94	94	97	98	98	98	98	98	98
Cows	89	92	91	94	95	95	95	95	95	95
Replacements 7–11 months	54	57	56	59	60	60	60	60	60	60
Replacements 12–23 months	63	66	66	68	70	70	70	70	70	70
Steer Stockers	55	57	58	58	58	58	58	58	58	58
Heifer Stockers	52	56	60	60	60	60	60	60	60	60
Feedlot Cattle	39	38	39	39	42	42	42	43	43	43

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

Table A-171: Emission Factors for Cattle by Animal Type and State, for 2015 (kg CH_4/head/year)

State	Dairy Calves	Dairy Cows	Dairy Replace-ment Heifers 7-11 Months	Dairy Replace-ment Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replace-ment Heifers 7-11 Months	Beef Replace-ment Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot
Alabama	12	128	53	80	97	10	94	60	69	58	60	33
Alaska	12	103	46	69	104	11	100	64	74	62	65	33
Arizona	12	154	46	69	104	11	100	64	74	62	65	34
Arkansas	12	117	49	74	97	10	94	60	69	58	60	33
California	12	147	46	69	104	11	100	64	74	62	65	33
Colorado	12	150	43	65	104	11	100	64	74	62	65	34
Conn.	12	148	48	73	98	11	94	60	69	58	60	34
Delaware	12	143	48	73	98	11	94	60	69	58	60	35
Florida	12	165	53	80	97	10	94	60	69	58	60	34
Georgia	12	169	53	80	97	10	94	60	69	58	60	35
Hawaii	12	120	46	69	104	11	100	64	74	62	65	36
Idaho	12	152	46	69	104	11	100	64	74	62	65	35
Illinois	12	129	43	65	95	10	92	58	68	56	58	34
Indiana	12	137	43	65	95	10	92	58	68	56	58	34
Iowa	12	140	43	65	95	10	92	58	68	56	58	34
Kansas	12	137	43	65	95	10	92	58	68	56	58	35
Kentucky	12	151	53	80	97	10	94	60	69	58	60	33
Louisiana	12	119	49	74	97	10	94	60	69	58	60	35
Maine	12	143	48	73	98	11	94	60	69	58	60	34
Maryland	12	144	48	73	98	11	94	60	69	58	60	34
Mass.	12	136	48	73	98	11	94	60	69	58	60	36
Michigan	12	148	43	65	95	10	92	58	68	56	58	35
Minn.	12	131	43	65	95	10	92	58	68	56	58	35
Miss.	12	139	53	80	97	10	94	60	69	58	60	33
Missouri	12	112	43	65	95	10	92	58	68	56	58	34
Montana	12	134	43	65	104	11	100	64	74	62	65	32
Nebraska	12	140	43	65	95	10	92	58	68	56	58	35
Nevada	12	148	46	69	104	11	100	64	74	62	65	34

N. Hamp.	12	145	48	73	98	11	94	60	69	58	60	34
N. Jersey	12	136	48	73	98	11	94	60	69	58	60	34
N. Mexico	12	153	46	69	104	11	100	64	74	62	65	35
New York	12	156	48	73	98	11	94	60	69	58	60	35
N. Car.	12	166	53	80	97	10	94	60	69	58	60	34
N. Dakota	12	132	43	65	95	10	92	58	68	56	58	35
Ohio	12	131	43	65	95	10	92	58	68	56	58	35
Oklahoma	12	140	49	74	97	10	94	60	69	58	60	34
Oregon	12	138	46	69	104	11	100	64	74	62	65	35
Penn.	12	146	48	73	98	11	94	60	69	58	60	33
R. Island	12	135	48	73	98	11	94	60	69	58	60	34
S. Car.	12	150	53	80	97	10	94	60	69	58	60	33
S. Dakota	12	137	43	65	95	10	92	58	68	56	58	35
Tenn.	12	146	53	80	97	10	94	60	69	58	60	40
Texas	12	156	49	74	97	10	94	60	69	58	60	35
Utah	12	149	46	69	104	11	100	64	74	62	65	34
Vermont	12	145	48	73	98	11	94	60	69	58	60	34
Virginia	12	159	53	80	97	10	94	60	69	58	60	34
Wash.	12	151	46	69	104	11	100	64	74	62	65	35
W. Virg.	12	126	48	73	98	11	94	60	69	58	60	33
Wisconsin	12	139	43	65	95	10	92	58	68	56	58	34
Wyoming	12	138	43	65	104	11	100	64	74	62	65	34

Note: To convert to a daily emission factor, the yearly emission factor can be divided by 365 (the number of days in a year).

For quality assurance purposes, U.S. emission factors for each animal type were compared to estimates provided by the other Annex I member countries of the United Nations Framework Convention on Climate Change (UNFCCC) (the most recently available summarized results for Annex I countries are through 2012 only). Results, presented in Table A-172, indicate that U.S. emission factors are comparable to those of other Annex I countries. Results in Table A-172 are presented along with Tier I emission factors provided by IPCC (2006). Throughout the time series, beef cattle in the United States generally emit more enteric CH_4 per head than other Annex I member countries, while dairy cattle in the United States generally emit comparable enteric CH_4 per head.

Table A-172: Annex I Countries' Implied Emission Factors for Cattle by Year (kg CH_4/head/year)[83]

	Dairy Cattle		Beef Cattle	
Year	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)	United States Implied Emission Factor	Mean of Implied Emission Factors for Annex I countries (excluding U.S.)
1990	107	96	71	53
1991	107	97	71	53
1992	107	96	72	54
1993	106	97	72	54
1994	106	98	73	54
1995	106	98	72	54
1996	105	99	73	54
1997	106	100	73	54
1998	107	101	73	55
1999	110	102	72	55
2000	111	103	72	55
2001	110	104	73	55
2002	111	105	73	55
2003	111	106	73	55
2004	109	107	74	55
2005	110	109	74	55
2006	110	110	74	55
2007	114	111	75	55
2008	115	112	75	55
2009	115	112	75	56
2010	115	113	75	55

[83] Excluding calves.

2011	116	113	75	55
2012	117	112	75	51
2013	117	NA	75	NA
2014	118	NA	74	NA
2015	117	NA	75	NA
Tier I EFs For North America, from IPCC (2006)		**121**		**53**

Step 3c: Estimate Total Emissions

Emissions were summed for each month and for each state population category using the daily emission factor for a representative animal and the number of animals in the category. The following equation was used:

$$Emissions_{state} = DayEmit_{state} \times Days/Month \times SubPop_{state}$$

where,

$Emissions_{state}$	=	Emissions for state during the month (kg CH_4)
$DayEmit_{state}$	=	Emission factor for the subcategory and state (kg CH_4/head/day)
Days/Month	=	Number of days in the month
$SubPop_{state}$	=	Number of animals in the subcategory and state during the month

This process was repeated for each month, and the monthly totals for each state subcategory were summed to achieve an emission estimate for a state for the entire year and state estimates were summed to obtain the national total. The estimates for each of the 10 subcategories of cattle are listed in Table A-173. The emissions for each subcategory were then aggregated to estimate total emissions from beef cattle and dairy cattle for the entire year.

Table A-173: CH_4 Emissions from Cattle (kt)

Cattle Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Dairy	**1,574**	**1,498**	**1,519**	**1,503**	**1,645**	**1,670**	**1,664**	**1,679**	**1,706**
Calves (4–6 months)	62	59	59	54	57	58	58	58	58
Cows	1,242	1,183	1,209	1,197	1,302	1,326	1,325	1,337	1,355
Replacements 7–11 months	58	56	55	56	63	62	61	63	65
Replacements 12–23 months	212	201	196	196	223	224	220	221	228
Beef	**4,763**	**5,419**	**5,070**	**5,007**	**4,873**	**4,763**	**4,722**	**4,660**	**4,724**
Calves (4–6 months)	182	193	186	179	166	161	157	156	159
Bulls	196	225	215	214	212	206	203	200	207
Cows	2,884	3,222	3,058	3,056	2,927	2,868	2,806	2,754	2,774
Replacements 7–11 months	69	85	74	80	74	76	78	83	89
Replacements 12–23 months	188	241	204	217	202	208	213	218	239
Steer Stockers	563	662	509	473	436	413	431	426	434
Heifer Stockers	306	375	323	299	283	266	267	256	264
Feedlot Cattle	375	416	502	488	573	565	568	567	558
Total	**6,338**	**6,917**	**6,589**	**6,510**	**6,518**	**6,433**	**6,386**	**6,339**	**6,430**

Notes: Totals may not sum due to independent rounding.

Emission Estimates from Other Livestock

"Other livestock" include horses, sheep, swine, goats, American bison, and mules and asses. All livestock population data, except for American bison for years prior to 2002, were taken from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) agricultural statistics database (USDA 2016) or earlier census data (USDA 1992, 1997). The Manure Management Annex discusses the methods for obtaining annual average populations and disaggregating into state data where needed and provides the resulting population data for the other livestock that were used for estimating all livestock-related emissions (see Table A-175). For each animal category, the USDA publishes monthly, annual, or multi-year livestock population and production estimates. American bison estimates prior to 2002 were estimated using data from the National Bison Association (1999).

Methane emissions from sheep, goats, swine, horses, mules and asses were estimated by multiplying national population estimates by the default IPCC emission factor (IPCC 2006). For American bison the emission factor for buffalo (IPCC 2006) was used and adjusted based on the ratio of live weights of 300 kg for buffalo (IPCC 2006) and 1,130 pounds (513 kg) for American Bison (National Bison Association 2011) to the 0.75 power. This methodology for determining emission factors is recommended by IPCC (2006) for animals with similar digestive systems. Table A-174 shows the emission factors used for these other livestock. National enteric fermentation emissions from all livestock types are shown in Table A-175 and Table A-176. Enteric fermentation emissions from most livestock types, broken down by state, for 2015 are shown in Table A-177 and Table A-182. Livestock populations are shown in Table A-179.

Table A-174: Emission Factors for Other Livestock (kg CH_4/head/year)

Livestock Type	Emission Factor
Swine	1.5
Horses	18
Sheep	8
Goats	5
American Bison	82.2
Mules and Asses	10.0

Source: IPCC (2006), except American Bison, as described in text.

Table A-175: CH_4 Emissions from Enteric Fermentation (MMT CO_2 Eq.)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Beef Cattle	119.1	135.5	126.7	125.2	121.8	119.1	118.0	116.5	118.1
Dairy Cattle	39.4	37.5	38.0	37.6	41.1	41.7	41.6	42.0	42.6
Swine	2.0	2.2	2.2	2.3	2.5	2.5	2.5	2.4	2.6
Horses	1.0	1.2	1.5	1.7	1.7	1.6	1.6	1.6	1.5
Sheep	2.3	1.8	1.4	1.2	1.1	1.1	1.1	1.0	1.1
Goats	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.3
American Bison	0.1	0.2	0.4	0.4	0.3	0.3	0.3	0.3	0.3
Mules and Asses	+	+	+	0.1	0.1	0.1	0.1	0.1	0.1
Total	**164.2**	**178.7**	**170.6**	**168.9**	**168.9**	**166.7**	**165.5**	**164.2**	**166.5**

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

Table A-176: CH_4 Emissions from Enteric Fermentation (kt)

Livestock Type	1990	1995	2000	2005	2011	2012	2013	2014	2015
Beef Cattle	4,763	5,419	5,070	5,007	4,873	4,763	4,722	4,660	4,724
Dairy Cattle	1,574	1,498	1,519	1,503	1,645	1,670	1,664	1,679	1,706
Swine	81	88	88	92	98	100	98	96	102
Horses	40	47	61	70	67	65	64	62	61
Sheep	91	72	56	49	44	43	43	42	42
Goats	13	12	12	14	14	13	13	12	12
American Bison	4	9	16	17	14	13	13	12	12
Mules and Asses	1	1	1	2	3	3	3	3	3
Total	**6,566**	**7,146**	**6,824**	**6,755**	**6,757**	**6,670**	**6,619**	**6,572**	**6,661**

Note: Totals may not sum due to independent rounding.

Table A-177: CH_4 Emissions from Enteric Fermentation from Cattle (metric tons), by State, for 2015

State	Dairy Calves	Dairy Cows	Dairy Replacement Heifers 7-11 Months	Dairy Replacement Heifers 12-23 Months	Bulls	Beef Calves	Beef Cows	Beef Replacement Heifers 7-11 Months	Beef Replacement Heifers 12-23 Months	Steer Stockers	Heifer Stockers	Feedlot	Total
Alabama	50	1,025	48	169	4,379	3,523	61,361	1,617	4,359	1,388	936	215	79,069
Alaska	2	31	1	5	249	25	432	14	38	9	3	1	810
Arizona	1,216	29,979	893	3,147	2,078	1,021	17,582	530	1,420	8,216	705	11,002	77,789
Arkansas	44	819	59	208	5,352	4,664	81,219	2,166	5,837	3,609	1,590	496	106,063
California	11,102	261,579	10,573	37,283	7,272	3,442	59,276	2,025	5,429	16,433	4,703	18,975	438,091
Colorado	904	21,739	1,300	4,585	5,714	4,229	72,840	2,648	7,099	23,305	15,788	40,154	200,306
Conn.	119	2,806	116	410	49	27	472	36	98	56	16	7	4,211
Delaware	31	715	36	128	39	14	236	10	27	61	22	7	1,327
Florida	773	20,432	558	1,967	5,839	4,896	85,266	1,877	5,059	694	936	144	128,440
Georgia	505	13,714	430	1,517	2,725	2,589	45,080	1,300	3,502	1,249	936	191	73,738
Hawaii	14	264	14	48	416	401	6,912	171	459	269	168	35	9,172
Idaho	3,611	88,218	4,394	15,494	4,155	2,689	46,316	1,869	5,011	8,366	5,711	10,421	196,256
Illinois	586	12,154	676	2,384	2,378	1,927	33,674	900	2,431	5,685	3,010	10,129	75,935
Indiana	1,129	24,757	1,040	3,668	1,617	1,048	18,309	704	1,899	3,140	1,338	4,377	63,026
Iowa	1,310	29,347	1,690	5,961	5,708	4,738	82,805	2,533	6,837	34,920	19,152	52,417	247,419
Kansas	892	19,606	1,170	4,127	9,038	7,513	131,292	4,080	11,016	51,162	40,433	93,069	373,397
Kentucky	393	9,504	717	2,529	6,325	5,388	93,830	2,022	5,448	5,552	3,274	670	135,652
Louisiana	87	1,664	74	260	2,919	2,518	43,856	1,069	2,880	666	717	122	56,832
Maine	187	4,301	232	820	146	60	1,038	65	176	125	78	18	7,247
Maryland	306	7,079	363	1,281	390	228	3,964	130	351	418	282	429	15,220
Mass.	78	1,703	102	359	98	30	519	29	78	56	31	8	3,090
Michigan	2,514	59,590	2,172	7,658	1,427	563	9,845	324	874	4,602	1,064	6,775	97,405
Minn.	2,869	60,246	3,641	12,839	3,330	1,790	31,282	1,266	3,419	13,535	4,864	16,426	155,507
Miss.	75	1,667	96	337	3,698	2,529	44,044	1,401	3,775	1,555	1,029	241	60,447
Missouri	555	9,983	780	2,751	10,465	9,745	170,302	4,854	13,105	10,828	6,840	3,046	243,254
Montana	87	1,874	91	321	10,389	8,727	150,301	6,776	18,165	5,229	6,651	1,839	210,450
Nebraska	337	7,544	260	917	9,038	9,245	161,561	5,910	15,954	63,073	38,913	107,555	420,306
Nevada	175	4,150	124	436	1,247	1,237	21,299	576	1,545	1,315	974	172	33,249
N. Hamp.	87	2,027	80	282	49	16	283	14	39	28	16	4	2,925
N. Jersey	44	955	55	195	98	41	708	19	51	56	28	8	2,256
N. Mexico	2,015	49,363	1,510	5,326	3,636	2,374	40,891	1,324	3,549	2,838	2,351	429	115,607
New York	3,836	95,883	5,084	17,929	1,464	569	9,909	594	1,600	975	1,376	1,089	140,309
N. Car.	293	7,814	287	1,012	2,822	1,962	34,163	1,011	2,724	999	842	167	54,095
N. Dakota	100	2,106	78	275	4,757	4,707	82,253	2,378	6,419	5,820	5,624	1,835	116,351
Ohio	1,672	35,095	1,625	5,732	2,378	1,485	25,946	704	1,899	5,279	1,520	7,204	90,538

Oklahoma	249	5,602	368	1,299	13,624	10,160	176,931	6,065	16,345	24,151	11,382	11,367	277,542
Oregon	780	17,222	824	2,905	4,155	3,063	52,746	1,713	4,593	4,930	3,527	3,558	100,016
Penn.	3,306	77,283	4,431	15,624	2,440	813	14,156	797	2,147	4,038	1,721	4,036	130,789
R. Island	6	121	7	26	10	8	142	7	20	14	6	2	368
S. Car.	94	2,249	80	281	1,362	919	15,999	433	1,167	250	374	57	23,265
S. Dakota	617	13,582	845	2,980	9,513	8,482	148,221	5,698	15,384	18,408	14,896	16,426	255,053
Tenn.	293	6,850	398	1,405	5,839	4,718	82,160	2,022	5,448	3,331	2,027	410	114,901
Texas	2,932	73,299	3,683	12,987	31,140	22,319	388,683	10,830	29,187	69,955	43,346	107,136	795,495
Utah	599	14,257	659	2,324	2,285	1,890	32,552	1,215	3,257	2,330	2,150	1,047	64,566
Vermont	823	19,144	813	2,869	293	65	1,132	58	156	111	156	24	25,645
Virginia	580	14,817	685	2,416	3,892	3,442	59,949	1,588	4,281	4,303	1,310	858	98,123
Wash.	1,728	41,902	1,867	6,585	1,870	1,155	19,893	841	2,255	5,229	4,535	8,876	96,736
W. Virg.	56	1,136	58	205	1,269	1,003	17,459	478	1,288	1,225	626	180	24,983
Wisconsin	7,953	177,016	9,492	33,473	3,330	1,448	25,301	1,055	2,849	10,151	1,368	11,152	284,588
Wyoming	37	830	65	229	4,155	4,048	69,725	3,006	8,059	4,033	4,770	3,217	102,177

Table A-178: CH_4 Emissions from Enteric Fermentation from Other Livestock (metric tons), by State, for 2015

State	Swine	Horses	Sheep	Goats	American Bison	Mules and Asses	Total
Alabama	150	894	97	181	15	117	1,454
Alaska	2	21	97	3	149	1	273
Arizona	198	1,919	1,200	447	-	37	3,800
Arkansas	249	907	97	181	7	85	1,525
California	143	2,154	4,800	728	72	64	7,961
Colorado	1,076	1,893	3,360	131	648	65	7,173
Connecticut	4	378	57	21	11	10	481
Delaware	5	135	97	5	8	1	250
Florida	24	2,183	97	243	-	101	2,648
Georgia	240	1,184	97	322	13	88	1,943
Hawaii	14	77	97	76	4	4	271
Idaho	38	970	2,080	92	373	39	3,592
Illinois	7,238	948	456	151	28	34	8,855
Indiana	5,644	1,928	400	168	79	55	8,274
Iowa	31,575	1,014	1,400	282	99	44	34,414
Kansas	2,861	1,185	528	190	377	36	5,178
Kentucky	623	2,190	384	218	102	131	3,648
Louisiana	12	1,068	97	86	2	77	1,341
Maine	7	214	57	34	15	4	331
Maryland	32	493	97	35	19	12	688
Massachusetts	17	363	57	44	6	5	492
Michigan	1,676	1,442	608	133	71	41	3,971
Minnesota	12,075	938	1,040	159	97	29	14,339
Mississippi	773	985	97	104	-	91	2,049
Missouri	4,481	1,767	680	540	84	93	7,645
Montana	263	1,684	1,720	46	1,211	48	4,971
Nebraska	4,838	1,144	648	103	2,164	40	8,936
Nevada	2	448	552	135	3	6	1,147
New Hampshire	6	155	57	27	27	2	274
New Jersey	18	471	97	34	17	9	646
New Mexico	2	882	720	141	441	18	2,204
New York	114	1,679	640	172	40	38	2,682
North Carolina	12,863	1,079	240	236	9	94	14,521
North Dakota	207	821	512	25	474	13	2,052
Ohio	3,611	2,000	968	204	45	71	6,899
Oklahoma	3,289	2,789	424	337	764	136	7,738
Oregon	15	1,063	1,560	151	125	31	2,945
Pennsylvania	1,748	2,197	688	224	39	94	4,989
Rhode Island	2	32	57	5	-	1	98
South Carolina	353	1,042	97	179	10	59	1,739
South Dakota	1,999	1,227	2,040	100	2,515	15	7,896
Tennessee	330	1,247	352	341	0	137	2,407
Texas	1,324	6,660	5,760	3,611	285	636	18,276
Utah	1,058	1,053	2,320	66	80	33	4,610
Vermont	6	193	57	65	6	13	340
Virginia	405	1,525	600	217	80	70	2,898
Washington	38	892	416	118	51	35	1,550
West Virginia	8	355	264	67	-	29	722
Wisconsin	480	1,684	616	321	256	58	3,415
Wyoming	158	1,218	2,760	49	638	28	4,850

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