

Estimation of Emission Factors of Particulate Black Carbon and Organic Carbon from Stationary, Mobile, and Non-point Sources in the United States for Incorporation into GREET

Energy Systems Division

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NOTATION

The following is a list of acronyms, abbreviations, and units of measure used in this document. Some acronyms used only in tables may be defined only in those tables.

GENERAL ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ACES	Advanced Collaborative Emission Study
AEAB	Atrax Energi AB
BC	black carbon
CARB	California Air Resources Board
CI	confidence interval
CO ₂	carbon dioxide
CRC	Coordinating Research Council
DOC	diesel oxidation catalyst
DPF	diesel particulate matter filter
E0	zero ethanol blending by volume
E10	10% ethanol blending by volume
E85	85% ethanol blending by volume
EC	element carbon
ECA	Emission Control Area
EPA	U.S. Environmental Protection Agency
ERG	Eastern Research Group
FTD	Fischer–Tropsch diesel
REET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GVW	gross vehicle weight
HDV	heavy-duty vehicle
HRSG	heat recovery steam generator
IPCC	Intergovernmental Panel on Climate Change
LDV	light-duty vehicle
LHV	lower heating value
MOVES	Motor Vehicle Emission Simulator
MY	model year

NCDC	National Climatic Data Center
NGCC	natural gas combined cycle
NM	number of measurement
OC	organic carbon
PDF	probability distribution function
PM _{2.5}	particulate matter with an aerodynamic diameter of 2.5 µm or less
RFG	reformulated gasoline
RICE	reciprocating internal combustion engine
RVP	Reid Vapor Pressure
SO _x	sulfur oxides

UNITS OF MEASURE

Btu	British thermal unit
h	hour(s)
g	gram(s)
kg	kilogram(s)
kWh	kilowatt hour(s)
L	liter(s)
lb	pound(s)
m ³	cubic meter(s)
mi	mile(s)
MJ	megajoule(s)
mm	millimeter(s)
ppm	part(s) per million
psi	pounds per square inch
µm	micron(s)

ESTIMATION OF EMISSION FACTORS OF PARTICULATE BLACK CARBON AND ORGANIC CARBON FROM STATIONARY, MOBILE, AND NON-POINT SOURCES IN THE UNITED STATES FOR INCORPORATION INTO GREET

ABSTRACT

This document contains emission factors of black carbon (BC) and organic carbon (OC) from stationary, mobile, and non-point sources in the United States. These data are to be incorporated into Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET™) model for the purpose of evaluating the climate forcing and air quality impacts of BC and OC emissions of various vehicle/fuel systems. The BC and OC emission factors for stationary sources were estimated based on multiple measurement-based studies. Simulations with the U.S. Environmental Protection Agency's (EPA)'s Motor Vehicle Emission Simulator were conducted to estimate the BC and OC emission factors of a variety of categories of on-road vehicles. Particularly, we consulted findings in the literature about the impacts of recent advances in vehicle emission control technologies (e.g., diesel particulate filters) on both the total mass and chemical compositions of tailpipe PM_{2.5} (particulate matter with an aerodynamic diameter of 2.5 μm or less) emissions. We developed new PM_{2.5} emission factors from various types of off-road agricultural equipment used for biofuel feedstock production, using the EPA's NONROAD model. We developed and applied an approach to estimate the mean value and probability distribution of the BC and OC emission factors of a specific emission source when multiple data sources were available, so that the variation and uncertainty associated with the BC and OC emission factors can be assessed. We found distinct OC/BC emission ratios and total BC and OC emission portions in the PM_{2.5} emissions among different fuels and combustion technologies, which indicates that changes in fuel properties and switching of combustion technologies can lead to dramatic changes in BC and OC emission characteristics.

1 INTRODUCTION

Particulate black carbon (BC) and organic carbon (OC) contribute to the adverse impacts associated with particulate matter with an aerodynamic diameter of 2.5 μm or less (PM_{2.5}) on visibility (Park et al. 2003) and human health (Pope and Dockery 2006; Mauderly and Chow 2008; Saikawa et al. 2009), and they affect climate (Ramanathan and Carmichael 2008; Saikawa et al. 2009; Bond et al. 2013) through multiple mechanisms such as direct effect, snow/ice albedo effect, and other effects.

In direct effect, BC absorbs both incoming and outgoing radiation of all wavelengths, which contributes to warming of the atmosphere and dimming at the surface, while OC perturbs the radiative balance of the earth directly by scattering incoming solar radiation.

In the snow/ice albedo effect, BC deposited on snow and ice darkens the surface and decreases reflectivity, thereby increasing absorption and accelerating melting.

In other effects, BC alters the properties of clouds, affecting cloud reflectivity and lifetime (“indirect effects”), and stability of the atmospheric boundary layer (“semi-direct effect”) and precipitation. OC perturbs the radiative balance of the earth indirectly by acting as cloud condensation nuclei and modifying cloud properties such as cloud droplet number, size, and lifetime (Andreae et al. 2005).

The direct and snow/ice albedo effects of BC are widely understood to lead to climate warming, while the direct effects of OC are generally known to lead to climate cooling (IPCC 2013). The United States accounts for approximately 5.6% of the total global BC emissions (Chow et al. 2010). In 2005, BC was estimated to account for approximately 12% of all direct PM_{2.5} emissions within the United States (EPA 2012a).

According to the U.S. Environmental Protection Agency (EPA), BC can be defined specifically as a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths, and OC is the mix of compounds containing carbon bound with other elements; for example, hydrogen and oxygen (EPA 2012a). BC is produced by incomplete combustion and is the most effective form of PM, by mass, at absorbing solar energy, while OC may be a product of incomplete combustion, or formed through the oxidation of volatile organic compounds in the atmosphere. Both primary and secondary OC possess radiative properties that fall along a continuum from light-absorbing to light-scattering (EPA 2012a). Overall, OC causes a negative forcing with uncertainties (IPCC 2013). Therefore, estimates of the net effect of BC emissions sources on climate should include the offsetting effects of co-emitted pollutants like OC (Yang et al. 2014). This is particularly important for evaluating mitigation options in favor of climate benefits, as emission reductions of combustion sources that emit more BC than OC may have the greatest likelihood of providing climate benefits.

In this work, we estimated and compiled BC and OC emission factors, which are expressed in mass fractions (%) of the PM_{2.5} emissions, for various stationary, mobile, and non-point sources based on model simulations and literature review. These emission factors are to be incorporated into the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREETTM) model (Argonne 2014) for the purpose of evaluating the climate forcing and air quality impacts of BC and OC emissions on life-cycle greenhouse gas emissions and air pollutant emissions of various vehicle/fuel systems.

2 METHODOLOGY AND DATA

2.1 ESTIMATION OF BC AND OC EMISSION FACTORS

BC and OC are major components of $PM_{2.5}$, and their emission factors can be expressed as mass fractions of the $PM_{2.5}$ emission factor. A source profile represents the mass fractions of these species in the $PM_{2.5}$ emissions from a specific emission source. Unlike carbon dioxide (CO_2) or sulfur oxides (SO_x) emissions from fuel combustion, which can be estimated on a carbon or sulfur mass balance basis, BC and OC are not predictable from overall stoichiometry, because their formation and destruction are limited by kinetics, not equilibrium states (Bond et al. 2004). As a result, source profiles that include the mass fractions of BC and OC in $PM_{2.5}$ emissions have to be determined via direct measurements of combustion processes. Thermal-optical and filter-based optical techniques have been adopted in most measurement of BC emissions so far (EPA 2012a).

With a source profile and the $PM_{2.5}$ emission factor of a specific emission source, the BC and OC emission factors can be estimated by Equation 1.

$$EF_{s,i} = EF_{PM_{2.5},i} \times MF_{s,i} \quad (1)$$

Where

$EF_{s,i}$ is the emission factor of species s of $PM_{2.5}$ emissions of emission source i , including BC and OC;

$EF_{PM_{2.5},i}$ is the $PM_{2.5}$ emission factor of emission source i ; and

$MF_{s,i}$ is the mass fraction of species s , in %, of the $PM_{2.5}$ emission factor of emission source i .

We collected multiple source profiles for many of the stationary and mobile emission sources in this analysis. For an emission source of which multiple source profiles are available, the uncertainties associated with each source profile and the number of measurement (NM) on which each source profile was based, were taken into account to estimate the mass fractions of BC and OC emissions of the $PM_{2.5}$ emission from the same emission source. The uncertainties associated with a source profile are essential to the magnitude of estimated BC and OC emissions. The uncertainties of source profiles result from both instrument calibration or test measurement uncertainties, which are difficult to quantify, and statistical uncertainties resulting from multiple tests for the same emission source. Some of the source profiles we collected have their uncertainties quantified by a statistical distribution that is characterized with its mean and standard deviation, in most cases; others lack any quantification of the possible uncertainties associated.

Being aware of the BC and OC emission uncertainties, we adopted the Monte Carlo stochastic simulation technique to quantify the uncertainties of BC and OC emission mass

fractions when combining different source profiles for an individual emission source. For a given source profile with its uncertainties quantified by a particular type of statistical distribution, the Monte Carlo stochastic simulation technique randomly generates surrogate values to represent its statistically true value based on its known probability distribution function (PDF). This process was repeated to generate a thousand data points for the source profile. For a given source profile without any statistical distribution to define its uncertainties, the same static value was reproduced a thousand times, and the same 1,000 static values were added to the pool of each set of the thousand surrogate values generated by the Monte Carlo technique for other source profiles with defined uncertainties for the same emission source. Moreover, the NM from which a source profile was derived was used as a weighting factor among different source profiles for the same emission source, because the degree of the measurement accuracy tends to increase and the uncertainty tends to decrease with increased NM. A new PDF was developed based on all the data points representing all source profiles with and without PDFs for the emission source, using Equation 2. In particular, we assumed that the NM for a source profile that had a defined PDF but did not reveal the NM was 5, which is usually the minimum NM required to define the PDF. For those source profiles that did not define a PDF and did not reveal the NM, we assumed that the NM was 3, which is usually the minimum NM required to meet the quality assurance and quality control procedures for the measurement, as depicted in Figure 1.

$$MF_{s,i} = \sum_j (WF_{i,j} \times MF_{s,i,j}) \quad (2)$$

$$WF_{i,j} = \frac{N_{i,j}}{\sum_j N_{i,j}} \quad (3)$$

Where

$WF_{i,j}$ is the weighting factor of source profile j for emission source i ;

$N_{i,j}$ is the NM on which source profile j for emission source i was based; and

$MF_{s,i,j}$ is the mass fraction of species s , in %, of the $PM_{2.5}$ emission factor as represented by source profile j for emission source i

Using this approach, we incorporated the recognized uncertainties of source profiles and the levels of accuracy and uncertainty associated with the source profiles that are indicated by the NM into our estimation of the BC and OC mass fractions. This was the best available approach for this analysis. This is because it is difficult and prohibitive in many circumstances to fully evaluate the degree of differences in the quality, representativeness, and magnitude of uncertainty associated with the measurement in one source profile compared with another, given the complexities of the varying conditions for both the formation of emissions and the measurements, which are rarely fully characterized in the source profiles. In addition, use of the NM as a weighting factor reduces the uncertainties of the alternatively oversimplified approach that calculates the arithmetic mean of the available multiple source profiles.

Source profile:	SP ₁	SP ₂	SP ₃	...	SP _n
Availability of PDF:	Yes	Yes	No	...	No
Availability of NM:	Yes	No	Yes	...	No
NM assumed:	Actual	5	Actual	...	3

FIGURE 1 Assumptions for the NM for Source Profiles with and without Known PDF and NM

2.2 EMISSION SOURCES AND PM_{2.5} EMISSION FACTORS

GREET considers activities in multiple industries that produce emissions, for example, via process fuel combustion, vehicle operations, and flaring of oil field associated gas. Table 1 lists the emission sources for which BC and OC emission factors are needed for GREET to perform the life-cycle analysis with the climate forcing and air quality impacts of such species considered. The PM_{2.5} emission factors of these emission sources in GREET are also summarized in Table 1. The PM_{2.5} emission factors of various types of electricity generation technologies that are modeled in GREET are summarized in Table 2.

In addition to on-road motor vehicles, of which the emission factors were simulated using the EPA's MOVES (Motor Vehicle Emission Simulator) model (Cai et al. 2013b), as shown in Table 1 for some of the on-road vehicle types, the EPA's NONROAD2008a model (EPA 2010a), which takes into account the emission impacts of nonroad emission standards promulgated in 2008, was employed to estimate the PM_{2.5} emission factors of a variety of agricultural farming equipment operating on gasoline, diesel, or liquefied petroleum gas (LPG). These emission factors are needed in GREET to simulate the emissions from biofuel feedstock production activities that involve the use of various types of agricultural farming equipment for land preparation, feedstock seeding, irrigation, and feedstock harvest, which results in fuel consumption and produces air pollutant emissions, including BC and OC. Agricultural farming tractors, irrigation sets, combines, mowers, sprayers, balers, harvesters, and crushing and processing equipment may be employed for biofuel feedstock production. These farming machineries vary in engine horse power ratings, and, therefore, may differ in fuel consumption rate and air pollutant emission factors per horsepower.

TABLE 1 Emission Sources and their PM_{2.5} Emission Factors in GREET for 2010 Technologies

Emission Source	Combustion Fuel Type	Combustion Technology	PM _{2.5} Emission Factor (g/mmBtu)	Availability of PDF	Data Source ^a
Natural gas (NG)-fired utility/industrial boilers (>100 mmBtu/h input)	NG	Utility/industrial boilers	3.493	Yes	Eastern Research Group (ERG) 2014
NG-fired utility/industrial boilers (10–100 mmBtu/h input)	NG	Utility/industrial boilers (10–100 mmBtu/h input)	3.175	Yes	ERG 2014
NG-fired gas turbines	NG	Gas turbines	3.575	Yes	Cai et al. 2013a
NG-fired combined cycle turbines	NG	Combined cycle turbines	0.133	Yes	Cai et al. 2013a
NG-fired reciprocating engines	NG	Reciprocating engines	7.197	Yes	ERG 2014
NG-fired kilns	NG	Kilns	90.000	No	Dunn et al. 2012
Residual fuel oil (RFO)-fired utility boiler	RFO	Utility boilers	13.349	Yes	Cai et al. 2013a
RFO-fired industrial boilers	RFO	Industrial boilers	16.173	Yes	ERG 2014
RFO-fired commercial boilers	RFO	Commercial boilers	16.173	Yes	ERG 2014
RFO-fired reciprocating engines	RFO	Reciprocating engines	54.043	Yes	Cai et al. 2013a
RFO-fired turbines	RFO	Turbines	6.574	Yes	Cai et al. 2013a
Diesel-fired industrial boilers	Diesel	Industrial boilers	5.473	Yes	ERG 2014
Diesel-fired commercial boilers	Diesel	Commercial boilers	7.522	Yes	ERG 2014
Diesel-fired reciprocating engines	Diesel	Reciprocating engines	54.043	Yes	ERG 2014
Diesel-fired turbines	Diesel	Turbines	6.574	No	Cai et al. 2013a
Gasoline-fired reciprocating engines	Gasoline	Reciprocating engines	52.558	No	ERG 2014
Crude oil-fired industrial boilers	Crude oil	Industrial boilers	19.313	No	
Liquid petroleum gas (LPG)-fired industrial boilers	LPG	Industrial boilers	3.738	No	ERG 2014
LPG-fired commercial boilers	LPG	Commercial boilers	3.738	No	ERG 2014

TABLE 1 (Cont.)

Emission Source	Combustion Fuel Type	Combustion Technology	PM _{2.5} Emission Factor (g/mmBtu)	Availability of PDF	Data Source
Coal-fired industrial boilers	Coal	Industrial boilers	24.485	Yes	ERG 2014
Coal-fired kilns	Coal	Kilns	20	No	Dunn et al. 2012
Biomass-fired boilers	Biomass	Boilers	32.837	No	ERG 2014
Sugarcane field burning	Sugarcane	Field burning	2.6 (g/kg•dry straw)	No	Franca et al. 2012
Sugarcane bagasse-fired boilers	Sugarcane bagasse	Boilers	45.359	No	ERG 2014
Petroleum coke-fired boilers	Petroleum coke	Boilers	24.485	Yes	Cai et al. 2013a
Biogas-fired reciprocating engines	Biogas	Reciprocating engines	6.942	No	ERG 2014
Flared associated gas in oil fields	Associated gas	Flaring	3.700	No	
Char-fired boilers	Char	Boilers	20.278 ^b	No	Cai et al. 2013a
Ocean tankers using bunker fuel	Bunker fuel	Ocean tankers	166.841	No	
Barges using RFO	RFO	Barges	38.885	No	
Diesel locomotive	Diesel	Locomotives	29.365	No	Dunn et al. 2013
NG-fired pipeline reciprocating engines	NG	Reciprocating engines	0.997	No	Dunn et al. 2013
Diesel trucks, class 6	Diesel	Class 6 trucks	0.195 (g/mi)	Yes	Cai et al. 2013b
Diesel trucks, class 8b	Diesel	Class 8b trucks	0.449 (g/mi)	Yes	Cai et al. 2013b
Gasoline cars	Gasoline	Cars	0.0071 (g/mi)	Yes	Cai et al. 2013b
Diesel cars	Diesel	Cars	0.0049 (g/mi)	Yes	Cai et al. 2013b
Gasoline light-duty truck (LDT, maximum 3,750 lb loaded vehicle weight)	Gasoline	LDT1	0.0112 (g/mi)	Yes	Brinkman et al. 2005

TABLE 1 (Cont.)

Emission Source	Combustion Fuel Type	Combustion Technology	PM _{2.5} Emission Factor (g/mmBtu)	Availability of PDF	Data Source
Gasoline LDT (loaded vehicle weight 3,750–6,000 lb)	Gasoline	LDT2	0.0140 (g/mi)	Yes	Brinkman et al. 2005
Diesel LDT (maximum 3,750 lb loaded vehicle weight)	Diesel	LDT1	0.0129 (g/mi)	Yes	Brinkman et al. 2005
Diesel LDT (loaded vehicle weight of 3,750–6,000 lb)	Diesel	LDT2	0.0175 (g/mi)	Yes	Brinkman et al. 2005

^a Entries without a data source are based on expert engineering judgment.

^b Assumed the same as coal-fired utility boilers.

TABLE 2 PM_{2.5} Emission Factors of Electricity Generation Technologies by Fuel Type

Emission Source	Combustion Fuel Type	Combustion Technology	PM _{2.5} Emission Factor (g/kWh)	Availability of PDF
Coal-fired boilers	Coal	Boilers	0.1994	Yes
Coal-fired integrated gasification combined cycle (IGCC)	Coal	IGCC	0.7198	No
Natural gas (NG)-fired combined cycle	NG	Combined cycle	0.0009	Yes
NG-fired turbines	NG	Turbines	0.0386	Yes
NG-fired internal combustion engines	NG	Internal combustion engines	0.4718	Yes
NG-fired boilers	NG	Boilers	0.0426	Yes
Oil-fired boilers	Oil	Boilers	0.1395	Yes
Oil-fired turbines	Oil	Turbines	0.0763	Yes
Oil-fired internal combustion engines	Oil	Internal combustion engines	0.0130	Yes
Biomass-fired boilers	Biomass	Boilers	1.9763	Yes

Source: Cai et al. (2013a).

Major NONROAD model inputs required include ambient air temperature, the Reid Vapor Pressure (RVP) and the oxygen content of gasoline, and the sulfur contents of gasoline and diesel. Biofuel feedstocks, such as corn and switchgrass, are grown in various states in the United States. With expected differences in the ambient air temperature and fuel quality, especially the RVP of gasoline, among the crop-growing states, differences in PM_{2.5} emission factors among the states were also anticipated, because of the known impacts of the temperature and fuel quality on the PM_{2.5} emissions from operations of farming equipment in different environments with different fuel quality (EPA 2010b; EPA 2005). Therefore, we used the NONROAD model to generate the PM_{2.5} emission factors at the state level, considering the meteorological variation and fuel quality differences among the states. This is the same approach we took to estimate the emission factors of on-road vehicles with MOVES.

We collected the annual averaged minimum, maximum, and average ambient air temperature data by state for 2001–2011 from the National Climatic Data Center (NCDC 2013). The EPA has federal and state summer RVP standards for gasoline (EPA 2013a), and various states have implemented boutique fuel programs that control the RVP of gasoline (EPA 2012b). We estimated the RVP of gasoline by state based on these regulations. For reformulated gasoline (RFG) that is used in places with high smog levels (e.g., California), the RVP of RFG was collected from the EPA’s RFG survey data; California has a RVP of 7.0 psi in the local RFG (Auffhammer and Kellogg 2011). We estimated the sulfur contents of gasoline and diesel according to the fuel sulfur requirements as regulated by the EPA (EPA 2013b,c). In particular, we considered the recently finalized EPA Tier 3 fuel standards for gasoline and diesel, which become effective in 2017 (EPA 2013d). The input data in 2010, 2013, and 2020 were prepared for the NONROAD model. Table 3 summarizes the state-level averaged PM_{2.5} emission factors for various types of agricultural equipment as generated by NONROAD.

TABLE 3 PM_{2.5} Emission Factors (g/mmBtu) of Various Types of Agricultural Equipment Operating in 2010, 2013, and 2020

Agricultural Equipment	2010	2013	2020
Agricultural mowers, diesel	109.7	92.3	53.3
Agricultural mowers, gasoline	12.6	11.6	10.8
Agricultural tractors, 4-stroke gasoline	7.7	7.8	7.9
Agricultural tractors, diesel	72.5	56.0	29.8
Balers, diesel	92.8	74.3	44.5
Balers, gasoline	6.4	6.5	6.9
Combines, diesel	88.7	67.9	39.6
Combines, gasoline	6.4	6.5	6.9
Irrigation sets, diesel	53.5	41.9	21.9
Irrigation sets, gasoline	12.5	11.0	11.0
Irrigation sets, liquid petroleum gas (LPG)	7.3	7.5	7.6
Other agricultural equipment, diesel	85.0	66.7	37.9
Other agricultural equipment, gasoline	9.2	8.9	8.7
Other agricultural equipment, LPG	6.3	6.5	6.8
Sprayers, 4-stroke gasoline	9.2	9.2	8.8
Sprayers, diesel	91.4	74.3	46.0

2.3 PM_{2.5} EMISSION SOURCE PROFILES

PM_{2.5} source profiles vary with combustion technologies, for example, boilers, engines and turbines, and with different burning fuels. To identify PM_{2.5} emission source profiles for specific emission sources employing particular combustion technologies and fuels, we mainly consulted the EPA's SPECIATE database (EPA 2014a), which compiles 5,728 source profiles for PM_{2.5} emissions by source category, and the PM speciation database maintained by the California Air Resources Board (CARB 2014). Furthermore, we conducted a literature review of recent studies on measurements of stationary, mobile, and non-point emission source profiles, which shed light on new and updated knowledge of emission characteristics for BC and OC by the research community. For tailpipe emissions from on-road vehicles, we mainly relied on the simulation results of the EPA's MOVES model, which is capable of quantifying the impacts of recent engine and tailpipe emission control technologies on tailpipe emissions of PM_{2.5}, BC, and OC, among other pollutants, owing to incorporating in the model some recent chassis dynamometer measurements of tailpipe emission factors of on-road vehicles running on gasoline and diesel (EPA 2014c). BC emission inventories nearly always use mass fractions of element carbon (EC) from PM emission source profiles in SPECIATE and/or the literature. We used the same EC data in SPECIATE and the literature to represent BC in this analysis.

2.3.1 Boilers

We collected source profiles for utility, industrial, or commercial boilers that burn coal, natural gas, residual fuel oil, distillate fuel oil, and biomass for steam and/or electricity generation, and aggregated the BC and OC emission factors according to the source profiles for each combination of combustion technology and fuel type using the Monte Carlo technique, as shown in Table 4. The ranges from the lower bound to upper bound represent the 95% confidence intervals (CI) of the BC and OC emission factors, according to the uncertainties in BC and OC emissions revealed by multiple measurements.

For natural gas-fired boilers, the SPECIATE database has a composite source profile (ID 91112) based on a recent study on estimating emission inventories of PM_{2.5} trace elements in the United States (Reff et al. 2009). In addition, CARB's PM Profile Database reported BC to be 7% of PM_{2.5} by weight. England et al. (2007) conducted dilution-based emissions sampling of PM_{2.5} emissions from natural gas-fired boilers and measured the average mass fractions of the BC and OC components to be 13% and 61%, respectively, with the 95% confidence upper and lower bounds being 22% and 4% for BC and 81% and 41% for OC, on the basis of 10 runs of measurement. We do not have enough information to differentiate the influencing factors for the variation in BC and OC emission shares as shown by these studies, and, therefore, we averaged them for the mean values and estimated the upper and lower bounds of the 95% CI based on those measurements. In addition, we assumed that the BC and OC emission shares of PM_{2.5} emissions are the same for utility, industrial, and commercial boilers of all sizes, despite the known differences in the PM_{2.5} emission factors for these different types of boilers of varying sizes (EPA 2014b).

TABLE 4 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Boilers

Fuel	Combustion Technology	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Natural gas	Industrial, commercial, and utility boilers	13.0 7.0 38.0	4.0	22.0	61.0 24.7	41.0	81.0	England et al. 2007 CARB 2014 Reff et al. 2009
Natural gas, average		16.5	13.0	20.0	42.8	34.7	50.6	
Bituminous coal	Industrial, commercial, and utility boilers	8.1 1.2 1.7 4.1	0.0 0.0 0.0 0.0	16.7 3.6 6.2 12.9	2.2 2.6 11.7 5.2	0.0 1.4 0.0 0.0	5.7 3.9 50.5 25.7	Watson et al. 1996 Watson et al. 2001 Watson et al. 2002
Bituminous coal, average		4.5	2.7	6.3	9.0	4.2	14.2	
Subbituminous coal	Industrial, commercial, and utility boilers	6.7 1.9	1.6 0.8	11.8 3.0	4.4 1.9	0.0 0.0	12.8 5.1	Watson et al. 1988a,b,c
Subbituminous coal, average		4.3	2.6	6.0	3.9	1.7	6.4	
Lignite coal	Industrial, commercial, and utility boilers	2.7 2.4 0.1 1.6 1.4	0.0 0.0 0.0 0.0 0.0	9.2 10.5 3.5 3.1 5.8	62.9 55.7 22.8 4.2 27.2	33.2 31.8 14.5 1.1 0.0	92.5 79.6 31.1 7.2 78.7	Chow et al. 2004
Lignite coal, average		2.7	1.6	3.8	35.8	28.8	43.1	
Coal, average^a	Industrial, commercial, and utility boilers	4.3	3.2	5.5	8.1	5.3	11.1	
Distillate oil	Industrial, commercial, and utility boilers	10.0	6.4	13.6	25.0	16.0	34.0	EPA 2014a
Residual oil	Industrial and commercial boilers	1.0 7.1 8.0	1.0 0.4 8.0	1.0 13.8 8.0	1.0 7.9 3.0	1.0 4.3 3.0	1.0 11.5 3.0	EPA 2014a England et al. 2007 Bond et al. 2004
Residual oil, average		6.3	3.6	9.4	4.4	2.6	6.2	
Crude oil	Industrial boilers	1.8 3.2 3.0 3.4	0.0 1.3 0.8 1.5	3.7 5.2 5.3 5.4	1.7 2.0 2.0 2.0	0.6 0.0 0.0 0.0	2.8 5.0 4.7 5.0	Houck et al. 1989

TABLE 4 (Cont.)

		BC			OC			
Fuel	Combustion Technology	Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	Reference
Crude oil, aggregated		2.9	2.3	3.5	2.1	1.4	2.8	
Biomass	Industrial, commercial, and utility boilers	13.8	7.6	20.0	32.6	16.6	48.6	EPA 2014a
Char	Industrial and commercial boilers	2.3	0.0	4.9	81.0	67.8	94.2	Zielinska et al. 1998
								Fujita et al. 1998
								Watson et al. 1998
		10.2	0.0	22.7	86.6	54.0	100.0	Chow et al. 2004
		4.8	4.8	4.8	66.6	66.6	66.6	CARB 2014
Char, aggregated		6.2	3.3	9.4	79.9	71.5	88.3	

^a Based on the relative shares of bituminous, subbituminous, and lignite coal for electricity generation (Cai et al. 2012).

Because of the lack of data, the same mass fractions of BC and OC in PM_{2.5} emissions from natural gas-fired boilers were assumed for LPG-fired boilers.

For coal-fired boilers, the current SPECIATE database has four source profiles (IDs 3690, 3694, 3700, and 3701) for bituminous coal-fired utility boilers; two source profiles (IDs 3191 and 3192) for subbituminous coal-fired utility boilers; and five source profiles (IDs 4367, 4368, 4369, 4370, and 4373) for lignite-fired boilers. The bituminous coal profiles are based on previous measurements by Watson et al. (1996, 2001, 2002); the subbituminous coal profiles are based on previous measurements by Watson et al. (1988a,b,c); and the lignite profiles are based on previous measurements by Chow et al. (2004). We applied our methodology to estimate the mean values and 95% CI of the BC and OC mass fractions in PM_{2.5} emissions from the bituminous-, subbituminous-, and lignite-fired boilers. Furthermore, the source profiles of these subtypes of coal were aggregated to represent the general coal-fired boilers on the basis of the relative shares of coal by subtype fed to power generation (Cai et al. 2012). Because of the lack of data for industrial and commercial boilers, it was assumed that the BC and OC emission characteristics of these boilers are the same as those of utility boilers. Due to the lack of source profile measurement for petroleum coke-fired boilers, it was assumed that their BC and OC emission factors are the same as those of coal-fired boilers.

Boilers are employed to combust distillate fuel oil, residual fuel oil, and other oil (e.g., crude oil) for steam and/or electricity generation. There is one source profile (ID 4736) in SPECIATE for distillate fuel oil-fired boilers based on an EPA study on testing an industrial-scale distillate oil-fired boiler with a rated capacity of 60,000 lb/h. The measurement data were representative of six individual source tests performed over summer and winter (EPA 2014a). For residual fuel oil-fired boilers, the SPECIATE database contains measurement results from one such boiler that was tested over a 3-day period by the National Risk Management Research

Laboratory of the EPA (ID 4737), eight commercial and industrial boilers (ID 1350110), and four sampling runs by Core et al. (1989) (IDs 1350510 and 135052.5). In addition, England et al. (2007) conducted four measurement runs of a residual fuel oil–fired industrial boiler. With these source profiles, we estimated the mean values and the 95% CI for residual fuel oil–fired boilers using Equation 2. Also, we assumed that the BC and OC emission shares of PM_{2.5} emissions are the same for utility, industrial, and commercial boilers of all sizes. For crude oil–fired boilers, the SPECIATE database contains nine source profiles (IDs 3251, 3252, 3253, 3254, 3255, 3291, 3292, 3293, and 3295), primarily based on the Houck et al. (1989) study; we estimated the mean values and the 95% CI based on these measurements.

For biomass-fired boilers, we relied on a source profile (ID 4704) with the highest quality rating in SPECIATE that was based on a study on source sampling of fine PM emissions from wood-fired industrial boilers by the National Risk Management Research Laboratory of the EPA (EPA 2014a).

Char is co-produced and can be combusted in boilers for electricity generation in new biofuel pathways like pyrolysis-based biofuel production (Wang et al. 2014). For char-fired boilers, we collected two source profiles for charbroiling from SPECIATE (IDs 3915 and 4383) and one from the CARB PM Profile Database. We ignored the potential differences in source profiles between charbroiling and char combustion in boilers due to lack of data for the latter. We estimated the mean values and the 95% CI of BC and OC emissions for char-fired boilers based on these measurements.

2.3.2 Engines

Stationary reciprocating internal combustion engines (RICEs) burning diesel are primarily used in oil and gas exploration. Those burning gasoline are primarily mobile and portable engines, while natural gas–fired engines are primarily used to provide mechanical shaft power for compressors and pumps at pipeline compressors, storage stations, and natural gas processing plants. These engines may also be used in electricity generation applications or smaller applications such as industrial generators or material handling equipment.

For diesel-fired RICE, the SPECIATE database has a source profile (ID 5673) based on the multiple measurement of such a RICE with and without diesel particulate matter filters (DPFs) (England et al. 2004, 2007). The impact of the DPF is small, though, with 83% and 78% of the PM_{2.5} emissions being BC with and without the DPF installed, respectively. Because of the lack of the population distribution of diesel engines with and without DPF, the BC and OC mass fractions of diesel engines with and without DPF installed were averaged, as shown in Table 5. Due to the lack of data, it was assumed that residual oil–fired RICE has the same BC and OC mass fractions for residual oil–fired barges.

For gasoline-fired RICE, we adopted the BC mass fraction of 10% based on the EPA’s Report to Congress on Black Carbon (EPA 2012a). For the OC mass fraction, we adopted that for gasoline light-duty vehicles (LDVs) as a surrogate due to lack of data.

For natural gas–fired RICE, we adopted the BC emission factor from the CARB PM Database. However, the OC emission factor is not reported in the same source profile from the CARB PM Database, and we assumed that the OC emission factor is the same as that for natural–fired boilers.

TABLE 5 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Engines

Fuel	Combustion Technology	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Diesel	Reciprocating engines	83.0	78.0	88.0	16.0	11.7	20.3	England et al. 2004
		78.0	74.9	81.1	22.0	19.4	24.6	England et al. 2007
Diesel, aggregated		81.3	76.6	85.8	18.1	14.3	22.0	
Natural gas	Reciprocating engines	20	20	20	42.8	33.0	52.1	
Gasoline	Reciprocating engines	10	10	10	32	32	32	EPA 2012a Hays et al. 2013
Residual oil	Reciprocating engines	15.0	9.0	21.8	39.0	24.1	55.1	Lack et al. 2009

2.3.3 Turbines

Another type of combustion technology for combusting natural gas, diesel, and residual oil is turbine. The majority of natural gas–fired combustion turbines are used at power plants to generate electricity. England et al. (2007) conducted six runs of source profile measurement of PM_{2.5} emissions from natural gas combined cycle (NGCC) turbines and reported the mean and 95% CI of the measurements, as shown in Table 6. Because of the lack of data, it was assumed that the natural gas–fired simple cycle turbine has the same mass fractions of BC and OC emissions in PM_{2.5} as a NGCC turbine does. This is a reasonable assumption because the major difference between the simple cycle and combined cycle turbines is that the latter integrates a simple cycle turbine with a heat recovery steam generator (HRSG) that recovers hot exhaust gas from the simple cycle to generate steam, despite the fact that the HRSG can be designed with supplementary firing of fuel after the gas turbine in order to increase the quantity or temperature of the steam generated, and the PM_{2.5} emission profile for the supplementary firing of fuel could be different.

Because of the lack of data for diesel- and residual oil-fired turbines, it was assumed that they have the same mass fractions of BC and OC in PM_{2.5} emissions from diesel-fired boilers and residual oil–fired boilers, respectively.

TABLE 6 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Turbines

Fuel	Combustion Technology	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Natural gas	Combined cycle	2.9	0.8	5.2	68.0	53.9	82.1	England et al. 2007
Residual oil	Simple cycle	6.3	3.6	9.4	4.4	2.6	6.2	
Diesel	Simple cycle	10.0	6.4	13.6	25.0	16.0	34.0	

2.3.4 On-road Vehicles

The EPA's MOVES model has incorporated PM emission source profiles primarily from measurements of model year (MY) 2006 and older vehicles and is capable of calculating the BC and OC emissions from operations of on-road vehicles (EPA 2014c). Using MOVES, we generated BC and OC emission factors in g/mi of gasoline and diesel passenger cars, light-duty commercial trucks, passenger trucks, short-haul and long-long single-unit trucks, short-haul and long-long combination trucks, school buses, transit buses and intercity buses covering MY 1990–2020 (Cai et al. 2013b). MOVES also calculates tire and brake wear PM_{2.5} emissions. We collected and applied speciation factors, as shown in Table 7, to calculate the BC and OC emission factors for tire and brake wear on the basis of the MOVES PM_{2.5} emission factors.

TABLE 7 Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Tire and Brake Wear

Emission Source	BC			OC			Reference
	Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Tire wear	60.9	60.9	60.9	21.8	21.8	21.8	EPA 2014a
	22.0	22.0	22.0	47.2	47.2	47.2	EPA 2014a
Tire wear, aggregated	41.4	41.4	41.4	34.5	34.5	34.5	
Brake wear	2.6	2.6	2.6	10.7	10.7	10.7	CARB 2014

The use of DPF, which is required for heavy-duty diesel trucks up to 80,000 lb gross vehicle weight (GVW) beginning with MY 2007, would significantly reduce the BC fraction emitted from on-road diesel vehicles. As a result, MOVES accounts for the lower BC/PM fraction (about 10%) for diesels with DPFs for MY 2007 and later diesel vehicles. This was based on Phase 1 of the Advanced Collaborative Emission Study (ACES). This study was sponsored by the Health Effects Institute (HEI) and Coordinating Research Council (CRC) (Khalek et al. 2009), which characterized the BC/PM and OC/PM fractions of MY 2007–2009 heavy-duty diesel engines using DPFs. This study found a fraction of about 10% for vehicles with DPF versus the more typical 70% to 80% for vehicles without DPF. The recently published Phase 2 of the ACES conducted dynamometer testing and completed detailed chemical characterization of exhaust species emitted from three MY 2011 highway heavy-duty diesel engines that utilized diesel oxidation catalyst (DOC) and a catalyzed DPF for PM emissions control in compliance with EPA 2010 emissions standards (Khalek et al. 2013). The results showed that emissions from post-2010 modern heavy-duty diesels are well below required levels. In addition, the study found that the very low level of PM emissions was dominated by OC (66%) followed by BC (16%) and nitrate (14%) for 2010 technology engines, compared with sulfate (53%) followed by OC (30%) and EC (13%) for the 2007 technology engines. In particular, the study commented on the use of DOC and DPF as the cause of the substantial reduction in sulfate between 2007 and 2010 when the sulfur content in the fuel and lube oil was no different.

We are aware that the latest version of MOVES was developed on tailpipe emissions data, mostly from the CRC E-55/59 Program, and covered MY 1974–2004 for PM_{2.5} emissions (EPA 2012c). Emission data were not available for heavy-duty trucks MY 2007 and newer, and thus the EPA estimated the emission rates of newer model years based on 2003–2006 emission rates and the ratio between the emission standards for 2003–2006 and those for newer diesel engines (EPA 2009). With the publication of the recent findings of PM emission speciation characterization for MY 2007–2010 heavy-duty vehicles (HDVs) from both the Phase 1 and Phase 2 ACES Studies, we used the BC/PM and OC/PM ratios as reported in the Phase 1 Study for MY 2007–2009 HDVs on the basis of the MOVES-generated PM_{2.5} emission factors for long-haul combination trucks, of which the majority consist of heavy-duty trucks with a GVW of no less than 33,001 lb (Cai et al. 2013b). In addition, we used the BC/PM and OC/PM ratios as reported in the Phase 2 ACES Study for MY 2010 and newer HDVs. In this effort, we adopted the MOVES-based BC and OC emission factors for light-commercial trucks, of which the majority consist of LDVs with a maximum GVW of 10,000 lb, for MY 2006 and older LDVs. For MY 2007 and newer gasoline LDVs that are subject to EPA Tier 2 emission standards, we consulted recent dynamometer measurements of the PM emission speciation on three Tier 2 compliant LDVs (Hays et al. 2013). We used the results that the BC/PM and OC/PM ratios are 68% and 32%, respectively, on a normalized basis. Without any recent, available measurement for diesel LDVs, we adopted our MOVES-based BC and OC emission factors for diesel light commercial trucks, of which the majority consist of LDVs with a GVW of 8,501–10,000 lb. For medium heavy-duty trucks, we adopted our MOVES-based BC and OC emission factors for short-haul single-unit trucks, of which the majority consist of medium-duty vehicles with a GVW of 19,501–26,000 lb. The MOVES-based BC and OC emission factors for these vehicle categories by model year can be found in Cai et al. (2013b).

2.3.5 Off-road Vehicles

Diesel-powered off-road HDVs are known to be PM-intensive emitters (EPA 2014d) and are widely employed in construction, mining, and industrial operations. For diesel agricultural tractors, we consulted the CARB PM Database, which contains multiple emission source profiles for off-road diesel vehicle models ranging from 2009 to 2020. The variation in mass fraction of the BC emission is pretty small, which indicates CARB's assumption of nearly equal reductions of the PM_{2.5} and BC emissions therein as a result of the advancement of tailpipe emission control technologies and engine improvement for the vehicles in a few years to come. Table 8 shows the mean and 95% CI of the BC and OC emissions factors for off-road vehicles based on the CARB source profiles.

For diesel locomotives, the PM_{2.5} and BC emissions data are very limited. Bond et al. (2007) once assumed 20% of PM_{2.5} emissions were BC, and there is no literature reporting the OC emissions from diesel locomotive. We adopted the BC and OC mass fractions for on-road heavy-duty trucks as surrogates, which are 8.4% and 88.6% of the PM_{2.5} emissions, respectively (Cai et al. 2013b).

TABLE 8 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Diesel Off-road Vehicles

Fuel	Vehicle Type	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Diesel	Off-road vehicles	40.8	21.3	64.4	61.5	44.8	82.2	Chow et al. 2010 CARB 2014
		64.7	64.7	64.7	22.7	22.7	22.7	
		64.5	64.5	64.5	22.8	22.8	22.8	
		64.1	64.1	64.1	22.9	22.9	22.9	
		64.0	64.0	64.0	22.9	22.9	22.9	
		63.8	63.8	63.8	22.9	22.9	22.9	
		63.5	63.5	63.5	23.0	23.0	23.0	
		63.3	63.3	63.3	23.0	23.0	23.0%	
		63.1	63.1	63.1	23.1	23.1	23.1	
		62.7	62.7	62.7	23.1	23.1	23.1	
		62.0	62.0	62.0	23.3	23.3	23.3	
		61.4	61.4	61.4	23.4	23.4	23.4	
		61.0	61.0	61.0	23.4	23.4	23.4	
	Diesel off-road vehicles, aggregated	56.3	52.5	60.1	34.9	31.5	38.1	

2.3.6 Aircraft

Numerous studies have conducted measurement of BC and OC emission factors from jet fuel combustion. Kinsey et al. (2011) reported that the BC and OC emission factors of jet fuel combustion during aircraft cruise were 0.0211 to 0.275 and 0.0371 to 0.082 g/kg jet fuel, respectively, for a variety of aircraft engines. According to Petzold et al. (1999), the BC emission factor ranged from 0.01 to 0.149 g/kg. The wide variation in BC emissions resulted from variation in jet fuel quality, primarily the sulfur content, and in engine performances. These reported BC and OC emission factors in g/kg of jet fuel were converted to mass fractions, as shown in Table 9, according to the PM_{2.5} emission factors of jet fuel combustion we previously estimated (Elgowainy et al. 2012), which is 0.19 g/kg. In addition, Table 9 shows the mass fractions of BC and OC on the basis of CARB PM source profiles.

We further estimated the average mass fractions of BC and OC in jet fuel PM_{2.5} emissions based on Table 9, with lower and upper bounds of the 95% CI given in Table 10.

TABLE 9 Compilation of BC and OC Emission Factors of Jet Fuel Combustion^a

Aircraft Operations	BC (g/kg)	OC (g/kg)	BC (%)	OC (%)	Reference
Cruise	0.0211	0.0832	11	44	Kinsey et al. 2011 ^b
Cruise	0.0261	0.0371	14	20	Kinsey et al. 2011
Cruise	0.0324	0.0507	17	27	Kinsey et al. 2011
Cruise	0.0281	0.082	15	43	Kinsey et al. 2011
Cruise	0.0251	0.0422	13	22	Kinsey et al. 2011
Cruise	0.0919	0.0504	48	27	Kinsey et al. 2011
Cruise	0.0984	0.0547	52	29	Kinsey et al. 2011
Cruise	0.134		71		Petzold et al. 1999
Cruise	0.01		5		Petzold et al. 1999
Cruise	0.021		11		Petzold et al. 1999
Cruise	0.09		47		Pueschel et al. 1997
Cruise	0.18		95		Anderson et al. 1998
Cruise	0.015		8		Doppelheuer 2001
Landing and take-offs ^c			15		CARB 2014
Landing and take-offs ^c			17	24	CARB 2014
Landing and take-offs ^c			21	42	CARB 2014
Landing and take-offs ^c			48	27	CARB 2014
Landing and take-offs ^c			78	11	CARB 2014
Landing and take-offs			13		EPA 2012a

^a Blank cells indicate a lack of data reported in the studies or databases.

^b The highest BC emission factor reported was 0.275 g/kg, which is higher than the PM_{2.5} emission factor we estimated. Therefore, this record is considered an outlier and was excluded in this analysis.

^c These are assumed for landing and take-off emission profiles, as the EPA does not recognize these CARB emission profiles as one of the limited cruise phase emission profiles (EPA 2012a).

TABLE 10 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Jet Fuel Combustion during Cruise, Landing, and Take-offs

Fuel	Operation Phase	BC			OC		
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)
Jet fuel	Cruise	31.3	6.8	80.6	30.3	20.6	43.7
	Landing and take-offs	35.8	13.5	70.5	26.0	13.0	39.8

2.3.7 Ocean Tankers and Barges

Murphy et al. (2009) measured the chemical composition of particulate ship emissions burning heavy fuel oil and found that sulfate and OC dominated the PM emissions, with a minimum fraction of the PM emissions being BC. Findings by Lack et al. (2009), however, differed, as a much higher BC/PM ratio of 15% was measured upon characterization of the particulate emissions from commercial vessels. The Lack et al. (2009) study showed that BC emissions appear to be inversely correlated to fuel sulfur content, while OC emissions appear to be linearly correlated with fuel sulfur content. Despite the inconsistent findings about the BC/PM ratio among studies, we adopted the findings of Lack et al. (2009) for ocean tankers and barges that burn heavy fuel oil, because their relatively higher BC/PM than the measurement by Murphy et al. (2009) could better reflect the impact of tighter marine fuel standards with reduced sulfur content for marine vessels (EPA 2010c) on possibly increased BC/PM and possibly decreased OC/PM emissions, as shown in Table 11.

TABLE 11 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Residual Fuel Oil Combustion by Ocean Tankers and Barges

Fuel	BC			OC			Unit
	Mean	Lower Bound	Upper Bound	Mean	Lower Bound	Upper Bound	
Residual fuel oil	0.41	0.27	1.57	0.83	0.41	1.57	g/kg
	0.97	0.66	0.65	0.44	0.97	0.65	g/kg
	0.36	0.23	0.75	0.22	0.36	0.75	g/kg
	0.38	0.27	1.42	0.98	0.38	1.42	g/kg
	0.8	0.23	2.1	0.92	0.8	2.1	g/kg
	0.38	0.16	1.9	1.26	0.38	1.9	g/kg
Residual fuel oil, aggregated	15.0	9.0	21.8	39.0	24.1	55.1	% by weight

Source: Lack et al. (2009).

2.3.8 Gas Flaring at Oil Fields

The EPA specifically identifies BC emissions from flaring as being of “particular concern,” for which uncertainties are high and measured data are lacking (EPA 2012a). Efforts to accurately quantify, regulate, and mitigate PM emissions from flaring have led to the recent development of an in situ measurement technique, known as sky-LOSA (Line-of-Sight Attenuation of sky-light) (Johnson et al. 2013). Using the technique, McEwen and Johnson (2012) measured lab-scaled flares for a range of burner diameters, exit velocities, and fuel compositions, and obtained a BC emission factor of 0.51 kg per 1,000 m³ flared gas with a heating value of 45 MJ/m³, which translates into 0.0264 lb/mmBtu. The EPA has recently corrected a clerical error in the soot emission factors for flares in the Emission Estimation Protocol for Petroleum Refineries – Version 2.0 (EPA 2013e). The emission factor for lightly smoking flares as recommended by the EPA is comparable to what McEwen and Johnson (2012) recently found, as shown in Table 12. Smokeless combustion for industrial gas flares is mandated in current regulations (USG, 2009). Steam and excess air flows may be added into the flare combustion zone in order to reduce BC production and achieve smokeless combustion (Fortner et al. 2012). We consulted a recent comprehensive flare emission study, in which particulate emissions and their BC and OC compositions from flaring of industrial gases were measured (Fortner et al. 2012). For PM emissions from gas flared at oil fields, we adopted the mass fractions of 95% and 5% for BC and OC, respectively, according to the average BC and OC mass fractions of the PM emissions from flared gases with high (>98%) destruction efficiency of the vent gases (Fortner et al. 2012), assuming the gas flared at oil fields has the same BC and OC mass fractions as Fortner et al. (2012) found for flared industrial gases that included a mixture of propane, propene, and natural gas.

TABLE 12 BC Emission Factors from Flaring in Oil Fields

Source	BC Emission Factor	Unit	Reference
Associated gas flaring	0.0264	lb/mmBtu	McEwen and Johnson 2012
Nonsmoking flares of associated gas	0.0	lb/mmBtu, LHV basis	EPA 2013e
Lightly smoking flares of associated gas	0.027	lb/mmBtu, LHV basis	EPA 2013e
Average smoking flares of associated gas	0.12	lb/mmBtu, LHV basis	EPA 2013e
Heavily smoking flares of associated gas	0.19	lb/mmBtu, LHV basis	EPA 2013e

2.3.9 Open Burning of Waste Agricultural Biomass

Open burning of waste agricultural biomass is known as another major source responsible for BC emissions both in the United States (EPA 2012a) and worldwide (Kondo et al. 2011; Bond et al. 2013). Biomass open burning associated with biofuel feedstock production can lead to significant air pollutant emissions. For example, open burning of sugarcane straws and residues associated with the manual harvest of Brazilian sugarcane (Seabra et al. 2011) has been found to be responsible for increased estimates of air pollutant emissions, including PM_{2.5}, from

Brazilian sugarcane ethanol (Tsao et al. 2012). For this emission source, we collected seven source profiles for agricultural vegetation burning and field burning of perennial grasses from SPECIATE (IDs 3243, 3258, 3448, 3453, 423222.5, 423232.5, and 423242.5), and six source profiles for agricultural field burning of crop residues, including corn residue, wheat straw, and rice straw from the CARB PM Database. These measurements show comparable mass fractions of BC and OC emissions with moderate variations. We estimated the statistics of the mean values and 95% CI of the BC and OC mass fractions in PM_{2.5} emissions based on these measurements, as shown in Table 13.

TABLE 13 Mean, Upper, and Lower Bounds of the 95% CI of the Mass Fraction (%) of BC and OC in PM_{2.5} Emissions from Agricultural Biomass Open Burning

Fuel	BC			OC			Reference
	Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Agricultural biomass open burning	12.3	0.0	26.0	44.4	24.7	64.1	Houck et al. 1989
	9.6	5.2	14.0	38.8	21.0	56.7	Houck et al. 1989
	13.1	4.8	21.4	39.8	18.3	61.3	Houck et al. 1989
	10.9	4.4	17.4	34.5	18.4	50.6	Houck et al. 1989
	6.8	5.3	8.3	41.5	35.2	47.7	Core et al. 1989
	8.2	6.2	10.2	30.5	22.3	38.6	Core et al. 1989
	9.7	7.2	12.2	32.8	26.7	38.8	Core et al. 1989
	11.5	11.5	11.5	0.0	0.0	0.0	CARB 2014
	16.2	16.2	16.2	33.0	33.0	33.0	CARB 2014
	20.2	20.2	20.2	22.0	22.0	22.0	CARB 2014
	14.0	14.0	14.0	37.1	37.1	37.1	CARB 2014
	13.9	13.9	13.9	33.5	33.5	33.5	CARB 2014
	19.3	19.3	19.3	37.6	37.6	37.6	CARB 2014
Biomass open burning, aggregated	12.1	11.0	13.1	33.9	31.5	36.3	

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3 BC AND OC EMISSIONS FROM ALTERNATIVE FUEL VEHICLES

3.1 BIODIESEL

A review of studies on biodiesel fuel impacts on emissions showed that a noticeable decrease in PM emissions with the biodiesel content can be considered as an almost unanimous trend for vehicles without DPF, owing primarily to the favorable properties of biodiesel. These properties include (1) the oxygen content of the biodiesel molecule that enables more complete combustion even in regions of the combustion chamber with fuel-rich diffusion flames, and which promotes the oxidation of the already formed soot; (2) the absence of aromatics in biodiesel fuels that are considered soot precursors; and (3) the nil sulfur content of most biodiesel fuels that prevents the formation of sulfate, a significant component of typical diesel PM, among others, although some authors have occasionally reported some increases in PM emissions when substituting conventional diesel fuel by biodiesel (Lapuerta et al. 2008). The EPA revealed that PM emissions decrease with an increased blending ratio of biodiesel with conventional diesel, with a maximum reduction of PM emissions of close to 50% for pure biodiesel for vehicles without DPF (EPA 2002), which agreed with the findings of 20% reductions with 20% blends and 50% reductions with pure biodiesel by Haas et al. (2001). However, smaller PM decreases (EPA 2002) were found when the biodiesel fuel was compared with an ultra-low sulfur diesel fuel rather than with a conventional low sulfur one. With further emission controls of diesel vehicles to meet stringent tailpipe emission standards, PM emission reductions by biodiesel are even less.

The change in PM composition is more dramatic with biodiesel. The BC mass fraction is reduced and the OC/BC ratio increases as the biodiesel blending ratio increases (Aakko et al. 2002). The reduced BC/PM ratio is related to the oxygen content in biodiesel, and the increased OC/PM ratio is related to the lower volatility of saturated esters (Schmidt and Van Gerpen 1996). For engines with an oxidation catalyst, BC and OC accounted for 33% and 46%, respectively, of the PM from 100% biodiesel combustion (Aakko et al. 2002). When the Continuously Regenerating Trap (CRT), which is a combination of an oxidation catalyst and a particulate trap, is used, the PM emission level is greatly reduced and the OC/BC ratio increases, with 63% and 9% of the PM emissions being OC and BC, respectively (Aakko et al. 2002). On the basis of the Aakko et al. (2002) study, we assumed that biodiesel vehicles prior to MY 2007 produce BC and OC emissions of 33% and 46% of the PM_{2.5} emissions, and MY 2007 and later vehicles generate BC and OC emissions of 9% and 63% of the PM_{2.5} emissions, respectively.

3.2 ETHANOL

Gasoline with ethanol blending reduces BC emissions compared with gasoline (Dutcher et al. 2011). Recent dynamometer measurements on three Tier 2 compliant LDVs clearly exhibit that the BC/PM ratio decreases linearly with increasing fuel ethanol content ($R^2 = 0.97$). The BC/PM ratio decreases from 60% for gasoline with 85% ethanol blending by volume (E85) to 10% for gasoline with zero ethanol blending by volume (E0 – 10%), while an OC/PM trend is less apparent (Hays et al. 2013). On average, the BC/PM ratio for gasoline with

10% ethanol blending by volume (E10) and E85 is 64% and 22%, respectively, and the OC/PM ratio for E10 and E85 is 19% and 48%, respectively. Compared with E0 and E10, the use of E85 produces significantly less BC emissions and a decrease in BC particle proportions on average. As pointed out by Hays et al. (2013), the fuel oxidation potential increases with the addition of ethanol to petroleum, which explains why the BC/PM ratio decreases with increasing fuel ethanol content (Dutcher et al. 2011; Inal and Senkan 2002). We adopted the BC/PM and OC/PM ratios for E10 and E85 vehicles for LDVs based on the work of Hays et al. (2013).

3.3 FISCHER–TROPSCH DIESEL

Diesel produced from natural gas, coal, or biomass via the Fischer–Tropsch synthesis technologies enjoys great attention as an option for clean transportation fuels production (Schulz 1999; AEAB 2007; Hu et al. 2012). Compared with combustion of ultra-low sulfur diesel (with sulfur content of less than 10 ppm), Sasol has consistently observed 31% to 44% and 19% to 21% reductions in total PM emissions from Fischer–Tropsch diesel (FTD) combustion in LDV and HDV engines, respectively, without particulate filters running under the steady-state cycle (Schaberg and Bell 2010). For jet engines burning 100% Fischer-Tropsch jet (FTJ) and 50% conventional jet blended with 50% FTJ, a reduction of 62% and 39%, respectively, in PM emissions from the landing and take-off operations was measured, in comparison to conventional jet combustion (Lobo et al. 2011). Further, measurements made with a photo-acoustic soot (BC) sensor indicate that the BC proportion of the PM is approximately the same for different fuels, indicating that BC is reduced by approximately the same amount despite different fuels for diesel engines (Forman et al. 2014). Therefore, we assumed that the BC/PM and OC/PM ratios for FTD and FTJ were the same as those for the U.S. low-sulfur diesel vehicles and conventional jet fuel engines.

4 DISCUSSION AND SUMMARY

4.1 DISCUSSION

4.1.1 Impacts of Advances in Emission Control Technologies

Both on-road and off-road diesel vehicles are known to be major PM and BC emission sources. Stringent fuel standards with a focus on low-sulfur diesel, as well as advanced emission control technologies, are taking effects hand-in-hand to reduce diesel PM and BC emissions. It has been observed that the use of DPF reduces the BC/PM ratio from the more typical 70% to 80% for vehicles without DPF to about 10% for vehicles with DPF (Khalek et al. 2009). Without triggering any active DPF regeneration operations, the total mass and BC fraction of the PM are reduced with HDVs using DPF and DOC. Meanwhile, the OC/PM ratio increases significantly with a significant decrease in sulfate (Khalek et al. 2013) when no active DPF regeneration operations are allowed. Because of the lack of active DPF regeneration, it is likely that the internal surfaces of the DOC and DPF never got hot enough for the adsorbed sulfur to be released in high concentration (Khalek et al. 2013). For non-road diesel engines, the 15-ppm ultra-low sulfur diesel has been phased in for use since 2010 (EPA 2014e). It is expected that both the total PM emission and the sulfate/PM and BC/PM will decrease, while the OC/PM will act in the same fashion as the heavy-duty diesel vehicles (Cai et al. 2013b). In this analysis, we assumed that the diesel non-road engines from 2010 models have the same reduced BC/PM and increased OC/PM ratios as those for diesel HDVs.

Emission control technologies, such as electrostatic precipitator and fabric baghouse filters, are used in about 99.6% of the coal-fired power plants in the United States (Cai et al. 2013a). The electrostatic precipitator system usually captures about 99% of the PM (Helble 2000), and up to 99.9% of the PM is removed if fabric baghouse filters are used (EPA 2003). BC is associated with PM with an aerodynamic diameter of less than 1 μm (EPA 2012a). Therefore, it is believed that mitigation technologies such as fabric filters and electrostatic precipitators for fine PM are equally effective for BC mitigation. The earlier measurement of PM speciation in the flue gas of the coal-fired power plants employed electrostatic precipitators for PM emission control (Watson et al. 1988a,b,c; 1996; 2001; 2002). Recent field measurement has suggested that particulate BC and OC emissions from power plants with flue gas desulfurization, electrostatic precipitators, and baghouse filters (Saarnio et al. 2014) are lower than what the earlier measurement by Watson et al. (1988a,b,c; 1996; 2001; 2002;) had revealed. This is partly due to the use of the more efficient baghouse filters in the Saarnio et al. (2014) study, because baghouse filters are especially capable of removing fine and ultrafine PM and are consequently efficient to remove BC. Since a majority of U.S. power plants are employing only the electrostatic precipitator for PM emission control (EPA 2014h), we assumed that the BC and OC mass fractions of the likely reduced PM emissions as a result of possibly more efficient electrostatic precipitators for PM removal today remain the same. The potential bias of this assumption for the BC and OC emission factors in g/kWh of power generation is small, because the PM emission has reached a very low emission level with the advanced emission control technologies.

For residual oil-fired boilers, the total PM emissions are known to decrease with lowered fuel sulfur content (EPA 2014g). Without further characterization of the impacts of emission control technologies on the PM compositions from studies available to us, we assumed that PM emission control technologies, including scrubbers, electrostatic precipitators, and fabric baghouse filters, are capable of reducing the BC and OC emissions in proportion to the total PM emissions, resulting in the same BC and OC mass fractions of the total PM emissions as those without emission controls.

The global community has also been working to reduce the sulfur content of fuels used in marine vessels. Currently, the EPA has established requirements for the sulfur content of bunker type fuel used in per-cylinder displacement at or above 30-L (C3) marine vessels on both a global basis and for an Emission Control Area (ECA) in specific target years (EPA 2014f). More stringent sulfur content standards can decrease both sulfate and OC emissions, according to the finding by Lack et al. (2009) that the OC is linearly dependent on the fuel sulfur content as being $(0.65 \times S\% + 0.5)$ in g/kg bunker fuel. There is no such simple dependence of BC emissions on fuel sulfur content as one major determining factor is engine load, although fuel quality also plays a role (Lack and Corbett 2012). In addition, the EPA's fuel sulfur requirements are designed to reduce sulfate emissions rather than enable the use of DPFs, because even the cleanest fuel with 1,000-ppm sulfur within the ECA by 2015 would not enable the use of DPFs. Therefore, we assume that the OC/PM ratio will decrease linearly with decreased sulfur content in bunker fuel, while the BC/PM ratio will remain the same as the current level as revealed by Lack et al. (2009).

4.1.2 BC and OC Emission Characteristics

BC and OC are usually co-emitted but in different proportions and different combined BC and OC mass fractions for different emission sources. For example, the average OC/BC ratio could range from approximately 1/4 (diesel heavy-duty engines), which agrees with the EPA (EPA 2012a), to approximately 3/1 for open biomass burning. The combined BC and OC mass fractions for coal-fired boilers are low, accounting for only 12% of the PM_{2.5} emissions, with trace metals such as iron (Fe), copper (Cu), calcium (Ca), potassium (K), and zinc (Zn) coming from ash-forming impurities in the coal-dominant PM emissions (Saarnio et al. 2014). In contrast, PM_{2.5} emissions of low-sulfur diesel-fired engines and low-sulfur diesel HDVs are dominated by BC and OC, accounting for more than 95%. Therefore, fuel properties and combustion technologies drive the changes in both the OC/BC ratio and the combined BC and OC mass fraction of the PM_{2.5} emissions.

4.2 SUMMARY OF BC AND OC EMISSION FACTORS

Table 14 summarizes the BC and OC emission factors in mass fractions (%) of the corresponding PM_{2.5} emissions from stationary, mobile, and non-point emission sources, as detailed in Section 2. This table was incorporated into GREET as input parameters to define the BC and OC emission factors of various emission sources. The intermediate BC and OC emission

TABLE 14 BC and OC Mass Fractions in PM_{2.5} Emissions by Emission Source

Fuel	Technology	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Natural gas	Boiler	16.5	13.0	20.0	42.8	34.7	50.6	England et al. 2007 CARB 2014 Reff et al. 2009
Coal	Boiler	4.3	3.2	5.5	8.1	5.3	11.1	Watson et al. 1988a,b,c; 2001; 2002 Chow et al. 2004
Distillate oil	Industrial, commercial, and utility boilers	10.0	6.4	13.6	25.0	16.0	34.0	EPA 2014a
RFO	Boiler	6.3	3.6	9.4	4.4	2.6	6.2	EPA 2014a England et al. 2007 Bond et al. 2004
Crude oil	Boiler	2.9	2.3	3.5	2.1	1.4	2.8	Houck et al. 1989
Biomass	Industrial, commercial, and utility boilers	13.8	7.6	20.0	32.6	16.6	48.6	EPA 2014a
Char	Boiler	6.2	3.3	9.4	79.9	71.5	88.3	Zielinska et al. 1998 Fujita et al. 1998 Watson et al. 1998 Chow et al. 2004 CARB 2014
Diesel	Engine	81.3	76.6	85.8	18.1	14.3	22.0	England et al. 2004, 2007
Natural gas	Engine	20	20	20	42.8	34.7	50.6	CARB 2014
Gasoline	Engine	10	10	10	32	32	32	EPA 2012a Hays et al. 2013
RFO	Engine	15.0	9.0	21.8	39.0	24.1	55.1	Lack et al. 2009
Natural gas	Combined cycle	2.9	0.8	5.2	68.0	53.9	82.1	England et al. 2007
RFO	Simple cycle	6.3	3.6	9.4	4.4	2.6	6.2	
Diesel	Simple cycle	10.0	6.4	13.6	25.0	16.0	34.0	
Tire wear		41.4	41.4	41.4	34.5	34.5	34.5	EPA 2014a

TABLE 14 (Cont.)

Fuel	Technology	BC			OC			Reference
		Mean (%)	Lower Bound (%)	Upper Bound (%)	Mean (%)	Lower Bound (%)	Upper Bound (%)	
Brake wear		2.6	2.6	2.6	10.7	10.7	10.7	CARB 2014
Jet fuel	Cruise	31.3	6.8	80.6	30.3	20.6	43.7	Kinsey et al. 2011 Petzold et al. 1999 Pueschel et al. 1997 Anderson et al. 1998 Doppelheuer 2001
Jet fuel	Landing and take-offs	35.8	13.5	70.5	26.0	13.0	39.8	EPA 2012a CARB 2014
Diesel	Off-road vehicles	56.3	52.5	60.1	34.9	31.5	38.1	Chow et al. 2010 CARB 2014
RFO	Ocean tanker	15.0	9.0	21.8	39.0	24.1	55.1	Lack et al. 2009
Biomass	Open burning	12.1	11.0	13.1	33.9	31.5	36.3	Houck et al. 1989 Core et al. 1989 CARB 2014

factors expressed in g/mmBtu for stationary emission sources and off-road vehicles, in g/kWh for electricity generation, and in g/mi for on-road vehicles are summarized in Table 15. These emission factors are based on the PM_{2.5} emission factors in GREET and the BC and OC mass fractions in PM_{2.5} emissions by emission source, as shown in Table 14 and using Equation 1.

TABLE 15 BC and OC Emission Factors of Stationary, Mobile, and Non-point Sources

Emission Source	BC			OC			Unit
	Mean	Lower Bound	Upper Bound	Mean	Lower Bound	Upper Bound	
Natural gas (NG)-fired utility/ industrial boilers (>100 mmBtu/h input)	0.577	0.387	0.769	1.495	1.066	1.921	g/mmBtu
NG-fired utility/industrial boilers (10–100 mmBtu/h input)	0.523	0.352	0.699	1.359	0.969	1.746	g/mmBtu
NG-fired gas turbines	0.104	0.007	0.232	2.431	1.670	3.185	g/mmBtu
NG-fired combined cycle turbines	0.004	0.000	0.009	0.090	0.062	0.119	g/mmBtu
NG-fired reciprocating engines	1.439	1.439	1.439	3.080	2.375	3.750	g/mmBtu
Flared NG in oil fields	12.247						g/mmBtu
NG-fired kilns ^a	14.850	9.990	19.800	38.520	27.450	49.500	g/mmBtu
Residual fuel oil (RFO)-fired utility boiler	0.841	0.240	1.455	0.587	0.227	0.961	g/mmBtu
RFO-fired industrial boilers	1.019	0.291	1.763	0.712	0.275	1.164	g/mmBtu
RFO-fired commercial boilers	1.019	0.291	1.763	0.712	0.275	1.164	g/mmBtu
RFO-fired reciprocating engines	8.107	4.864	11.782	21.076	13.024	29.779	g/mmBtu
RFO-fired turbines	0.394	0.210	0.651	0.263	0.125	0.421	g/mmBtu
Diesel-fired industrial boilers	0.547	0.263	0.854	1.368	0.624	2.096	g/mmBtu
Diesel-fired commercial boilers	0.752	0.361	1.173	1.881	0.858	2.881	g/mmBtu
Diesel-fired reciprocating engines	43.937	40.154	47.774	9.782	6.485	13.078	g/mmBtu
Diesel-fired turbines	0.657	0.316	1.025	1.644	0.749	2.518	g/mmBtu
Diesel farming tractors	40.818	36.468	45.095	25.303	21.533	29.000	g/mmBtu
Gasoline-fired reciprocating engines	5.256	5.256	5.256	16.819	16.819	16.819	g/mmBtu
Crude oil-fired industrial boilers	0.560	0.367	0.753	0.406	0.212	0.618	g/mmBtu
LPG-fired industrial boilers	0.617	0.415	0.822	1.600	1.140	2.056	g/mmBtu
LPG-fired commercial boilers	0.617	0.415	0.822	1.600	1.140	2.056	g/mmBtu

TABLE 15 (Cont.)

Emission Source	BC			OC			Unit
	Mean	Lower Bound	Upper Bound	Mean	Lower Bound	Upper Bound	
Coal-fired utility boilers	0.872	0.527	1.257	1.643	0.892	2.596	g/mmBtu
Coal-fired industrial boilers	1.053	0.637	1.518	1.983	1.077	3.134	g/mmBtu
Coal-fired kilns ^b	0.860	0.520	1.240	1.620	0.880	2.560	g/mmBtu
Biomass-fired boilers	9.330	5.139	13.523	22.042	11.224	32.860	g/mmBtu
Sugarcane field burning	21.215	18.410	24.021	59.438	52.775	66.101	g/mmBtu
Sugarcane bagasse-fired boilers	6.260	3.447	9.072	14.787	7.530	22.044	g/mmBtu
Petroleum coke-fired boilers	1.054	0.637	1.519	1.982	1.077	3.133	g/mmBtu
Biogas-fired reciprocating engines	1.388	1.388	1.388	2.971	2.291	3.617	g/mmBtu
Flared associated gas	3.515	3.515	3.515	0.185	0.185	0.185	g/mmBtu
Char-fired boilers	1.257	0.345	2.170	16.203	13.506	18.920	g/mmBtu
Ocean tankers using bunker fuel	25.026	15.016	36.371	65.068	40.209	91.929	g/mmBtu
Barges using RFO	5.833	3.500	8.477	15.165	9.371	21.426	g/mmBtu
Diesel locomotive	2.480	2.480	2.480	26.004	26.004	26.004	g/mmBtu
NG-fired pipeline reciprocating engines	0.199	0.199	0.199	0.427	0.329	0.519	g/mmBtu
Diesel trucks, class 6 ^c	0.001	0.001	0.001	0.013	0.013	0.013	g/mi
Diesel trucks, class 8b ^c	0.006	0.006	0.006	0.024	0.024	0.024	g/mi
Gasoline cars ^c	0.005	0.005	0.005	0.002	0.002	0.002	g/mi
Diesel cars ^c	0.001	0.001	0.001	0.004	0.004	0.004	g/mi
Gasoline light-duty truck ^c	0.008	0.008	0.008	0.004	0.004	0.004	g/mi
Diesel light-duty truck ^c	0.001	0.001	0.001	0.009	0.009	0.009	g/mi
Coal-fired boilers	0.009	0.005	0.012	0.016	0.009	0.026	g/kWh
Coal-fired integrated gasification combined cycle	0.031	0.019	0.045	0.058	0.032	0.092	g/kWh

TABLE 15 (Cont.)

Emission Source	BC			OC			Unit
	Mean	Lower Bound	Upper Bound	Mean	Lower Bound	Upper Bound	
NG-fired combined cycle	0.00003	0.000002	0.00006	0.0006	0.0004	0.0008	g/kWh
NG-fired turbines	0.001	0.0001	0.003	0.026	0.018	0.034	g/kWh
NG-fired internal combustion engines	0.094	0.094	0.094	0.202	0.156	0.246	g/kWh
NG-fired boilers	0.007	0.005	0.009	0.018	0.013	0.023	g/kWh
Oil-fired boilers	0.009	0.003	0.015	0.006	0.002	0.010	g/kWh
Oil-fired turbines	0.005	0.002	0.008	0.003	0.001	0.005	g/kWh
Oil-fired internal combustion engines	0.002	0.001	0.003	0.005	0.003	0.007	g/kWh
Biomass-fired boilers	0.273	0.150	0.395	0.644	0.328	0.960	g/kWh

^a Assumed the same as NG-fired boilers.

^b Assumed the same as coal-fired boilers.

^c For MY 2010 and newer vehicles.

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