Climate Change – Characterization of Black Carbon and Organic Carbon Air Pollution Emissions and Evaluation of Measurement Methods

Phase II: Characterization of Black Carbon and Organic Carbon Source Emissions

DRI Contract Number: 04-307

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Submitted

December 2, 2008

Revised and Resubmitted

February 12, 2009

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Executive Summary

Background: Direct and indirect radiative effects of suspended particulate matter (PM) are major sources of uncertainty in current climate models. While aerosol organic carbon (OC) contributes to cooling through light scattering, black or elemental carbon (BC or EC) absorbs light, producing a forcing of +0.2 to +1 W/m^2 that leads to global warming. BC and OC nearly always accompany each other in PM emissions from incomplete combustion of carbon-containing fossil and biomass fuels. Including the direct and indirect effects of BC into the global- and regional-scale climate models requires accurate BC emission inventories and conversion factors (i.e., mass absorption efficiencies, σ_{abs} [λ]) that translate BC concentration into light absorption coefficients (b_{abs}) for different wavelengths. The overall objective of this study is to improve BC/EC and OC emission inventories by understanding what is currently available, by better characterizing BC and EC measurement methods, and by measuring emission rates and profiles from BC-emitting sources. One of the major issues is that there is no single, universally accepted standard for BC or EC measurement, and the available thermal and optical methods vary by more than two to three orders of magnitude. Neither are there widely accepted methods to connect BC or EC to b_{abs}, the relevant observable for radiative transfer. Simplified optical theory for calculating σ_{abs} (λ) and single scattering albedo of BC may not be applied to BC from various sources featuring different size, morphology, and internal mixing.

To meet the overall goal of the study, the Desert Research Institute has completed a comprehensive study on BC measurements and emissions. The first phase of this study evaluated methods for measuring BC and light absorption (b_{abs}). The goals of Phase I include: 1) critically review the literature on carbon analysis methods and comparisons; 2) create carbon analysis QA/QC methods and plans; 3) conduct laboratory inter-comparison experiments of organic carbon (OC), EC, BC, and light absorption (b_{abs}) measurement methods; and 4) perform a field comparison of different measurement methods for b_{abs}, BC, EC, and OC at the Fresno Supersite. The Phase I report was reviewed by the California Air Resources Board (ARB), accepted on October 6, 2006, and is included as an appendix to this report. The second phase of the study evaluated global and regional BC inventories and approaches for constructing a BC inventory for California. The goals of Phase II include: 1) review emission inventory methodology and current inventories for BC, EC, and OC; 2) review BC/EC and OC emission factors used in the ARB emission inventory and compare with emission factors for mobile and biomass burning sources from recent studies; 3) review models and source profiles used to convert estimated particulate matter (PM) emissions to BC/EC and OC emissions; 4) apply a model using the ARB $PM_{2.5}$ emission inventory to estimate BC/EC and OC emissions in California; 5) evaluate uncertainties in estimated BC/EC and OC emissions; 6) summarize database availability and quality assurance/quality control; and 7) develop recommendations for constructing BC/EC and OC emission inventories for California. Study outline and major findings of each Phase are summarized below.

Phase 1: Phase I of this study was carried out through four major tasks: 1) the first task is a critical review of literature on 19 different carbon-analysis methods and 80 carbon intercomparison studies published between 1981 and 2005 was conducted; 2) the second task focused on developing carbon analysis quality assurance and quality control (QA/QC) plans; 3) for the third task, pure and externally mixed (with sodium chloride [NaCl]) aerosols from diesel engine, acetylene flame, electric arc, and wood-combustion aerosols were generated and sampled in the laboratory under controlled conditions. Continuous b_{abs} and BC measurements were made using the photoacoustic analyzer (PA, 1047 nm) and a seven-color aethalometer (7-AE, 370, 470, 520, 590, 660, 880, 950 nm), along with sample collection on Teflon-membrane and quartz-fiber filters. In addition, carbon black and graphite powders were resuspended and collected on quartz-fiber filters for carbon analysis; and 4) the fourth task completed an intensive measurement campaign at the Fresno Supersite between 8/18/05 and 9/17/05, which included six continuous light absorption instruments (two wavelength [2-AE, 370, 880 nm] and 7-AE aethalometers, two PA [532 and 1047 nm], one particle soot absorption photometer [PSAP; 467, 530, 660 nm], and one multi-angle absorption photometer [MAAP; 670 nm]), along with 24-hr sample collection using integrated samplers. This complemented measurements taken during a winter intensive operating period (IOP, 12/1/03 to 12/22/03). Findings from the laboratory intercomparisons were applied in understanding the differences observed at Fresno.

The literature review identified possible biases in thermal and optical methods. For filter-based thermal/optical analyses, the charring correction followed by early EC evolution in an inert atmosphere (due to trace oxidants) represented the most important uncertainty in thermal/optical methods (Chow et al., 2004a), biasing the OC/EC split. For the DRI Model 2001 carbon analyzer, QA/QC procedures were developed including: 1) multi-point temperature calibrations;

2) characterization of analysis atmosphere; 3) carbon analyzer calibration; and 4) calibration of laser intensity using neutral density filters. These procedures have been shown to improve the precision of OC/EC and carbon fraction measurements. For instance, without temperature calibration, the sample temperature is typically biased high by 14 to 22 °C, causing up to 30% change in carbon fraction concentrations. This does not affect the OC/EC split, however. The review indicated that b_{abs} measurements by the PA compared well (within ±3%) with the difference between light extinction by optical extinction cell (OEC) and scattering by nephelometer for pure soot sample or soot mixed with salts (Sheridan et al., 2005). The studies also pointed out the need for correcting filter-based absorption methods for particle light scattering (b_{scat}), the uncertainty involved in σ_{abs} estimates and its effect on b_{abs} measurements, the influence of organic aerosols on b_{abs}, and its influence on the Angstrom absorption exponent (α).

In terms of total carbon (TC), diesel, acetylene flame, and electric arc samples were generated typically within 15% variability. Wood smoke samples showed as much as 50% variability. EC/TC ratios measured by thermal/optical methods showed consistency within each source type, as well as diversity between source types. The STN and French two-step protocols yielded EC/TC ratio similar to (within ±5%) those of the IMPROVE_A protocol for diesel soot (EC/TC ~60%), acetylene flame soot (~96%), and electric arc soot (~50%). The French two-step and STN protocols were lower for EC (86% and 46%, respectively) in wood smoke compared to the IMPROVE_A protocol. The presence of NaCl caused EC to be released at lower temperatures, and was limited by the presence of oxygen (O_2) and charring correction. While it affected the abundance in the EC fractions, it did not affect the OC/EC split in the IMPROVE_A and STN protocols. The French two-step protocol that operates in pure O_2, without charring corrections, reported >60 to 90% lower EC than IMPROVE_A_TOR for all 19 samples. When comparing the IMPROVE_A EC to PA (1047 nm) b_{abs}, the EC σ_{abs} (1047 nm) varied by ~50% in the range of 2.7 to 5.3 m^2/g among the different source types. There is no universal conversion factor that can be applied to convert b_{abs} to BC/EC concentrations. The ratio of AE b_{abs} to PA b_{abs} was influenced by BC concentrations; lower ratios were found to be associated with higher BC concentrations.

Using the IMPROVE_A protocol, the EC/TC ratios at the Fresno Supersite were 0.22 ± 0.04 and 0.26 ± 0.05 for summer and winter IOPs, respectively. The EC/TC ratio during winter was close to the EC fraction in wood smoke (0.26 ± 0.12). The σ_{abs} (1047 nm) of EC during the winter IOP (2.5 m^2/g) was also similar to that of wood smoke EC (2.7 m^2/g). The value of α in the Angstrom Power Law, determined by 7-AE during the summer IOP (0.95 ± 0.04) was 10–20% higher than that observed for diesel and acetylene flame soot (0.79 ± 0.09 to 0.86 ± 0.12), from both pure source aerosol and when mixed with NaCl. This indicates that the summer aerosol at Fresno, while being influenced by diesel emissions, might be mixed with aged or secondary aerosols. The α during the winter period (1.2 ± 0.11) was closer to that observed for emissions from wood combustion (1.2 ± 0.51). Despite the potential bias in the aethalometer, this study confirms a higher α for wood smoke than for diesel soot.

Results suggest that the IMPROVE_A and STN protocols estimate similar EC for the source samples (except wood smoke). The presence of a catalyst such as NaCl changes the abundances in EC fractions, but not the OC/EC split in IMPROVE_A and STN protocols. The French two-step protocol was influenced greatly by the aerosol matrix. A single value of σ_{abs} does not exist. Moreover, $\alpha = 1$ in the Angstrom Power Law that is commonly used to scale b_{abs} to different wavelengths varied from 0.5 to 1.4. These observations may be explained by more complex aerosol optical models that consider particle size distributions, morphology, and internal/external mixing characteristics.

Phase II: Phase II of this study describes and evaluates state-of-the-science BC/EC and OC emission inventories and provides a framework for creating inventories for California. Global BC and OC emission estimates range from 8 – 24 and 33 – 62 Tg/yr, respectively. North American BC emissions accounted for ~6% of the global total, and California BC emissions accounted for <~0.4% of global emissions. Global inventories are based on fuel use estimates and emission factors taken from published articles and reports. These emission factors vary regionally and depend on the degree of economic development. They do not represent California’s special mixture of fuels, combustion technology, operating conditions, and aggressive emission controls.

The most accurate inventories use a bottom-up approach where emission factors and activities are specified for all stationary, area, and mobile sources. Examples include the California Air Resources Board (ARB) inventory for criteria pollutants in California and the U.S. National Emissions Inventory (NEI). Because such inventories estimate PM emissions, they provide a basis for estimating BC and OC emissions when the BC and OC PM fractions are measured in specific source types. EC and OC mass fractions are included in source profiles that are used to produce speciated PM inventories and for receptor-oriented source apportionment modeling.

ARB PM emission factors are based on emission models such as EMFAC2007 and OFFROAD for mobile sources and the Emission Estimation System (EES) model for biomass burning sources. In this study, EMFAC2007 produced reasonable agreement with recently-measured values for heavy-duty diesel-fueled vehicles, but it did not capture the large variability in measured gasoline-fueled vehicle emissions. EES provided reasonable estimates for dry litter burning, but it underestimated PM emissions from wet herb and shrub, regen, and wet needles from Ponderosa and Lodgepole Pine trees. ARB emission factors overestimated Chemise (Chaparral) but underestimated rice straw and grass (Grassland) burning. The EES emission model can be updated with more recent emission factor measurements, provide flexibility for estimating specific fire events, and estimate the uncertainty of the emission factor estimates.

Recently measured source profiles were compiled into a database to supplement the U.S. EPA SPECIATE version 4.0 and ARB source profile libraries. Many of the recent studies lack EC and OC measurements, or they applied EC and OC analysis methods that are not compatible with ambient data. A set of the assembled source profiles was applied to the ARB 2006 $PM_{2.5}$ emission inventory to estimate BC/EC and OC emissions in California. Total BC/EC emissions were 52,084 tons/yr. Major sources included biomass burning (wildfires, managed burning, and residential fuel combustion), and off-road and on-road engine exhaust. Statewide OC emissions (107,979 tons/yr) were twice BC/EC emissions (52,084 tons/yr). BC/EC emissions derived from the 1995 ARB inventory (38,781 tons/yr) were in reasonable agreement (33,281 tons/yr) with those extracted from California's grid squares from a 1996 global inventory. However, there were large differences for fuel categories (e.g., fossil fuels and biofuels) and source types, indicating that the overall agreement may have been fortuitous.

California BC/EC and OC emission estimates are sensitive to the choice of source profiles used to convert $PM_{2.5}$ to BC/EC and OC. Recently measured gasoline- and diesel-fueled vehicle exhaust source profiles from the U.S. EPA's SPECIATE version 4.0 source profile library resulted in twice the mobile on-road BC/EC emissions compared with the profiles drawn from the ARB source profile library. Using ARB gasoline- and diesel-fueled vehicle source profiles provided 17% lower statewide BC emissions. Source profile documentation in both libraries is limited, making selection of appropriate profiles difficult to justify.

ARB can build on its current $PM_{2.5}$ emission inventory effort by coupling relevant source profiles containing BC/EC and OC abundances with its inventory system. Existing profiles were assembled into a database and documented, and this can serve as a starting point. Examination of these existing profiles indicates that they are insufficient to represent all of the major source types, especially for biomass burning and non-road engine exhaust. More systematic testing of these emissions, using diluted plumes and a common carbon analysis method, are needed to fill in the gaps.

Further traceability is also needed for emission factors and activity databases, especially those used by the local air districts to construct the emissions they submit to the state inventory. Such data are currently not always available but would enable studies to evaluate the sensitivity of BC/EC and OC emissions to variability and uncertainty in these parameters. California has a wealth of speciated $PM_{2.5}$ measurements from the long-term IMPROVE network operated in its national parks and wilderness areas and numerous special studies conducted in central California, the San Francisco Bay Area, and the South Coast Air Basin. Estimated $PM_{2.5}$, EC, and OC emission inventories can be evaluated by comparing measured concentrations with those estimated in air quality models.

1. INTRODUCTION

1.1 Background

Particulate matter (PM) emissions often accompany greenhouse gas (GHG) emissions such as carbon dioxide (CO_2) and methane (CH_4). These emissions affect the Earth's climate (MacCracken, 2008a; 2008b), human health (Chow et al., 2006a, Mauderly and Chow, 2008, Pope and Dockery, 2006), visibility (Chow et al, 2002, Watson, 2002), surface soiling (Sabbioni and Brimblecombe, 2003), and crop productivity (Grantz et al., 2003). Direct and indirect radiation forcing by atmospheric PM constitutes the largest uncertainty in current predictions of climate change (Twomey, 1977; Twomey et al., 1984; Charlson et al., 1992; Penner et al., 1994; Chuang et al., 1997; Chow et al., 2002; Watson, 2002; Intergovernmental Panel on Climate Change [IPCC], 2007; National Research Council [NRC], 2008; MacCracken, 2008a).

The global direct radiative effect of light-scattering PM containing sulfates and nitrates is on the order of -1 W/m^2 (IPCC, 2007) and causes global cooling. Light-absorbing PM, mainly black carbon (BC; also called elemental carbon [EC], light-absorbing carbon [LAC], or "soot") from fossil fuel and biomass combustion, produce a warm forcing of +0.2 to +1 W/m^2 (Chow, 2001; Lloyd and Cackette, 2001a; 2001b; IPCC, 2007). Combustion processes also produce organic carbon (OC) that affects radiative forcing mainly through light scattering. BC rarely occurs in the absence of OC, however, and light absorption efficiencies depend on the composition, shape, and sizes of the BC particles (Fuller et al., 1999).

BC aerosols contribute directly to warm forcing by heating the air around them as they re-radiate energy from the absorbed light. Radiative properties of cloud droplets and ice crystals are modified by the presence of BC. BC enhances evaporation of tropical cumulus (Ackerman et al., 2000; Jacobson, 2002). Deposited BC may change the planetary albedo (reflectivity) by darkening snow and ice surfaces (Warren, 1984; Warren and Clarke, 1990). Hansen and Nazarenko (2004) concluded that albedo effects of BC in snow and ice could account for 25% of observed global warming between 1880 and 2000.

To model the radiative effects of BC on climate, BC emission estimates are needed on a global scale. In the past, global BC emission inventories were based on international fuel consumption estimates (United Nations, 1993). These did not consider the inefficient fuel combustion processes that produce BC. Table 1-1 summarizes more recent BC and OC emission inventories that consider combustion processes.

The Global Emissions Inventory Activity (GEIA; http://www.geiacenter.org/; Molina, 1992; Penner et al., 1993), includes a BC inventory based on fuel consumption (12.6 teragrams [Tg] BC/yr or 12.6×10^{12} grams of BC emissions per yr) and one based on sulfur dioxide (SO_2) emissions (23.8 Tg BC/yr), relying on observed region-specific correlations between BC and SO_2. Liousse et al. (1996) estimated contributions from fossil fuel and biomass burning at 12.2 Tg BC/yr and 62.2 Tg OC/yr. Cooke and Wilson (1996) estimated anthropogenic fossil fuel emissions at 8.0 Tg BC/yr and biomass burning emissions at 6.0 Tg BC/yr. In a later update, Cooke et al. (1999) estimated BC and OC emissions from fossil fuel combustion at 5.1 Tg BC/yr and 7.0 Tg OC/yr for the submicron particle fraction and 6.4 Tg BC/yr and 10.1 Tg OC/yr for bulk PM. Bond et al. (2004) estimated 3.0 Tg BC/yr and 2.4 Tg OC/yr from fossil fuel combustion and 5.0 Tg BC/yr and 31.0 Tg OC/yr from biomass burning, with total combustion emissions of 8.0 Tg BC/yr and 33.4 Tg OC/yr. Global emissions vary substantially owing to the different methods, assumptions, and databases used to estimate these emissions. Estimates for BC and OC from fossil fuel combustion varied by eight- and fourfold, respectively. Most inventories did not report the emission estimates for biomass burning, especially for OC. Only Bond et al. (2004) provides uncertainty ranges of 4.3 – 22 Tg/yr for BC and 17 – 77 Tg/yr for OC.

Regional BC emission inventories have also been created. Bond et al. (2002) estimated that North American sources contribute 6% of global BC emissions. Battye et al. (2002) ranked the major contributors to U.S. BC emissions as: 1) non-road diesel exhaust (21%); 2) on-road diesel exhaust (15%); 3) prescribed forest fires (7.9%); 4) open burning (7.7%); and 5) residential wood combustion (RWC; 4.8%). Natural wildfires were not considered manmade sources in Battye et al. (2002), although 100 years of fire suppression have caused them to be large emitters in recent years. Gasoline engine cold-starts and high emitters, which have been shown to contain substantial BC fractions (Zielinska et al., 1998; Chow et al., 2006b), were not considered in this analysis.

On a national scale, the U.S. Environmental Protection Agency (U.S. EPA) maintains the National Emission inventory (NEI; http://www.epa.gov/ttn/chief/net/) for criteria pollutants. The NEI is based in large part on contributions from the individual states. California has developed detailed models for estimating emissions of criteria pollutants, including $PM_{2.5}$ (PM with aerodynamic diameters < 2.5 micrometers [µm]), PM_{10} (PM with aerodynamic diameters < 10 μm), and GHG. Thousands of sources have been identified, their activities quantified, and their emission estimated using state-of-science emission factors. These emission inventories integrate information at the county, air-basin, and state-wide levels. Much of the previous work depends on source profiles, i.e., the ratios of EC and OC to PM in source emissions to convert PM emissions to BC and OC emissions.

These emission inventories rely on different assumptions and on data related to PM emission factors, emission activities, and source profiles, all of which apportion PM mass to BC and other chemical constituents. These differences may be a major cause of discrepancies and uncertainties in model predictions. Bond et al. (1998) identified PM mass emission factors and BC fraction (f_{BC}) of emitted PM (i.e., "source profiles") as the most variable. Cooke et al. (1996) based the f_{BC} for heavy-duty diesel-fueled vehicles (HDDV) on source profiles from Cass et al. (1982), Lowenthal et al. (1994), and others. Streets et al. (2001) based f_{BC} for diesel-fueled vehicles in China on profiles from Gillies and Gertler (2000) and others. Detailed EC and OC analysis protocols to derive f_{BC} are summarized and reviewed by Watson et al. (2005).

Since radiative forcing calculations are based on aerosol optical properties, not BC mass concentration, Bond et al. (1998) recommended measuring emission absorption coefficients directly and reporting "absorption cross section" emission factors (i.e., in units of m^2/sec, m^2/unit of activity, m^2/unit CO_2, or m^2/unit fuel burned). In addition to characterizing $PM_{2.5}$ emissions in terms of BC, EC, or OC, Bond et al. (1998) suggested that particle light absorption (b_{ap}) should be quantified along with BC emission rates and source profiles.

While concurrent measurements of b_{ap}, BC, EC, and OC may be useful for understanding the relationships among these properties (Chow et al., 2006c; 2008a), the concept of an absorption cross section emission inventory is uncertain because the absorption cross section is not necessarily conservative. The amount of light absorbed by a population of externally mixed BC particles may be altered by a number of physical and chemical processes. The coating of some or all of the emitted BC particles by a non-absorbing but scattering substance such as ammonium sulfate [$(NH_4)_2SO_4$] will increase the absorption cross sections of the coated particles (Fuller et al., 1999). BC particles which become internally mixed with soluble substances may nucleate and become incorporated into cloud droplets, which in turn increases the absorption efficiency of the BC core (Chylek et al., 1984). It is unclear how such chemical transformations and phase transitions can be accounted for in a radiative transfer model when the only information available is the absorption emission factor of the emitted BC particles.

BC, EC, and OC are all operationally defined by the methods used to measure them (Watson et al., 2005). BC and EC are often used interchangeably. EC occurs as mineral graphite or as diamond in its purest forms, but these structures are not found in ambient PM (Chen et al., 2004; Chow et al., 2001; 2004a; 2007a). Even freshly emitted soot from incomplete combustion contains non-carbon components and has a non-crystalline structure (Akhter et al., 1984; 1985). It has a large surface-to-volume ratio and reactive surfaces, so it attracts condensable materials (e.g., polycyclic aromatic hydrocarbon [PAH] gases) soon after cooling. Of the major components of $PM_{2.5}$ and PM_{10}, EC and OC are the most uncertain with respect to sampling and analysis (Turpin et al., 1994; Huebert and Charlson, 2000; Jacobson et al., 2000; Chow et al., 2008b).

Most BC and EC characterization involves collecting PM on filters and measuring either the carbon content on the filter or the attenuation of light reflected from or transmitted through the filter. Filter-based optical techniques include the British Smoke Shade method (Hill, 1936), the coefficient of haze (COH; Hemeon et al., 1953), the "integrating plate" method (IPM; Lin et al., 1973), the aethalometer (Hansen et al., 1984), the multi-angle absorption photometer (MAAP; Petzold et al., 2005), and the particle soot absorption photometer (PSAP; Bond et al., 1999). The scattering and absorption properties of particles distributed on top of and throughout a filter are not the same as they are in the atmosphere, however, and b_{ap} determined from these methods is often biased (Horvath, 1993).

Thermal evolution methods quantify the amount of carbon that leaves the filter at different temperatures (Schmid et al., 2001; Currie et al., 2002; Watson et al., 2005). These carbon analysis protocols use different combinations of temperature and analysis atmospheres to evaporate, pyrolyze, and combust the carbon-containing compounds in a filter sample with subsequent detection of the evolved carbon gases. The separation of EC from OC is ambiguous because some of the EC combusts in an oxidizing atmosphere, and some of the OC chars (turns to EC) in an oxygen-free atmosphere. Light reflected from (Johnson et al., 1981; Huntzicker et al., 1982; Chow et al., 1993; 2001; 2004a; 2007a) or transmitted through (Turpin et al., 1990; Birch and Cary, 1996a; 1996b; Chow et al., 2001) the filter during the analysis is used to monitor and correct for this charring. In this sense, EC measured by thermal/optical techniques is BC.

Interlaboratory and intermethod comparisons (Countess, 1990; Chow et al., 2001; Schmid et al., 2001; Currie et al., 2002) show EC differences of a factor of seven or more among different thermal methods, depending on the analysis protocol and type of sample. Most commonly used thermal/optical carbon analysis protocols and their performance (e.g., minimum detectable limits [MDLs], precision, bias) are summarized by Chow et al. (2006d) for this study. Different analysis methods alone can account for the large differences in BC emission rates among inventories.

A fundamental measurement of in situ aerosol b_{ap} can be achieved by the photoacoustic (PA) instrument (Arnott et al., 1999; 2003; Moosmüller et al., 1997), which quantifies minute changes in the speed of sound in response to heating and cooling of PM by a modulated laser beam. PA measurements collocated with filter samples offer the best method of relating BC/EC measurements to their absorption properties. Chow et al. (2006c; 2008a) performed extensive comparisons of various techniques for measuring b_{ap}, BC, and EC. The most significant results were that filter-based approaches for measuring b_{ap} (including aethalometer, MAAP, and PSAP), are routinely biased by optical artifacts caused by interactions between incident light, the filter material, and particles entrained in or on the filter. While empirically-based algorithms were developed to account for these artifacts (Arnott et al., 2005; Virkkula et al., 2005; Chow et al., 2006d), systematic biases remained in comparison with b_{ap} measured in situ with the PA. Nonetheless, BC (measured with various filter-based techniques) and EC (measured using different thermal protocols) were all well correlated. Nearly a hundred carbon analysis intercomparison studies have been reported, as summarized by Chow et al. (2006d) for this study. These comparisons demonstrate that functional relationships can be derived to convert b_{ap} to BC or EC (Chow et al., 2006c; 2008a). In the following sections, BC is referenced in the reported inventory and EC is reported in the source profiles, recognizing the functional relationships among BC, EC, and OC.

1.2 Objectives

The overall goal of this study is to better understand how well California's BC emissions can be estimated. This is a first step toward designing effective emission reduction strategies. Specific objectives are:

- Review emission inventory methodology and current inventories for BC, EC, and OC.
- Review BC/EC and OC emission factors used in the California Air Resources Board (ARB) emission inventory and compare with emission factors for mobile and biomass burning sources from recent studies.
- Review models and source profiles used to convert estimated PM emissions to BC/EC and OC emissions.
- Apply a model using the ARB $PM_{2.5}$ emission inventory to estimate BC/EC and OC emissions in California.
- Evaluate uncertainties in estimated BC/EC and OC emissions.
- Summarize database availability and quality assurance/quality control.
- Develop recommendations for constructing BC/EC and OC emission inventories for California.

1.3 Contents of the Report

This Section documents the background and objectives of this study. Section 2 reviews and evaluates current BC emission inventories. Section 3 describes emission factors and compares engine exhaust and biomass burning emission factors used in the ARB emission inventory with corresponding emission factors measured in recent studies. Section 4 documents a modeling framework for estimating BC/EC and OC emissions from $PM_{2.5}$ emission inventories, provides a compilation of source profiles needed to accomplish this, and estimates BC/EC and OC emissions in California using the ARB $PM_{2.5}$ emission inventory along with different source profiles. Section 5 discusses the major sources of uncertainty in constructing BC/EC and OC emission inventories, compares modeled BC and measured EC based on NEI, compares BC/EC and OC emission estimated for California with those from a global inventory, and evaluates uncertainties in the California BC/EC and OC inventories with sensitivity analyses. Section 6 describes the deliverables including the emission factor database, the source profiles, and the quality assurance/quality control (QA/QC) procedures used to measure them. Conclusions and recommendations for developing BC/EC and OC emission inventories for California are given in Section 7. References and bibliography are given in Section 8. A List of Abbreviations and List of Websites is given in Section 9. Appendix A contains the three publications from this study. Appendix B includes the Phase I Report and Quality Assurance Project Plan (QAPP).

Table 1-1. Summary of global black carbon and organic carbon emission inventories.

		Global Black Carbon (BC) and Organic Carbon (OC) Emissions (Tg/yr)					
	Reference	**Anthropogenic Fossil Fuels**		**Biomass Burning**		**Sum of Fossil Fuel and Biomass Burning**	
		BC	**OC**	**BC**	**OC**	**BC**	**OC**
I	Penner et al. (1993)	12.6[a]	NA	NA	NA	NA	NA
		23.8[b]	NA	NA	NA	NA	NA
II	Liousse et al. (1996)	6.6	21.9	5.6	40.3	12.2	62.2
III	Cooke and Wilson (1996)	8.0	NA	6.0	NA	14.0	NA
IV	Cooke et al. (1999)	5.1[c]	7.0[c]	NA	NA	NA	NA
		6.4[d]	10.1[d]	NA	NA	NA	NA
V	Bond et al. (2004)	3.0	2.4	5.0	31.0	8.0[e]	33.4[e]

[a] Part of Global Emissions Inventory Activity (GEIA; Molina, 1992), estimated based on fuel consumption.
[b] Estimated based on SO_2 emissions (e.g., correlations between SO_2 and BC).
[c] For the sub-micron particle fraction.
[d] For bulk particulate matter.
[e] The estimated uncertainty ranges are 4.3 – 22 Tg (teragrams or 1×10^{12} grams) BC/yr and 17 – 77 Tg OC/yr

2. EMISSION INVENTORY LITERATURE REVIEW AND COMPARISON

2.1 Global and Regional Inventories

Table 2-1 describes eight BC and OC emission inventories in terms of geographical extent (global, regional, or national), resolution, base year, and source categories, as well as the sources of the emission factors and the activity data. The Penner et al. (1993) and Liousse et al. (1996) global inventories had resolutions of 5° × 5° and 4.5° × 7.5°, respectively, with a base year of 1980. The Cooke and Wilson (1996), Cooke et al. (1999) and Bond et al. (2004) global inventories had a resolution of 1° × 1° with base years of 1984, 1984, and 1996, respectively. For the regional inventories, the Reddy and Venkataraman (2002a; 2002b) India inventory had a resolution of 0.25° × 0.25° with a base year of 1996-1997. The Streets et al. (2003) Asian inventory varied in resolution from 1° × 1° to 0.08° × 0.08° grid cells and the Cao et al. (2006) China inventory had a resolution of 0.2° × 0.2°, both with a base year of 2000. As shown in Table 2-1, the sub-categorizations of the emission sources were not consistent across each of these eight emission inventories. However, the major sectors (e.g., power generation, industry, residential, and transportation) were included in all inventories as well as the major fuel types (e.g., fossil fuels and biofuels). Emission factors were drawn from a variety of sources, including literature review, U.S. EPA's AP-42 compendium (http://www.epa.gov/ttn/chief/ap42/), and emission models. For the regional inventories, Reddy and Venkataraman (2002a; 2002b) customized their emission factors to fit Indian technology; and Cao et al. (2006) included emission estimates from 363 large Chinese point sources, mainly coal-fired power plants and iron and steel industries. Each of the eight emission inventories used different sources of information to determine activity levels.

Tables 2-2a and 2-2b compare the BC and OC emission factors for major air pollution sources (e.g., mobile, coal combustion, biomass burning). Fossil fuel combustion emission factors in Cooke and Wilson (1996) were based on fuel type and source sector: 1 – 10 g BC/kg for solid fuels, 0.06 – 2 g BC/kg for liquid fuels, and 6 x 10^{-5} – 0.05 g BC/kg for gaseous fuels. BC emission factors for biomass burning ranged from 1 – 2.2 g BC/kg for 17 categories. Each of the remaining emission factors was categorized into general source categories to facilitate a comparison. Source category-specific BC or OC emission factors are not available in Penner et al. (1993).

Table 2-2a presents emission factors for BC. There was a variation of two orders of magnitude among the emission factors for the on-road light-duty gasoline engine category, from 0.006 g BC/kg (Cao et al., 2006) to 0.43 g BC/kg (Bond et al., 2004). For the global inventory, Cooke et al. (1999) and Bond et al. (2004) had a similar range of 0.03 and 0.08 g BC/kg at the low end, respectively, and 0.15 and 0.43 g BC/kg at the high end, respectively. Results from Reddy and Venkataraman (2002a) and Cao et al. (2006) for the India and China inventories, respectively, showed the same high value (0.08 g BC/kg), which matches the low end value of Bond et al. (2004). The low end value of Reddy and Venkataraman (2002a), 0.05 g BC/kg, is within the low end range of 0.03 – 0.08 g BC/kg used by Cooke et al. (1999) and Bond et al. (2004). The low end value from Cao et al. (2006), 0.006 g BC/kg, is one order of magnitude lower than any of the other BC emission factors. Liousse et al. (1996) did not report BC emission factors for the on-road light-duty gasoline engine category.

For the on-road diesel engines, BC emission factors also varied by two orders of magnitude, from 0.11 g BC/kg (Cao et al., 2006) to 10 g BC/kg (Cooke et al., 1999). Reddy and Venkataraman (2002a) showed a range for the heavy- and light-duty diesel engine categories of 1.93 – 2.42 g BC/kg, comparable to those of Bond et al. (2004; 1.3 – 3.6 g BC/kg) and Streets et al. (2003; 1.1 g BC/kg). These factors are one to two orders of magnitude higher than those for the on-road gasoline engines. Cooke et al. (1999) had a higher range of 2 - 10 g BC/kg. Liousse et al. (1996) reported a value of 0.4 g BC/kg, within the range of 0.11 – 2 g BC/kg by Cao et al. (2006), though no distinction was made between emission factors for heavy- and light-duty diesel engines.

Streets et al. (2003) and Bond et al. (2004) reported off-road gasoline emission factors of 0.08 and 0.10 g BC/kg, respectively. Three of the six studies reported BC emission factors for off-road diesel engines ranging from 0.34 g BC/kg to 3.7 g BC/kg (Bond et al., 2004). Reddy and Venkataraman (2002a) reported a value of 0.29 g BC/kg for diesel-powered locomotives, which is similar to the low end values of 0.34 – 0.35 g BC/kg reported by Bond et al. (2004) and Cooke et al. (1999). The high end values reported by Streets et al. (2003), Cooke et al. (1999), and Bond et al. (2004) were 1.1, 2.0, and 3.7 g BC/kg, respectively.

Coal-fired power plant BC emission factors spanned four orders of magnitude. Low end values ranged from 0.0001 g BC/kg (Streets et al., 2003) to 1.1 g BC/kg (Liousse et al., 1996). High end values ranged from 0.009 g BC/kg (Bond et al., 2004) to 2.2 g BC/kg (Liousse et al., 1996). For domestic coal combustion, Reddy and Venkataraman (2002a), Streets et al. (2003) and Cao et al. (2006) reported similar low end values (0.12 – 0.18 g BC/kg), while high end values ranged from 1.83 g BC/kg (Reddy and Venkataraman, 2002a) to 5 g BC/kg (Cao et al., 2006), similar to the 4.1 and 5.4 g BC/kg reported by Cooke et al. (1999) and Bond et al. (2004), respectively.

The Cooke et al. (1999) BC emission inventory focused only on fossil fuel combustion and did not report biomass burning BC emission factors. Fireplace and woodstove biomass burning emission factors for Liousse et al. (1996), Reddy and Venkataraman (2002b), and Cao et al (2006) are within the range of 0.3 – 1.4 g BC/kg range of Bond et al. (2004). Only Bond et al. (2004) reported boiler biomass burning BC emission factors (0.044 – 0.55 g BC/kg). All five emission inventories reported similar emission factors for agricultural biomass burning (0.47 – 1.2 g BC/kg), with the exception of the low value of 0.06-0.10 g BC/kg by Liousse et al. (1996). BC emission factors for the forest biomass burning category were also similar, ranging from 0.56-0.61 g BC/kg by Bond et al. (2004) to 0.81-1.53 g BC/kg by Liousse et al. (1996).

Table 2-2b presents emission factors for organic carbon (OC). No OC emissions were reported by Penner et al. (1993), Cooke and Wilson (1996), or Streets et al. (2003). OC emission factors for the on-road light-duty gasoline engine category ranged from 0.01 g OC/kg (Cao et al., 2006) to 0.73 g OC/kg (Cooke et al., 1999). While low end values showed large variations (0.01 g OC/kg [Cao et al., 2006] to 0.26 g OC/kg [Reddy and Venkataraman, 2002a]), the high end values were similar, ranging from 0.39 g OC/kg (Reddy and Venkataraman, 2002a) to 0.73 g BC/kg (Cooke et al., 1999). On-road light- and heavy-duty diesel engine emission factors varied by two orders of magnitude within the range of 0.03-6.7 g OC/kg by Cao et al. (2006). Intermediate values of 0.4-1.1, 0.86-1.66, 1.42, and 1-5 g OC/kg were reported by Bond et al. (2004), Reddy and Venkataraman (2002a), Liousse et al. (1996), and Cooke et al. (1999), respectively.

Only a single value (0.03 g OC/kg) was reported for off-road gasoline engine exhaust by Bond et al. (2004). For off-road diesel engines, Bond et al. (2004) reported emission factors of 0.84-1.6 g OC/kg, which is much higher than the 0.28 g OC/kg (for diesel locomotives) reported by Reddy and Venkataraman (2002a).

Variations in OC emission factors for coal-fired power plants were comparable to those for BC: 0-0.001 g OC/kg by Bond et al. (2004) to 3.9-7.8 g OC/kg by Liousse et al. (1996).

Liousse et al. (1996) reported the same values for domestic coal combustion as for coal power plants. For domestic coal combustion, low end values ranged from 0.12 g OC/kg (Cao et al., 2003) to 5.83 g OC/kg (Cooke et al., 1999), while high end values ranged from 4.3 g OC/kg (Bond et al., 2004) to 24.5 g OC/kg (Cooke et al., 1999).

Fireplace and woodstove biomass burning OC emission factors varied by over 20-fold, ranging from 0.41 g OC/kg (Reddy and Venkataraman, 2002b and Cao et al., 2006) to 7.8 and 9.7 g OC/kg (Bond et al., 2004 and Liousse et al., 1996, respectively). Boiler biomass burning OC emission factors were only reported by Bond et al. (2004), ranging from 0.18 to 3.2 g OC/kg. Agricultural burning OC emission factors from Cao et al. (2006; 0.47 – 0.73 g OC/kg) and Reddy and Venkataraman (2002b; 0.47 g OC/kg) fell into the range of 0.19 – 1.1 g OC/kg reported by Liousse et al. (1996). The highest value (3.3 g OC/kg) for agricultural burning was reported by Bond et al. (2004). Large variations in forest biomass burning were found for the OC emission factors between the two regional-scale (0.56 – 0.98 and 0.98 g OC/kg for Cao et al. [2006] and Reddy and Venkatamaran [2002b], respectively) and the two global-scale (5.2 – 8.0 and 16.5 g OC/kg for Bond et al. [2004] and Liousse et al. [1996], respectively) inventories.

In conclusion, there is a large degree of variation in BC and OC emission factors used in the existing global- and regional-scale emission inventories. Streets et al. (2003) reported the specific factors (central and maximum values) used to construct their inventory. This was also the case for Cooke et al. (1999) and Reddy and Venkataraman (2002a; 2002b). Bond et al. (2004) reported individual (central) values for stationary source and vehicle fuels and ranges of values in other cases. Cao et al. (2006) reported ranges of values for emission factors. But it is not clear how these emission factors were used to construct the inventory. It was difficult to extract the BC and OC emission factors from Liousse et al. (1996). For some sources, both the BC and OC fractions of particulate mass were specified while for other sources, only the BC fraction was given. In those cases, it was assumed that the OC fraction was one minus the BC fraction. The global emission inventories use different emission factors for developed and undeveloped regions and countries. This complicates the presentation of the data used to generate the inventories. These inventories are less than transparent to those unfamiliar with them.

2.2 General Methodology of Emission Inventories

The basis for BC, EC and OC emission inventories is conceptually the same as methodology used for other pollutants. In the U.S., comprehensive inventories have been developed for criteria (i.e., regulated) air pollutants, including carbon monoxide (CO), volatile organic compounds (VOCs), SO_2, nitrogen oxides (NO_x), and PM ($PM_{2.5}$ and PM_{10}). These procedures integrate the fundamental processes of the emission sources, the activities which produce those emissions, and the effects of emissions control. On-road mobile sources, for example, are generally assessed through travel-based emission factors and vehicle miles traveled (VMT) data for criteria air pollutants (Parrish, 2006; ARB, 2007). This approach associates mobile emissions with traffic patterns leading to better spatial and temporal resolution of emissions, which is critical for modeling the formation of photochemical pollutants such as ozone (O_3) and secondary organic aerosol (SOA). However, it has been shown that motor vehicle emission factors may be highly variable depending on the type of vehicle, its age and maintenance, and mode of operation (Fujita et al., 2007a; 2007b).

VMT is indirectly inferred from traffic monitoring and/or modeling. Alternatively, fuel consumption data can be obtained more easily and accurately. Fuel-based emission factors are available for point sources through extensive in-plume and remote sensing measurements, while mobile emissions are generally evaluated from dynamometer tests that do not directly relate to fuel consumption. On the other hand, CO_2 emissions from mobile sources are more accurately estimated from fuel-based activity: e.g., Inventory of California Greenhouse Gas Emissions and Sinks: 1990 - 2004 (California Energy Commission, 2006). Fuel consumption based emissions are common in global- and large-scale BC and OC inventories where detailed information on source activity is limited (Bond et al., 2004). Mobile source emission models like California's EMFAC2007 (http://www.arb.ca.gov/msei/onroad/latest_version.htm; ARB, 2007) estimate fuel consumption as well as emission factors and emission rates.

In general, the creation of a BC and OC emission inventory involves the following three steps (Klimont et al., 2002): 1) country-, sector-, or source-specific PM emission factors are obtained directly from measurements or from the literature; 2) The BC and OC fractions in PM (bulk PM and in some cases size-resolved) from various source categories are estimated using "source profiles", i.e., the fractional abundances of BC and OC measured in emissions from those or similar sources; and 3) BC and OC emissions are calculated according to Equation 2-1:

$$BC_{i,y} = \sum_{j,k,m} BC_{i,j,k,m,y} = \sum_{j,k,m} \underbrace{A_{i,j,k} EF_{i,j,k,y} \chi_{k,y} (1-\mathrm{eff}_{m,y})}_{\substack{\textbf{Match specific source} \\ \textbf{characterization code} \\ \textbf{(SCC)}}} X_{i,j,k,m} \qquad (2\text{-}1)$$

where:

$BC_{i,y}$ emissions of BC (or OC) in region i for particle size fraction y;

$BC_{i,j,k,m,y}$ emissions of BC (or OC) in region i, sector j, source k, and emission control technology m for particle size fraction y;

$A_{i,j,k}$ activity for a given region i, sector j, and source k (e.g., coal consumption in power plants or VMT for diesel trucks);

$EF_{i,j,k,y}$ emission factor of PM in region i, sector j, source k, and size fraction y (e.g., in units of grams per VMT or unit fuel consumed);

$\chi_{k,y}$ BC (or OC) fraction or abundance in PM of source k and size fraction y;

$\mathrm{eff}_{m,y}$ emission reduction efficiency of the emission control technology m for size fraction y, and;

$X_{i,j,k,m}$ actual implementation rate of the emission control measure for region i, sector j, source k and emission control technology m (e.g., percent of total coal combusted in power plants that are equipped with electrostatic precipitators).

If no emission controls are applied, the abatement efficiency equals zero (i.e., eff = 0) and the implementation rate is one (i.e., X = 1). In that case, the emission calculation is reduced to the product of the activity (A) and the emission factor (EF).

2.3 Global Emission Inventories: Top-Down Approach

As shown in Table 1-1, there are five reported global BC and OC emission inventories. The interest in global particulate carbon emission inventories arose from the need to estimate radiative forcing and its effect on global climate change. Development of a global BC and OC emission inventory is a daunting task because detailed information on emission sources, their emission factors, and activities is simply not available in much of the developing world. In such cases, large-scale demographic and air quality characteristics have been used to estimate BC and OC emissions.

Penner et al. (1993) examined the relationship between ambient BC and SO_2 concentrations in urban areas around the world. They observed that BC, or surrogates such as total carbon (TC) and “smoke shade” were well-correlated with SO_2 concentrations in source areas and that various source areas had characteristic ratios. They then transformed site-specific BC/SO_2 ratios to BC emissions using estimates for areal SO_2 emissions by country, which were more widely available. This led to a global BC inventory of 23.8 Tg BC/yr. Penner et al. (1993) also calculated global BC emissions based on fuel consumption, assuming constant emission factors of 1.0, 0.2, and 0.5% for domestic coal, diesel fuel, and wood and bagasse combustion, respectively. A global inventory of 12.6 Tg BC/yr was estimated from these emission factors and fuel consumption by country. While the two methods differed by a factor of two on a global basis, much greater differences were found for various countries and regions.

Cooke and Wilson (1996) estimated a global BC inventory for fossil fuel and biomass combustion. Estimates for biomass areal density, the amount of biomass above the ground and the fraction of it which burns, and emission factors for various types of biomass (e.g., forests of different types, savanna) were taken from the literature. Agricultural burning and biomass combustion for heating or energy were not considered. Fuel use estimates were made by country for industrial, domestic, and combined sectors for various solid, liquid, and gaseous fuels based on available statistics on consumption and production. Emission factors were taken from the literature. Gridded emissions within a country were distributed according to population density.

The final global BC inventory of 13.9 Tg BC/yr (8.0 and 6.0 Tg BC/yr from fossil fuel and biomass combustion, respectively) was about half that estimated by Penner et al. (1993) using the BC/SO_2 ratio approach (i.e., 23.8 Tg BC/yr), but similar to their inventory based on fuel consumption (i.e., 12.6 Tg BC/yr). Similarly, Liousse et al. (1996) developed BC and organic mass (OM = OC × 1.3) inventories for biomass burning (i.e., savanna and forest fires) but also included agricultural waste, wood fuel, and dung combustion. BC and OM emissions from domestic coal and diesel fuel combustion were also estimated. Fossil fuel combustion (6.6 Tg BC/yr) and biomass burning (5.6 Tg BC/yr) totaled 12.2 Tg BC/yr on a global basis, which was lower than the estimate of 13.9 Tg BC/yr from Cooke and Wilson (1996), who considered neither agricultural burning nor combustion of biomass for fuel and energy.

Cooke et al. (1999) developed a BC inventory for fossil fuel based on the European Centre Hamburg model (ECHAM4), a global climate model (GCM). The methodology for developing their BC inventory was similar to those used previously. However, they considered factors such as the relative ages of vehicles used in developed and developing countries and differences in the size of particles emitted by various controlled and uncontrolled combustion processes in estimating emission factors. They estimated a global BC inventory from fossil fuel combustion of 6.4 Tg BC/yr for bulk PM, consistent with estimates of 8.0 Tg BC/yr by Cooke and Wilson (1996) and 6.6 Tg BC/yr by Liousse et al. (1996). Such consistency must be due in part to similar sources for fuel use data and estimates for emission factors.

Streets et al. (2001) constructed a more detailed BC inventory for China which included fuel use by 37 different power generation, residential, agricultural burning, and mobile sources. Mobile sources were distinguished according to vehicle and fuel types. A detailed literature review was used to estimate geometric average and high end emission factors, and to consider emission controls and the failure of such controls. The level of detail used in Streets et al. (2001) was considerably greater than those seen in previous global or regional estimates. This is due to information available from the Chinese government on a provincial basis.

2.4 Global Emission Inventories: Bottom-Up Approach

Bond et al. (2004) presented a global BC and OC inventory as a “bottom-up” approach. They recognized that various combustion processes had different emission characteristics and attempted to characterize emissions from a variety of processes. They identified 50 different combinations of fuel type and usage and sub-divided these into processes with distinctly different emission characteristics. However, as with previous inventories, source activity levels were based on fuel consumption estimates from the International Energy Agency (IEA; http://www.iea.org/). At the within-country level, the activity for many processes was distributed according to population. Biomass burning activity levels were taken from previous references, direct observations, and/or government data. Emission factors were compiled from a variety of sources. Total global BC emissions were estimated to be 8 Tg BC/yr (Bond et al., 2004). Uncertainties were propagated in a quasi-statistical manner. As noted above, the estimated uncertainty was very high (4.3 – 22 Tg BC/yr). This raises the question of the value of using traditional statistical approaches to estimating uncertainties in complex emission models.

Equation 2-1 represents a “bottom-up” approach that has been applied to geographically detailed measures of emissions. Equation 2-1 may be modified to use other available data. In some source characterization studies, for instance, CO_2 is quantified with a higher precision than PM due to known sampling artifacts for either filterable or condensable PM concentrations (e.g., Lipsky and Robinson, 2006; England et al., 2007a; 2007b). EC/CO_2 ratios and CO_2 emission factors could then be used to develop BC emission inventories (Chen et al., 2001; Dickerson et al., 2002). In other cases such as in-plume sampling (Chen et al., 2006a; Watson et al., 2008a) with photoacoustic sensors, the b_{ap} emission factor is the only available measurement to be applied in Equation 2-1. Appropriate absorption efficiencies would have to be estimated and used to convert photoacoustic b_{ap} to BC concentrations.

2.5 U.S. EPA National Emission Inventory (NEI) for Criteria Air Pollutants

Equation 2-1 serves as the basis for constructing emission inventories for criteria air pollutants by the U.S. EPA and ARB. The U.S. EPA NEI is essentially a compilation of inventory data generated by the states. The state inventories represent a true "bottom-up" approach because they collect extensively detailed activity data for a vast array of stationary, area, and mobile sources on small geographical scales, i.e., counties and districts. In general, the development of the California BC and OC emission inventories can be based on existing detailed emission inventories for PM with appropriate modifications.

Over the past ten years, the U.S. EPA has revised its methodologies to develop the NEI for criteria pollutants and hazardous air pollutants (HAPs) and to allow for an evaluation of changes in emissions from year to year. The NEI is a bottom-up inventory in which emissions are derived for point and area sources at the county level, and are useful in many applications such as providing inputs for atmospheric transport and air quality models. Starting with the National Air Pollutant Emission Trends, 1900-1998 (i.e., Emission Trends) report (U.S. EPA, 1993) and updated through 2006 (U.S. EPA, 2008a), the U.S. EPA began to incorporate these methodological changes. The county-based emission estimates enable the U.S. EPA to incorporate detailed emissions from state and local government agencies. Large source categories identified by the U.S. EPA include: 1) fuel combustion - electric utility, industrial, and other combustion (i.e., commercial/institutional and residential); 2) solvent utilization; 3) on-road vehicles; 4) non-road engines and vehicles; 5) fugitive dust; and 6) biogenic sources. Note that these categories include all major known sources of $PM_{2.5}$ and PM_{10}, both of which may contain BC and OC.

For most source categories, the U.S. EPA has compiled emission estimates at the county level for sources characterized by Source Classification Codes (SCCs) and then summed these emissions to the Tier level. The Tier categorization contains up to four levels corresponding to four SCCs (i.e., SCC1 to SCC4) with SCC1 representing the most general source characteristic and SCC4 representing the most specific source characteristic. SCC1 and SCC2 contain two characters each, while SCC3 and SCC4 contain three characters each. For example, the SCC code “2801500002” corresponds to an agricultural burning source where: 1) SCC1 (28) represents “Miscellaneous Area Sources”; 2) SCC2 (01) represents “Agricultural Production – Crops”; 3) SCC3 (500) represents “Agricultural Field Burning – Whole Field Set on Fire”; and 4) SCC4 (002) represents “Anthropogenic” source. A major source of emission factors is the “Compilation of Air Pollutant Emission Factors, Volume I, Stationary, Point, and Area Sources,” known as AP-42 (U.S. EPA, 1991). The Factor Information REtrieval (FIRE) Data System (http://www.epa.gov/ttn/chief/software/fire/index.html) assigns emission factors to each SCC source to facilitate the emission calculations.

Improvements to the NEI involve reviewing and updating emission factors periodically and matching emission composition profiles (i.e., source profiles) with the SCCs and/or higher Tier source categories. The FIRE 6.25 Data System represents the most comprehensive collection of emission factors (including AP-42, fifth edition). It currently contains 506 records of filterable $PM_{2.5}$ emission factors updated through September 2004. The most comprehensive $PM_{2.5}$ source profile database developed by the U.S. EPA is the SPECIATE version 4.0 model (http://www.epa.gov/ttn/chief/software/speciate/index.html). The source profiles were compiled from numerous studies by various institutions around the country over many years. *However, there is not yet a specified procedure for associating source profiles with pollution sources in the NEI.*

The U.S. EPA uses MOBILE models to generate emission factors for on-road mobile sources. For PM, the emission factors are expressed in units of grams per VMT. The most recent model, MOBILE 6.2 (http://www.epa.gov/otaq/m6.htm), is capable of estimating not only $PM_{2.5}$ from 28 vehicle types but also EC and OC from diesel-fueled vehicles. One of the disadvantages of MOBILE 6.2 model calculated $PM_{2.5}$ emission factors is that they reflect only vehicle type and age and ignore the influences of fuel type, driving mode, and maintenance (McCarthy et al., 2006). Development of the MOtor Vehicle Emission Simulator (MOVES; by the U.S. EPA) is underway to address these inadequacies (http://www.epa.gov/otaq/ngm.htm). MOVES, when completed, will estimate energy consumption, include a broad array of advanced technology vehicles, and model periods of extended idling by heavy-duty vehicles. Both mileage-based and fuel/energy-based emission factors will eventually be available from MOVES. Using total VMTs per state, the U.S. EPA allocates VMT by county, roadway type, and vehicle type for each year. Each state and county combination in the output files contains 96 assigned SCCs representing six rural and six urban roadway types and eight vehicle types. Instead of using the MOBILE 6.2 model, each of the SCCs could be matched with current emission factors and source profiles such as those measured in the Department of Energy (DOE) sponsored Gasoline/Diesel PM Split Study (i.e., Gas/Diesel Split Study; Fujita et al., 2007a; 2007b) and Kansas City Study (U.S. EPA, 2008b; 2008c).

The U.S. EPA estimates non-road vehicle emission with its NONROAD model (http://www.epa.gov/oms/nonrdmdl.htm). This model covers emissions from over 260 specific equipment types within ten broad categories: 1) airport ground support; 2) agricultural; 3) commercial; 4) construction and mining; 5) industrial; 6) lawn and garden; 7) lodging; 8) railway maintenance; 9) recreational vehicles; and 10) recreational marine equipment. Emission factors embedded in the NONROAD model result from Tier I and Tier II engine test certification data (in g/hp-hr) adjusted to engine deterioration, fuel sulfur, Reid vapor pressure (RVP), ambient temperature, etc. PM fractions in the emissions were retrieved from other tests. However, evaluations of the uncertainty of emissions determined from the NONROAD model are scarcer than those for the MOBILE models. This study has compiled PM EC and OC emission factors from a substantial number of non-road vehicles that could be used for model validation. The NONROAD model also provides estimates of activity data for specific scenarios (e.g., geographic allocation, seasonal correction, etc). In its final form, the MOVES model is expected to replace the MOBILE and NONROAD models, estimating emissions for both on-road and non-road mobile sources, covering a broad range of pollutants, and allowing multiple scale analysis, i.e., from fine-scale analysis to national inventory development.

2.6 California Emission Inventory for Criteria Air Pollutants

ARB has developed a comprehensive emission inventory analogous to the NEI. The ARB emission inventory (http://www.arb.ca.gov/ei/emissiondata.htm) groups air pollution sources into five major categories: stationary, area, on-road mobile, off-road mobile, and natural. This classification is similar to the U.S. EPA system but with minor differences. Wildfires are considered as natural sources in the ARB inventory but an area source in the NEI.

For stationary sources, each of the 35 local air districts estimates the emissions within its jurisdiction. ARB then compiles this information and makes it accessible to the public through a web-based "Facility Search" tool (http://www.arb.ca.gov/app/emsinv/facinfo/facinfo.php). Most of the districts maintain a computer database with detailed information on point sources. Almost all facilities emitting more than 2.5 tons/year of any air pollutant are included. Emissions are calculated using detailed data for each of the facilities by various processes. Each source is assigned an emission inventory code (EIC). These are analogous to and cross referenced with the SCCs in the NEI. Thus, emission data from the California inventory are transmitted directly to the NEI. Emissions from area sources such as biomass burning and fugitive dust are grouped into categories and calculated based on surrogate variables. Of the more than 500 area source categories established by ARB, each district is responsible for estimating emissions from approximately 100 categories. Emissions for the remaining approximately 400 categories are estimated by ARB based on statewide data. The emission factors used for stationary and area sources are consistent with those from the U.S. EPA FIRE data system, unless better or more source-specific factors are available from other studies.

ARB developed and maintains the Emission FACtor model (EMFAC, http://www.arb.ca.gov/msei/onroad/latest_version.htm) to estimate on-road mobile emissions of criteria pollutants. The current version, EMFAC2007, estimates emissions (over a specific period of time), emission factors, and fuel consumption for model year 1965 and newer vehicles, powered by gasoline, diesel, or electricity. Maintenance history is also included. EMFAC2007 produces emission inventories by location, environmental conditions (temperature and relative humidity), and time, including the past, present, and future from 1970 to 2040. A detailed breakdown of technology groupings is available as default values in the model and can be modified by the user. Similar to the U.S. EPA MOBILE model, the EMFAC model is based on travel-based emission factors, for example, grams of PM per VMT. The MOBILE6.2 model generally predicts lower emission factors than EMFAC for un-maintained heavy-duty diesel vehicles, although both models produce agreement (within an order of magnitude) with dynamometer tests under the Federal Test Procedure (FTP) cycle (Fujita et al., 2007b).

ARB's off-road emission inventory is estimated with the OFFROAD model (http://www.arb.ca.gov/msei/offroad/offroad.htm). This model estimates the number, activity, and emissions of the various types of off-road equipment. The major categories of stationary engines and off-road vehicles represent agricultural activities, construction, lawn and garden maintenance, and off-road recreation. The OFFROAD model is used to estimate the relative contribution of gasoline-, diesel-, compressed natural gas-, and liquefied petroleum gas-powered vehicles to the overall emission inventory of the state. Activity levels are estimated from vehicle registration data, inspection and maintenance (I/M) testing, and fuel consumption in the case of some off-road sources.

While on-road and off-road emissions are estimated by ARB using the EMFAC and OFFROAD models, respectively, emissions from stationary and area sources are calculated by district agencies, transmitted to ARB, and incorporated in the state-wide inventory. For stationary and area sources, the districts are required to provide emissions only, not the emission factors and activity data used to estimate them. However, estimates made by local agencies are rigorous. Before 2000, emission factors for agricultural burning in California were taken from AP-42. Subsequently, emission factors based on more current experimental data from Jenkins et al. (1996) were circulated by ARB and recommended for use by the districts with the caveat that the districts could use different emission factors more specific to their specific regions and activities. Scarborough et al. (2002) prepared an inventory for statewide emissions from agricultural burning in California. They employed a consistent set of emission factors for various fuels from AP-42 and Jenkins et al. (1996), as recommended by ARB. Activity data were obtained from burning permit databases maintained by local county and air districts. *It is clear that the current California emission inventory provides the most detailed and comprehensive assessment of PM ($PM_{2.5}$ and PM_{10}) emissions in California.*

2.7 Greenhouse Gas (GHG) Emission Inventories

GHG emissions, mainly for CO_2, are related to fuel consumption but depend less on specific combustion process than do PM and BC emissions. The U.S. EPA State Greenhouse Gas Inventory Tool (SGIT; http://www.epa.gov/climatechange/emissions/state_guidance.html) establishes the following source sectors for calculating GHG emissions: 1) utility generation (fossil and bio-fuel); 2) industrial/commercial/residential fuel consumption; 3) transportation; 4) fossil fuel industry (direct emission); 5) industrial processes; 6) waste management; and 7) agriculture (including agriculture burning). Sectors 1-3, 6, and 7 are potentially major PM, BC and OC sources. Sectors 1 and 2 contain stationary and area sources, respectively. Sector 6 contains both stationary (e.g., waste incineration) and area (e.g., open burning) sources, while Sector 7 represents mainly area sources. Since most of the fossil and biomass fuel is converted to CO_2 during combustion, the CO_2 emission factors depend only on the fuel combustion efficiency and its carbon content.

The transportation sector (Sector 3) is equivalent to on-road mobile sources in the criteria air pollutants emission inventory. CO_2 emissions from this sector are estimated from on-road gasoline- and diesel-fueled vehicle consumption, since fuel-based emission factors are much more accurate than travel-based emission factors in this case. Although the VMT is not explicitly used in the calculation, it may serve as a basis for forecasting fuel consumption in the future. Fuel-based emission factors are not available for CH_4 and nitrous oxide (N_2O), but there have been numerous studies, including this study, focused on acquiring fuel-based emission factors for BC and OC (e.g., Grieshop et al., 2006; Chen et al., 2007).

ARB has developed an extensive GHG inventory for CO_2, CH_4, and N_2O that is consistent with IPCC and U.S. EPA requirements (California Energy Commission, 2006). The inventory contains hundreds of sources consistent with the IPCC format in four main categories: 1) energy; 2) industrial processes and product use; 3) agriculture, forestry, and other land use; and 4) waste. If California was a country, its GHG emissions would rank 16th in the world. While California emits more GHG than any other state except Texas, its per capita emissions were the fourth lowest of any state in 2001 (California Energy Commission, 2006).

Figure 2-1 shows trends in California's GHG emissions from 1990 to 2004 (California Energy Commission, 2006). While California's economy grew by 83% over this period, GHG emissions increased by only 12%. In 2004, 41% of California's GHG emissions came from the transportation sector. Fossil fuel combustion accounts for the majority (96%) of California's CO_2 emissions. These emissions are estimated from fuel consumption data supplied by the U.S. Energy Information Administration (EIA; http://www.eia.doe.gov/) and the California Energy Commission (http://www.energy.ca.gov/). The fuel use data is converted to energy consumption and applied emission factors are expressed as mass of carbon per British Thermal Unit (BTU) obtained from the U.S. EPA (2003).

Using Chemical Mass Balance (CMB) receptor modeling, Chow et al. (2007b) attributed only ~20% of primary $PM_{2.5}$ to mobile sources in Fresno during the winter of 2000-2001; residential wood combustion (RWC) emissions accounted for 40% of primary $PM_{2.5}$. This mismatch illustrates that CO_2 emissions depend more on fuel consumption rather than the specific combustion process while the converse is true of $PM_{2.5}$ and, by extension, BC and OC, which are the major components of particulate motor vehicle exhaust and biomass combustion emissions. While the EMFAC and OFFROAD models estimate CO_2 and CH_4 emissions as well as those of criteria pollutants, neither model is currently incorporated into California's GHG inventory.

2.8 Comparison of the $PM_{2.5}$ and BC Emission Inventories

It is useful to examine the consistency between the ARB $PM_{2.5}$ emission inventory and a global BC inventory such as that described by Bond et al. (2004). The ARB inventory is available on-line (http://www.arb.ca.gov/app/emsinv/emssumcat.php). This web-based tool was used for this study to generate a statewide $PM_{2.5}$ emission inventory for 1995 that includes natural sources such as wildfires. Table 2-3 presents the major source categories and associated annual $PM_{2.5}$ emissions for 1995. The total $PM_{2.5}$ emissions were 266,581 tons/yr. Residential fuel combustion (40,067 tons/yr) and managed (agricultural) burning and disposal (33,725 tons/yr) accounted for 28% of the total. Mobile on-road (23,555 tons/yr) and mobile other (28,563 tons/yr) emissions together accounted for 20% of the total. Paved road dust (20,781 tons/yr), unpaved road dust (18,962 tons/yr), and fugitive windblown dust (17,591 tons/yr) together accounted for 22% of the total. Wildfires (15,901 tons/yr) accounted for only 6% of the total. The paved road dust contribution is much larger than the 0.1% estimated by the CMB model in Fresno during winter of 2000-2001 (Chow et al., 2007b). Bond et al's. (2004) global BC inventory for 1996 (labeled as "present day") was obtained on-line (http://cee.uiuc.edu/research/bondresearch/). The data are presented for 1° x 1° grid cells. Annual BC emissions for grid cells covering California were 33,281 tons BC/yr. The overall ratio of $BC/PM_{2.5}$ is thus 0.12. As will be demonstrated in Section 4.0, this ratio is comparable to within about a factor of three to the EC source profile composition of many of the combustion sources in California.

Table 2-1. Summary of data sources for black carbon and organic carbon emission inventories.

	Carbon Emission Inventory Reference	Region and Resolution (Base Year)	Emission Source Categories	Source of Emission Factors	Source of Activity Data
I	Penner et al. (1993) Black Carbon Only	Global, based on 18 regions 5° x 5° (1980)	Not specified.	Not used	BC emissions based on regional BC/SO_2 ratios derived from BC measurements and SO_2 emissions from Benkovitz (1982), Hameed and Dignon (1988), Lubkert and de Tilly (1989), and Organization for Economic and Cooperative Development/International Energy Agency (OECD/IEA; 1989a; 1989b). No OC data available.
II	Liousse et al. (1996) Black Carbon and Organic Carbon	Global 4.5° x 7.5° (1980)	Nine different fuel types, subcategorized by country level of development (i.e., developed and developing).	Literature review	Based on the literature and global distribution of fuel wood sources and agriculture crops from Food and Agriculture Organization (1991).
III	Cooke and Wilson (1996) Black Carbon Only	Global 1° x 1° (1984)	Fossil fuel and biomass burning.	Literature review	Literature review on biomass coverage and area burned. Fuel use for solid, liquid, and gaseous fuels for domestic, industrial, and other source categories was compiled from United Nations Statistical Division data and national statistical offices. No OC data was analyzed.
IV	Cooke et al. (1999) Black Carbon and Organic Carbon	Global 1° x 1° (1984)	Twenty-one different fuel types, subcategorized by country level of development (i.e., developed, semi-developed, and under-developed) and by energy sector (i.e., domestic, industry, and traffic).	Literature review	Seasonality of fossil fuel combustion from Rotty (1987). Fossil Fuel consumption published by United Nations (1993).

Table 2-1. Continued

	Carbon Emission Inventory Reference	Region, Resolution, and Base Year	Source Categories	Source of Emission Factors	Activity Data Source
V	Bond et al. (2004) Black Carbon and Organic Carbon	Global 1° x 1° (1996)	3 main categories (i.e., fossil fuels, biofuels, and biomass burning) sub-categorized into 14 sectors, including: power generation, industry, residential, and transportation.	Literature review U.S. EPA AP-42 U.S. EPA SPECIATE version 3.1	International Energy Agency (http://www.iea.org/) for total energy usage by country, fuel type, and different sectors (International Energy Agency, 1998a; 1998b). Grid emissions by proxy (e.g., population, forest/ savanna/agriculture coverage times fire counts, etc) on the country level, except for United States, China, and India (state/province).
VI	Reddy and Venkataraman (2002a; Fossil Fuel) Reddy and Venkatamaran (2002b; Biomass Combustion) Black Carbon and Organic Carbon	India 0.25° x 0.25° (1996-1997)	4 utilities, 5 coal combustion, 8 industrial, 2 residential/commercial, 8 transportation, and 4 biomass/biofuels burning categories.	Literature review U.S. EPA AP-42 Customized emission factors to fit Indian technology	Fossil fuel consumption from Central Board of Irrigation and Power (1997), Cement Manufacturers' Association (1999), Centre for Monitoring of India Economy (1999), The Fertiliser Association of India (1998), Ministry of Coal (1997), Ministry of Industry (1998), and Ministry of Petroleum and Natural Gas (1998), Statistics for Iron and Steel Industry in India (Steel Authority of India, 1998). Biofuel consumption in rural and urban from Tata Energy Research Institute (Joshi et al., 1992) and National Sample Survey (1996). Forest coverage from Forest Survey of India (1998).

Table 2-1. Continued

	Carbon Emission Inventory Reference	Region, Resolution, and Base Year	Source Categories	Source of Emission Factors	Activity Data Source
VII	Streets et al. (2003) Black Carbon Only	Asia 1° x 1° to 0.08° x 0.08° (2000)	Each of the 22 Asia countries (plus international shipping) has power generation, industry, and domestic sectors divided into 3 categories (i.e., coal, oil or biofuel, and other), 10 transportation categories, and 3 biomass burning categories.	Literature review U.S. EPA AP-42 MOBILE 5 model	RAINS-Asia simulation (2000 forecast from the 1995 base year), except for China, which was based on Sinton and Fridley (2000) on a provincial basis. For transportation sector, used World Road Statistics (International Road Federation, 2000) and World Motor Vehicle Data (American Automobile Manufacturers Association, 1998).
VIII	Cao et al. (2006) Black Carbon and Organic Carbon	China 0.2° x 0.2° (2000)	Includes 5 sectors (i.e., power generation, industry, residential, transportation, and biomass burning) separated by 363 large point (including 285 power plants) and area sources (e.g., population, gross domestic product) with 18 different sector-fuel type combination.	Literature review Laboratory tests of biofuel emissions from cooking stoves	Point source activity from State Power Corporation of China (2001) and Editorial Board of China Rural Energy Yearbook (2001). Area sources activity from National Bureau of Statistics and various government agencies, mainly at the county level.

Table 2-2. Summary of: a) black carbon and b) organic carbon emission factors for combustion sources among the global and regional emission inventories.[a]

a)	**Black Carbon (BC) Emission Factors (g/kg)**					
	Global-scale			**Regional-scale**		
	II	**IV**[b]	[c]	**VI**	**VII**[d]	**VIII**
	Liousse et al. (1996)	**Cooke et al. (1999)**	**Bond et al. (2004)**	**Reddy and Venkataraman (2002a, 2002b)**	**Streets et al. (2003)**	**Cao et al. (2006)**
Emission Source Categories[e]		**V**				
On-road Light-Duty Gasoline (LDG) Engine	NA	0.03 - 0.15	0.08 - 0.43	0.05 - 0.08	0.08[f]	0.006-0.08[f]
On-road Light-Duty Diesel (LDD) Engine	0.4[f]	2 – 10[f]	1.3 - 3.6[f]	2.42	1.1[f]	0.11 – 2[f]
On-road Heavy-Duty Diesel (HDD) Engine	0.4[f]	2 – 10[f]	1.3 - 3.6[f]	1.93	1.1[f]	0.11 – 2[f]
Off-road Gasoline Engine	NA	NA	0.1	NA	0.08[f]	
Off-road Diesel Engine	NA	0.35 - 2.0	0.34 – 3.7	0.29[g]	1.1[f]	
Coal-fired Power Plants	1.1 – 2.2	0.149 - 1.98	0.002 – 0.009	0.077	0.0001 – 0.032	0.003 - 0.32
Coal – Domestic	1.1 – 2.2	1.39 - 4.1	0.76-5.4	0.18-1.83	0.12 – 3.7	0.12 -5
Biomass - Fireplace and Woodstove	1.32	NA	0.3 - 1.4	0.41	1 NA	0.41 - 1.0
Biomass – Boiler	NA	NA	0.044 – 0.55	NA	NA	NA
Biomass – Agriculture	0.06 - 0.10	NA	1	0.47	NA 0.58-0.90	0.5 - 1.2
Biomass – Forest	0.81 - 1.53	NA	0.56 - 0.61	0.98	NA	0.56 - 0.98
Reported Uncertainties	No	No	Yes	No	Yes	No

[a] Category-specific BC and OC emission factors are only available for six and five of the eight inventories, respectively, listed in Table 2-1.

[b] Cooke et al. (1999), Tables 3a and 4.

[c] Bond et al. (2004), Tables 9 and 10.

[d] Central values for 1995.

[e] These categories may contain one or more subcategories from the emission inventories.

[f] Based on fuel type (gasoline and diesel), no distinction was made between light-duty gasoline and diesel (i.e., LDG and LDD) engines.

[g] Rail locomotives.

Table 2-2. Continued.

b)	Organic Carbon (OC) Emission Factors (g/kg)				
	Global			**Regional**	
	II	**IV**[b]	[c]	**VI**	**VIII**
	Liousse et al. (1996)	**Cooke et al. (1999)**	**Bond et al. (2004)**	**Reddy and Venkataraman (2002a, 2002b)**	**Cao et al. (2006)**
Emission Source Categories[a]					
On-road Light-Duty Gasoline (LDG) Engine	NA	0.07 - 0.73	0.19 - 0.54	0.26-0.39	0.01-0.5[d]
On-road Light-Duty Diesel (LDD) Engine	1.42[d]	1 – 5[d] **V**	0.4-1.1[d]	0.86	0.03 – 6.7[d]
On-road Heavy-Duty Diesel (HDD) Engine	1.42[d]	1 – 5[d]	0.4-1.1[d]	1.66	0.03 – 6.7[d]
Off-road Gasoline Engine	NA	NA	0.03	NA	NA
Off-road Diesel Engine	NA	NA	0.84 – 1.6	0.28[e]	
Coal-fired Power Plants	3.9-7.8	0.2 – 5.48	0-0.001	0.19-0.33	0.25
Coal – Domestic	3.9-7.8	5.83-24.5	0.4-4.3	3.9-10.2	0.12 -5
Biomass - Fireplace and Woodstove	9.7	NA	1.7-7.8	0.41	0.41 - 1.0
Biomass – Boiler	NA	NA	0.18 – 3.2	NA	NA
Biomass – Agriculture	0.19 - 1.1	NA	3.3	0.47	0.47 - 0.73
Biomass – Forest	16.5	NA	5.2-8.0	0.98	0.56 - 0.98
Reported Uncertainties	No	No	Yes	No	No

NA

[a] These categories may contain one or more subcategories from the emission inventories.

[b] Cooke et al. (1999), Tables 3a and 4.

[c] Bond et al. (2004), Tables 9 and 10.

[d] Based on fuel type (gasoline and diesel), no distinction was made between light-duty gasoline and diesel (i.e., LDG and LDD) engines.

[e] Rail locomotives.

Table 2-3. Statewide $PM_{2.5}$ emissions for major sources generated with the ARB emission inventory for 1995.[a]

Source Category	$PM_{2.5}$ Emissions (tons/yr)
• ***Fuel Combustion***	
Electric Utilities	1,504
Cogeneration	1,368
Oil and Gas Production	519
Petroleum Refining	2,045
Manufacturing and Industrial	2,617
Food and Agricultural Processing	1,243
Service and Commercial	2,107
Other	1,411
Total	12,816
• ***Waste Disposal***	
Sewage Treatment	1
Landfills	1,179
Incinerators	19
Soil Remediation	6
Other	56
Total	1,261
• ***Cleaning and Surface Coating***	
Coatings and Related Process Solvents	87
Printing	20
Other	1
Total	109
• ***Petroleum Production***	
Oil and Gas Production	18
Petroleum Refining	1,102
Petroleum Marketing	32
Total	1,152
• ***Industrial Processes***	
Chemical	1,647
Food and Agriculture	3,057
Mineral Processes	9,585
Metal Processes	512
Wood and Paper	2,881
Glass and Related Products	626
Electronics	1
Other	4,394
Total	22,703
• ***Solvent Evaporation***	
Asphalt Paving/Roofing	11
• ***Miscellaneous***	
Residential Fuel Combustion	40,067
Farming Operations	15,539
Construction and Demolition	6,053
Paved Road Dust	20,781
Unpaved Road Dust	18,962
Fugitive Windblown Dust	17,591
Fires	381
Managed Burning and Disposal	33,725
Cooking	7,223
Other	188
Total	160,509
• ***Mobile (On-Road)***	
Light-duty Passenger	3,033
Light-duty Trucks	2,331
Medium Duty Trucks	438
Light Heavy-duty Gas Trucks	150
Medium Heavy-duty Gas Trucks	38
Heavy Heavy-Duty Gas Trucks	16
Light Heavy-duty Diesel Trucks	133
Medium Heavy-duty Diesel Trucks	1,553
Heavy Heavy-duty Diesel Trucks	15,425
Motorcycles	70
Heavy-duty Diesel Urban Buses	148
Heavy-duty Gas Urban Buses	1
School Buses	128
Other Buses	62
Motor Homes	30
Total	23,555
• ***Mobile (Other)***	
Aircraft	3,627
Trains	1,390
Ships and Commercial Boats	5,666
Recreational Boats	1,622
Off-road Recreational Vehicles	460
Off-road Equipment	12,518
Farm Equipment	3,280
Total	28,563
• ***Natural Sources***	
Wildfires	15,901
Grand Total (tons/yr)	**266,581**

[a] Calculated emissions based on the ARB on-line website tool (http://www.arb.ca.gov/app/emsinv/emssumcat.php).

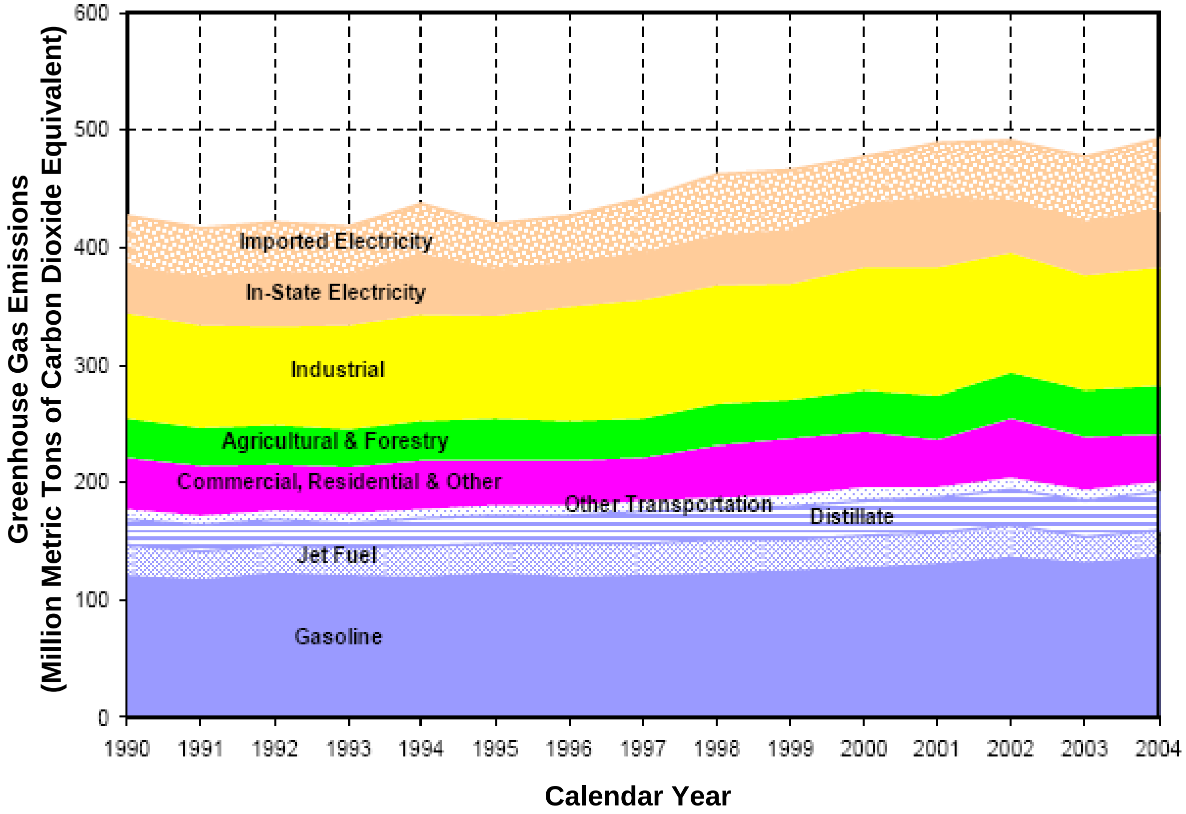


Figure 2-1. California's gross greenhouse gas (GHG) emissions trends from 1990 to 2004 (adapted from California Energy Commission, 2006).

3. EMISSION FACTORS

Emission factors in the California emission inventory were derived from a variety of sources. Some have been measured directly and some are estimated using models such as EMFAC2007 (for on-road mobile sources) and OFFROAD (for off-road or non-road sources). In this section, emission factors measured during several recent studies for mobile (i.e., Gas/Diesel Split; Kansas City; and Strategic Environmental Research & Development Program [SERDP] Studies), as well as biomass burning and RWC (FLAME at Missoula, MT) sources are compared with those used in the California emission inventory. Emission factors derived from the DRI laboratory testing for the diesel engine and wood smoke emissions as part of Phase I of this study (Chow et al., 2006d) are also summarized for comparison. These recent studies are more relevant than older emission factor reports owing to fleet penetration of engine designs, upgraded fuel formulations, and improved emission controls.

3.1 On-Road Gasoline and Diesel Emission Factors

The Gas/Diesel Split Study (Fujita et al., 2007a; 2007b) measured $PM_{2.5}$ mass and speciated inorganic and organic compound emission rates from 59 light-duty (including 57 gasoline- and 2 diesel-fueled vehicles) and 30 medium- and heavy-duty diesel-fueled vehicles. The vehicle emission tests were conducted at the Ralphs Grocery distribution center in Riverside, CA, during the summer of 2001 (June 2-23 for light-duty diesel- and gasoline-fueled vehicles and July 20 to September 19 for heavy-duty diesel-fueled vehicles). Emissions were determined with a “constant volume sampling system” (CVS) and continuous monitors for CO, CO_2, total hydrocarbons (THC), and NO_x. CVS emission factors are based on total emissions from tailpipe per vehicle mile traveled. Details of the testing program that are pertinent to the development of motor vehicle exhaust composition profiles are summarized in Fujita et al. (2007a; 2007b). The vehicles were operated on mobile dynamometers, whereas filter-based and continuous mass and chemical measurements were made on individual and/or composite vehicle emissions.

Emission data were aggregated for groups of vehicles with similar model year and odometer mileage. $PM_{2.5}$ emission rates were then estimated using the U.S. EPA MOBILE 6.2 and the ARB EMFAC2007 emission models under conditions corresponding to those in the Gas/Diesel Split Study (Fujita et al., 2007a; 2007b).

The MOBILE 6.2 and EMFAC2007 models are macroscopic emission models and are different in some respects (Rakha et al., 2003). As discussed in Section 2, for a particular calendar year and vehicle type/weight, the MOBILE 6.2 model only takes into account the vehicle model year (i.e., age of vehicle) while the EMFAC2007 model considers technology group and odometer mileage (i.e., design and usage of vehicle) in addition to model year. The MOBILE 6.2 model estimates particulate OC, EC, sulfate ($SO_4^=$), and lead (Pb) emissions from the tailpipe of diesel-fueled vehicles as well as contributions from brake and tire wear. The same parameters are estimated for gasoline-fueled vehicles except that the PM emission factor (i.e., GASPM, no specified size fraction) replaces OC and EC, assuming the EC fraction is minor in gasoline-fueled vehicle exhaust. The EMFAC2007 factor estimates non-speciated PM_{10} and $PM_{2.5}$ emission factors. To facilitate inter-comparisons of the model estimates with dynamometer measurements, which only account for tailpipe emissions, MOBILE 6.2 $PM_{2.5}$ emission factors are calculated from the sum of OC + EC + $SO_4^=$ + Pb for diesel-fueled vehicles and the sum of GASPM + $SO_4^=$ + Pb for gasoline-fueled vehicles.

Engine exhaust emissions depend on driving conditions. U.S. EPA established the FTP (Federal Register, 1996) to serve as a standard for regulatory emission testing of motor vehicles. A typical FTP consists of three phases: 1) cold start; 2) hot start; and 3) warm start, based on which the state-of-the-art MOBILE 6.2 and EMFAC2007 models were developed. However, during the Gas/Diesel Split Study, gasoline-fueled vehicles were tested with a unified driving cycle (UDC) that include FTP and an additional transient phase following the hot start (Fujita et al., 2007b). The first two phases of UDC are measured as “Cold Start (CS)” and the next two phases are measured as “Warm Start (WS)”. The true FTP emission factors are expected to be between the CS and WS emission factors. HDDV emissions from the FTP warm start test are based on the Urban Dynamometer Driving Schedule (UDDS). Several driving cycles besides UDDS were examined during the Gas/Diesel Split Study, such as: Cold City-Suburban Route (CCS), Hot City-Suburban Route (HCS), Highway Cycle (HW), and Manhattan Cycle (MC for transit buses).

Since factors from the Gas/Diesel Split Study consist of more than one vehicle, MOBILE 6.2 and EMFAC2007 model estimates are presented as ranges. Model estimates and observed $PM_{2.5}$ emission factors for diesel-fueled vehicles are presented in Figure 3-1. The emission estimates were determined for individual vehicles, and then the ranges of emissions for a sample composite are reported. Table 3-1 summarizes the vehicle composites of different vehicle test cycles and vehicle model years, as well as the vehicle categories (i.e., weight class) assigned to the MOBILE 6.2 and EMFAC2007 models. It includes 23 gasoline composites tested under CS and WS cycles and 17 diesel composites tested under various cycles. Since the HCS driving cycle is the only common cycle for all diesel vehicles (Table 3-1), $PM_{2.5}$ emissions quantified under HCS are compared with MOBILE 6.2 and EMFAC2007 model estimates (for FTP cycle) in Figure 3-1 with the understanding that other cycles may produce substantially different results (e.g., Fujita et al., 2007b).

Figure 3-1 shows that the EMFAC2007 model slightly overestimated the diesel emissions during the Gas/Diesel Split Study, especially for low emitters, but the overall agreement is reasonable ($r^2 = 0.8$) considering the variability among individual vehicles. The MOBILE 6.2 model underestimated diesel emissions, especially for high emitters, but they are within the same order of magnitude and show a reasonable correlation ($r^2 = 0.63$) with the Gas/Diesel Split Study measurements. Little difference was found for the minimum and maximum estimates by the MOBILE 6.2 model.

Both the MOBILE 6.2 and EMFAC2007 models estimated the increase of diesel $PM_{2.5}$ emissions with vehicle age (i.e., the difference between vehicle model year and the calendar year [2001] as shown in Figure 3-2). The narrower range of MOBILE 6.2 model estimates (0.1 to 1.8 g/mile), as compared to EMFAC2007 (0.3 to 2.1 g/mile) for all except urban buses is consistent with its neglecting the vehicle mileage traveled and different diesel technology groups. Figure 3-3 shows inter-cycle comparisons for typical medium- ($\geq$14,001 – 33,000 lbs) and heavy- (>33,000 lbs) duty vehicles. Both cold city- and hot city-suburban route (i.e., CCS and HCS, respectively) cycles produce similar emission factors, and they are about double those of the highway (HW) cycle emission factors. It should be noted that the FTP (i.e., UDDS) cycle was also run on the heavy-duty diesel vehicle (i.e., CI-9e in Table 3-1) producing emission factors slightly lower than the CCS or HCS cycles, but within 20%.

Gasoline-fueled vehicles tested during the Gas/Diesel Split Study (Fujita et al., 2007a; 2007b) are either passenger vehicles (LDA) or light-duty trucks (LDT). They are often mixed in a sample composite. The MOBILE 6.2 and EMFAC2007 models do report different emission factors for LDA and LDT, and therefore wider ranges of emission estimates could be anticipated. The comparisons in Figure 3-4 show that the measured emission factors for either CS or WS are more variable than model estimates, especially for vehicles manufactured before 1989 (i.e., Figure 3-4a). A few high-emitting vehicles (often referred to as smokers) produce clear outliers (e.g., SI_9_4 [model year 1980, 98,000 miles], SI_8_3 [model year 1984, 167,000 miles], and SI_10_4 [model year 1988, 149,000 miles]). On the other hand, vehicles SI_9_1 (model years 1979-1980, 159,000-182,000 miles), SI_7_1 (model years 1986-1989, 92,000-418,000 miles), and all vehicles manufactured after 1995 are cleaner than model estimates.

CS emissions were generally higher than WS emissions with a few exceptions. Compared to Figure 3-1, Figure 3-5 confirms that gasoline-fueled vehicles emit one to two orders of magnitude lower PM emissions than the diesel-fueled vehicles and that both the MOBILE 6.2 and EMFAC2007 models fail to capture the large variabilities in the gasoline-fueled vehicle emissions (e.g., low correlations between measured and model estimated values). It is likely that gasoline-fueled vehicle emissions are more sensitive to other factors such as engine design and vehicle maintenance.

Prior studies suggest that gasoline-fueled vehicles are responsible for a substantial portion of $PM_{2.5}$ emissions from on-road mobile sources since they greatly outnumber diesel vehicles (Gertler, 2005). As a continuing effort to improve mobile source emission models, particularly for gasoline-fueled vehicles, the U.S. EPA sponsored the Kansas City Study in the summer of 2004 and winter of 2005 (U.S. EPA, 2008b; 2008c). The Kansas City Study was designed to estimate average PM emissions for the fleet with attention to characterizing the contribution of high-emitting vehicles. Hundreds of gasoline-only vehicles were recruited while PM emissions were measured for ~100 vehicles. These vehicles were divided into four age groups by model year (i.e., pre-1981; 1981-1990; 1991-1995; and after-1995) for the two light-duty gasoline-fueled vehicle types (i.e., passenger vehicles and trucks). Emission measurements were typically made for each of the three phases of the FTP cycle (i.e., cold start, hot start, and warm start), but to compare with emission models, the FTP averages were reported.

Table 3-2 summarizes the sample composition and vehicle specifications. U.S. EPA (2008b; 2008c) reports a clear decrease in $PM_{2.5}$ emission levels with later model year vehicles, although they cannot determine whether the emission decrease is due to technology improvement or if it reflects "…varying levels of vehicle deterioration." The highest emission factors resulted from the three older vehicles (i.e., 1980 passenger vehicle [S5-5], 1985 truck [S2-4], and 1989 truck [S2-1], see Table 3-2) tested during the summer of 2004 and three pre-1989 vehicles (W6-

1, W6-4, and W2-1) tested during the winter of 2005. In general, gasoline-fueled light-duty trucks had slightly higher PM emissions than passenger vehicles. Compared to the MOBILE 6.2 model estimates, measured emission factors were generally higher in winter, as shown in Figure 3-6. The EMFAC2007 model estimates higher emission factors than the MOBILE 6.2 model for the most part, and agrees better with measurements during the winter study. However, as shown in Figure 3-7, neither model simulates the variability of actual gasoline-fueled vehicle emissions nor predicts the contribution from individual high-emitting vehicles. This is consistent with findings from the Gas/Diesel Split Study (Fujita et al., 2007a; 2007b)

For a gasoline fleet without an I/M program, the emission inventory based on the MOBILE 6.2 or EMFAC2007 model likely gives a lower-bound estimate of the actual emission(s). Unlike in Kansas City, there are existing I/M programs in California. I/M programs affect a vehicle's deterioration rate by requiring repairs and maintenance that otherwise might not typically be performed by the vehicle owner. How each I/M program changes the natural deterioration rate of a vehicle was not evaluated in this study due to lack of measurement data. U.S. EPA (2008b; 2008c) comments that there is much work to be done before a final estimate of inventory impacts can be determined. At the present time, a substantial uncertainty exists in the gasoline fleet emission inventories.

3.2 Off-Road Diesel Emission Factors

Diesel backup generators (BUGs) are often located close to hospitals, schools, and municipal buildings where the potential for human exposure is high. It has been estimated that there are 626,000 installed diesel BUGs in 1996 with a total generating capacity of 102,000 megawatts (MW) in the U.S. and the capacity is growing at an annual rate of 1.7% (Singh and Huber, 2001). In California, diesel BUGs are used to power agricultural irrigation pumps. Only a limited number of emission measurements for in-use diesel generators have been reported. As part of the U.S. Department of Defense (DOD) sponsored SERDP Study, off-road gaseous and particulate BUG emission factors were acquired on a California military base during November 2005 (Watson et al., 2008a). This study tested 14 diesel generators (Mobile Electrical Power) with rated capacities of 10, 30, 60, and 100 kilowatts (kW) under different load conditions (Watson et al., 2008a). Generator-specifications along with the test load conditions are summarized in Table 3-3.

Measurements of diesel generator emissions were conducted using the DRI In-Plume Emission Test Stand (IPETS). IPETS draws an exhaust sample into a flexible conductive inlet within ~1 m of the engine's exhaust pipe. The instrumentation and operating methods are described in detail by Nussbaum et al. (2008). Fuel-based emission factors are calculated from the ratio of the pollutant of interest to the sum of CO and CO_2 concentration (above the ambient background concentrations) in the plume and the carbon content of the fuel. The sum of CO and CO_2 typically account for more than 99% of the carbon emitted in engine exhaust (Kuhns et al., 2005).

To simplify the terminology, the emission factor, EF_P for pollutant P (e.g., $PM_{2.5}$), is defined as the ratio of the mass of pollutant (M_P) emitted per mass of fuel (M_{fuel}) consumed:

$$EF_P = \frac{M_P}{M_{fuel}} \tag{3-1}$$

The carbon mass fraction of the fuel (CMF_{fuel}) is the fuel carbon mass (CM_{fuel}) divided by M_{fuel} in which:

$$CMF_{fuel} = \frac{CM_{fuel}}{M_{fuel}} \tag{3-2}$$

M_{fuel} in Equation 3-1 can be replaced by Equation 3-2, yielding:

$$EF_P = CMF_{fuel}\frac{M_P}{CM_{fuel}} \tag{3-3}$$

The carbon mass emitted by each test equals the carbon mass of the fuel consumed (i.e., carbon balance). CM_{fuel} in Equation 3-3 can be replaced by the carbon mass of the emissions ($CM_{exhaust}$), which is the sum of the mass of its main carbon containing components i ($\sum_i CM_i$), weighted by their respective carbon mass fraction (i.e., $CM_{exhaust} = \sum_i CM_i = \sum_i CMF_i \times M_i$). Equation 3-3 can then be expressed as:

$$EF_p = CMF_{fuel}\frac{M_P}{CM_{exhaust}} = CMF_{fuel}\frac{M_P}{\sum_i CM_i} = CMF_{fuel}\frac{M_P}{\sum_i CMF_i \times M_i} = CMF_{fuel}\frac{\rho_{c\_P}}{\sum_i CMF_i \times \rho_{c\_i}} \tag{3-4}$$

where the mass ratios ($\frac{M_P}{\sum M_i}$) have been replaced by the ratios of the respective mass concentrations ρ_{c_P} (ρ indicates mass concentration, and $\rho \propto M$ assuming the same dispersion for every component), for pollutant P, and the sum of the ρ_{c_i}, for component i, as measured by the in-plume system. Expanding the sum over the main carbon-containing components of gaseous emissions (i.e., CO_2, CO, and hydrocarbon [HC]) and dividing the numerator and denominator by the CO_2 mass, (i.e., M_{CO2}), yields:

$$EF_P = CMF_{fuel} \frac{\frac{\rho_{c\_P}}{\rho_{c\_CO2}}}{CMF_{CO2} + \left(CMF_{CO} \frac{\rho_{c\_CO}}{\rho_{c\_CO2}} + CMF_{HC} \frac{\rho_{c\_HC}}{\rho_{c\_CO2}} \right)} \tag{3-5}$$

where the terms in the brackets in Equation 3-5 can be neglected for emission tests with high combustion efficiency. The contribution of particulate OC and EC emissions is even less significant and has been neglected in the denominator of Equation 3-5. The fuel-based emission factor, EF_P for pollutant P, can therefore be determined from an in-plume measurement of the mass concentration ρ_c using Equation 3-5 and the well known carbon mass fractions (CMFs; ~85.6% for diesel fuels).

Ten filter samples were acquired from the 14 diesel BUGs listed in Table 3-3, from which emission factors for $PM_{2.5}$ mass, OC, and EC were determined. As shown in Table 3-4, the $PM_{2.5}$ mass emission factors for the 14 BUGs ranged from 0.23 to 3.04 g/kg fuel with an average and standard deviation of 1.15 ± 0.93 g/kg fuel by excluding one outlier (15.02 g/kg). It should be noted that except for two runs with a 100 kW diesel generator (e.g., Run ID #6 and #10), which was a high emitter, the diesel BUG $PM_{2.5}$ emission factors were are all below 2.2 g/kg.

The diesel BUG EC and OC emission factors averaged 0.2 ± 0.16 g/kg and 0.43 ± 0.25 g/kg, respectively, but were highly variable. In addition to the high $PM_{2.5}$ emission factors found on the 100 kW generator (i.e., Run ID #6 and #10 in Table 3-4), $PM_{2.5}$ and OC emission factors for the three 10 kW generators (i.e., Run ID #1, #2, and #7) are also high (1.03 – 2.17 g/kg and 0.43 – 0.81 g/kg, respectively). Due to the organic sampling artifact (i.e., the adsorption of volatile organic compounds onto quartz-fiber sample filters), OC emission factors exceeded the corresponding $PM_{2.5}$ emission factors on Run ID #9 for the four 60 kW generators. The artifact is mitigated but not entirely compensated for by subtracting OC collected on a backup quartz-fiber filter (Watson and Chow, 2002; see corrected organic sampling artifact values in Table 3-4). The OC and EC fractions of $PM_{2.5}$ are included in Section 4.2 for comparison of source profiles.

The tactical military vehicles were tested at a Marine Corps Training Facility in southern California during April 2007 (Watson et al., 2008a). Vehicles were recruited for testing as they traveled to and from field training sites. A four-meter high sampling inlet pipe was set up across a paved tank trail and suspended on each end. A wrought iron pipe (0.75 inch inner diameter) with inlets mounted at ~1 m intervals was connected to the IPETS system via a flexible conductive tubing (1 inch inner diameter). The flexible tube was connected to a plenum within a cargo van on the side of the road to duct the exhaust to gas and particle sampling system.

The fixed height (i.e., 4 m above ground level) of the IPETS inlet precluded tests on all types of military vehicles. For example, Humvees have exhaust pipes at ~2 m above ground level; too low to allow sufficient exhaust to reach the IPETS sampling inlet. The Medium Tactical Vehicle Replacement (MTVR) and Logistics Vehicle System (LVS) had the highest exhaust pipes (3 m to 3.5 m) of the vehicles tested and represented the majority of valid IPETS measurements. A summary of the 14 military diesel-fueled vehicles for the 49 tests during the SERDP Study is shown in Table 3-5.

Multiple tests were conducted on several vehicles. Individual test results are shown in Table 3-6, with the exception of the two tests using the IPETS system. Emission factors from a single vehicle are expected to vary based on the mode of operation (i.e., slight, moderate, hard accelerations) and road grade (~1% at this test location). Therefore, $PM_{2.5}$ mass, EC, and OC emission factors of 0.05 – 0.17 g/kg, 0.02 – 0.07 g/kg, and 0.04 – 0.11 g/kg, respectively, for the two IPETS tests represent averages over multiple vehicles and operational modes.

In addition to IPETS, an on-board sampling system was mounted on: 1) two MTVRs (Vehicle IDs #1 and #2), 2) one LVS (Vehicle ID #12), and 3) one AAVP7A1 (Amphibious Assault Vehicle; Vehicle ID #14) to measure emission factors under loop driving, acceleration, extended driving, and idle conditions. Like IPETS, the 15 on-board samples reported fuel-based emission factors following Equations 3-1 to 3-5. Emission factors ranged from 0.15 – 1.67 g/kg for $PM_{2.5}$, 0.09 – 1.04 g/kg for EC, and 0.06 – 0.84 g/kg for OC, substantially higher than those from IPETS.

Table 3-7 compares average $PM_{2.5}$ vehicle engine emission factors among recent studies, including those obtained from the CRC E55/59 Phase I and II study (Clark et al., 2007). $PM_{2.5}$ emission factors for the light-duty gasoline vehicles and trucks (i.e., LDGV and LDGT1, respectively) are similar, ranging from 0.021 – 0.030 g/mile. $PM_{2.5}$ emission factors for the medium heavy-duty (MHDV; 0.70 ± 0.88 g/mile) and heavy heavy-duty (HHDV; 0.86 ± 0.62 g/mile) diesel vehicles are 20- to 30-fold higher than those of LDGV and LDGT1. $PM_{2.5}$ emission factors for urban buses (1.49 ± 0.89 g/mile) are twofold higher than the heavy-duty (i.e., MHDV and HHDV) diesel vehicles and over 50-fold higher than LDGV and LDGT1.

$PM_{2.5}$, BC/EC, and OC emission factors were determined for three and six on-road HDDVs during the CRC E55/59 Phase I and Phase II Studies, respectively, using chassis dynamometer test. These emission factors are modal-specific, including laden idle, creep, long creep, cruise, and transient modes such as UDDS. Individual emission factors are available in the emission factor database accompanying this report (see Section 6.2). Table 3-7 shows that $PM_{2.5}$ emission factors from HHDV are similar, 0.86 ± 0.62 g/mile in the Gas/Diesel Split Study (Fujita et al., 2007a; 2007b) and 0.63 ± 0.57 g/mile for the CRC E55/59 Studies (Clark et al., 2007). This information may be used for future emission inventory development.

For the fuel-based emission factors in g/kg for the SERDP Study (Watson, et al., 2008a), Table 3-7 shows that the average $PM_{2.5}$ emission factor for the diesel BUGs (1.15 ± 0.93 g/kg) is over twofold higher than the HHDV tests (0.53 ± 0.54 g/kg) using the IPETS or on-board sampling system (see Table 3-6).

3.3 Biomass Burning Emission Factors

Biomass burning in California includes managed forest and agricultural burns, RWC, and wild fires. One of the goals of the Joint Fire Science Project (JFSP; also known as the Fire Laboratory at Missoula Experiment [FLAME] Study; e.g., McMeeking et al., 2008) is to improve the emission factors of wildland fuel burning, though some agricultural and residential fuels were also examined during the study. FLAME is a joint effort among U.S. Forest Service Fire Science Laboratory (FSL), Colorado State University, National Park Service, Desert Research Institute, and many others (http://chem.atmos.colostate.edu/FLAME/.) The experiments were conducted at the FSL at Missoula, MT during November, 2003 (Pilot Study), May, 2006 (Phase I), and June, 2007 (Phase II). Fresh fuels were collected locally (e.g., grass) or shipped to the laboratory within one week of collection. Dried fuels were prepared by long-term indoor storage. Before the experiment, fuel moisture was determined by the weight difference prior to and after heating the fuel at 80 °C for 24 – 48 hrs, and reported as percentage of water with respect to dry fuel mass. Experimental details are in Chakrabarty et al. (2006), Chen et al. (2006b; 2007), and McMeeking et al. (2008). Table 3-8 summarizes the 17 types of biofuels and their fuel characteristics during the FLAME Study (McMeeking et al., 2008).

For the biomass burning sources, fuel-based emission factors may be quantified directly by determining the fuel mass consumed and the amount of pollutant flux integrated over time and the cross-section of the smoke plume (e.g., Hays et al., 2002; 2005). However, the pollutant flux integration is not usually straightforward as pollutant concentrations and wind velocities have to be profiled over the plume cross-section. A much more practical alternative is to use the fuel carbon content as a marker and measure pollutant emissions per unit carbon in the fuel. This can be done with a single set of instruments measuring carbon concentrations (mostly CO and CO_2) and other pollutant concentrations in the plume. These values can be ratioed after background subtraction to yield the amount of pollutant emitted per fuel carbon mass (see the method description of Equations 3-1 to 3-5 in Section 3.2). The fuel-based emission factor, EF_P for pollutant P, can be determined from an in-plume measurement of the mass concentration, ρ_c, using Equation 3-5 and the measured carbon mass fractions (CMFs of ~ 0.4 – 0.5 for most biomes [see carbon content in Table 3-8]).

ARB uses the Emission Estimation System (EES) Model developed by U.C. Berkley (http://www.arb.ca.gov/ei/see/see.htm) to estimate gaseous and particulate emissions from wildfires, prescribed burns, and wildland fires. The core of EES is the First Order Fire Effects Model (FOFEM 4.0) that determines the fuel loading characteristics for fuel component by vegetation type. Emission factors in EES are functions of fuel component (i.e., [1] litter; [2] small wood; [3] large wood; [4] herb, shrub, and regen; [5] duff; and [6] canopy fuels) and fuel moisture (i.e., [1] dry; [2] moderate; and [3] wet). However, emission factors from dry and wet fuels do not differ significantly in all fuel components. A separate set of emission factors are used to estimate emissions from agricultural and other management burns (http://www.arb.ca.gov/ei/see/mngdburnemissionfactors.xls), where emission factors are provided for CO, VOC, SO_2, NO_x, $PM_{2.5}$ and PM_{10} but do not depend on fuel moisture. The source of these emission factors includes: 1) the EPA's AP-42 – "Compilation of Air Pollutant

Emission Factors" Chapter 2.5 - Open Burning (U.S. EPA, 2006); and 2) the Jenkins Report - University of California at Davis in 1992 and 1993 Volume I and II (Jenkins et al., 1996). Hereafter these emission factors are noted as "San Joaquin Valley (SJV) emission factors" since they have been used to develop the biomass burning emission inventory for California's San Joaquin Valley.

The FLAME $PM_{2.5}$ emission factors that can be classified into six EES categories, separated by dry and wet moisture content, are compared with EES emission factors in Figure 3-8. It should be noted that the FLAME Study contains more detailed breakdowns of fuel properties such as shrubs (e.g., Chemise [Che] and Manzanita [Maz]), leaves, and branches than EES. Leaves generally produced more particles per unit dry mass of fuel burned, whether they were from dry or wet (e.g., newly harvested or fresh) plants. The highest emission factors resulted from burning fresh Ponderosa Pine (PP) needles (76.8 ± 37.5 g/kg), followed by burning fresh Manzanita leaves (62.3 g/kg; single test) and fresh Lodgepole Pine (LP) needles (56.2; single test). Burning plant branches never generated $PM_{2.5}$ emission factors exceeding 15 g/kg, even for fresh wood with a moisture content of ~70%. Considering the variability in burning different fuels and fuel components, Figure 3-8 shows that EES provides reasonable estimates for dry litter source (EES 1), dry small wood (EES 2), wet large wood (EES 3), dry herb and shrub (EES 4-dry), and dry duff burn (EES 5) emission factors. However, it appears to underestimate $PM_{2.5}$ emissions from wet herb, shrub, and regen (EES 4-wet), as well as wet needles from Ponderosa and Lodgepole Pine trees. Fresh pine needles should not burn much during prescribed burns, which focus on fuels from the forest floor, but are vulnerable to wild fires. The emission factors in EES should be updated with recent measurements. Chen et al. (2006a; 2007) suggest that EC is insignificant in burns of fresh fuels due to a lower combustion temperature, so most of the underestimation is attributed to OC.

Figure 3-9 shows $PM_{2.5}$ emission factors vary from 2.38 ± 1.38 g/kg (Dry Dambo Grass) to 12.8 g/kg dry fuel (Fresh Tundra; single test) based on other measurements in the FLAME Study. They covered a wide variety of fuels with relatively low moisture content (< 35%). These emission factors may be considered for EES by ARB in the future. As shown in Table 3-8, two pairs of samples were taken specifically for the flaming and smoldering phase of dry Chemise and rice straw burns. Each phase was distinguished visually according to whether flames existed or not. Smoldering combustion produced higher emission factors than those of flaming as shown in Figure 3-10 (3.2 vs. 2.8 g/kg in Chemise and 15.4 vs. 2.3 g/kg in rice straw, respectively) in both types of fuels, which is consistent with findings by Chen et al. (2007). The corresponding SJV emission factors overestimate Chemise (Chaparral) but underestimate rice straw and grass (Grassland) burn emissions by threefold (see Figure 3-10). Further investigation is needed to see how these differences will influence the emission inventory. It is essential that fuel moisture and combustion phase are incorporated into the current emission model. A more sophisticated model such as Fire Emission Production Simulator (FEPS; http://www.fs.fed.us/pnw/fera/feps/; Anderson et al., 2004) may be used to estimate the fraction of dry and wet vegetation, flaming, and smoldering combustion in a particular burn event.

3.4 Laboratory Emissions Tests

The first phase of this study (Chow et al., 2006d) included measurements from: a) diesel generator emissions (Onan Cummins 12.5 kW generator equipped with a Simplex Swifte Plus load bank); 2) RWC emissions from a commercial woodstove; 3) electric arc soot generator (Model G7G-1000, PALAS, Karlsruhe, Germany) emissions; and 4) acetylene combustion emissions generated from a torch with a number 1 level tip. While numerous samples were collected, emission factors for the diesel generator and RWC were estimated for a number of cases where CO_2 was measured concurrently with particle measurements. Diesel generator exhaust was collected at a 4 kW load. Wood smoke was produced in an uncontrolled (non-recirculating) woodstove burning white oak wood. The moisture content of the wood, the amount of wood burned, and burning conditions were the same throughout the experiment. Sample dilution ratios were varied using filtered room air during sampling of diesel generator and RWC emissions. Detailed parameters for each test are documented in Chow et al. (2006d) for this study.

Measured concentrations can be used without knowledge of the dilution ratio to determine the fuel-based emission factor, EF_P, for pollutant P, under the assumption that virtually all carbon mass emissions are represented by the CO_2 emissions. The fuel-based emission factor, EF_P, is described by Moosmüller et al. (2003), as follows:

$$EF_P = \frac{CMF_{fuel} \times C_P}{CMF_{CO2} \times C_{CO2}} , \tag{3-6}$$

where CMF_{fuel} and CMF_{CO2} are the carbon mass fractions of the fuel and CO_2, respectively, and C_p and C_{CO2} are the mass concentration of pollutant P and CO_2, respectively.

CMF_{CO2} can be calculated directly from the respective atomic masses of carbon and oxygen as $CMF_{CO2} = 12/(12+2\times16) = 27.3\%$. For diesel fuel, one may assume the empirical formula of C_nH_{2n}, resulting in $CMF_{diesel} = 12/(12+2) = 85.6\%$. For wood smoke, a value of 49.5% for CMF_{wood} was used (Gaur and Reed, 1998).

$PM_{2.5}$, EC, OC, and OC_{corr} (corrected for the artifact by subtracting backup quartz filter OC [Chow et al., 2008c; Watson et al., 2008b]) are presented in Table 3-9. The number of measurements at each dilution ratio is also shown. Average emission factors are presented for each source. The results indicate that emission factors for $PM_{2.5}$, EC, OC, and OC_{corr} were independent of the sample dilution ratio for the diesel generator but increased significantly for RWC as the dilution ratio increased from 18 to 105-107. On average, the emission factor for OC_{corr} was 17% lower than the uncorrected OC for the diesel generator but 45% lower for RWC. At the dilution ratio of 105-117, the OC emission factor (2.41 ± 0.35 g/kg) was larger than the $PM_{2.5}$ emission factor (1.74 ± 0.21 g/kg). Thus, the OC_{corr} emission factor of 1.17 ± 0.18 g/kg was probably more reliable. The increase in the RWC OC_{corr} emission factor with dilution ratio is inconsistent with expectations, since partitioning to the gas phase should increase with increasing dilution. Sample air dilution did not affect the flow through the woodstove and, as noted above, burning conditions remained constant at all dilution ratios.

The average diesel generator emission factors for EC and OC, determined during the SERDP Study (Watson et al., 2008a) were 0.20 ± 0.16 g EC/kg and 0.35 ± 0.21 g OC_{corr}/kg, respectively, as shown in Table 3-4. The corresponding average emission factors for the military vehicles in Table 3-6 were 0.25 ± 0.28 g EC/kg and 0.16 ± 0.19 g OC_{corr}/kg. These values were comparable to those of laboratory testing results (Table 3-9) within their uncertainties for both EC and OC.

Table 3-1. Descriptions of vehicle sample composites during the Gas/Diesel Split Study.[a]

Sample Composite Code	Vehicle Test Cycle[b]	MOBILE Model Vehicle Category[c]	EMFAC Model Vehicle Category[d]	Number of Vehicles Tested	Range of Vehicle Model Year	Odometer Range (miles)
SI_1_1	CS; WS	LDGV/LDGT1	LDA/LDT1	4	1995 – 1997	23K - 59K
SI_2_1	CS; WS	LDGV/LDGT1	LDA/LDT1	4	1995	32K - 83K
SI_3_1	CS; WS	LDGV/LDGT1	LDA/LDT1	4	1995 - 1999	95K - 125K
SI_4_1	CS; WS	LDGV/LDGT1	LDA/LDT1	4	1991 - 1992	52K - 134K
SI_5_1	CS; WS	LDGV/LDGT1	LDA/LDT1	2	1984 - 1995	84K - 154K
SI_5_2	CS; WS	LDGV/LDGT1	LDA/LDT1	6	1992 - 1995	103K - 216K
SI_6_1	CS; WS	LDGV/LDGT1	LDA/LDT1	6	1991 - 1995	120K - 172K
SI_6_2	CS; WS	LDGV/LDGT1	LDA/LDT1	2	1990 - 1991	149K - 160K
SI_6_3	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1992	160K
SI_7_1	CS; WS	LDGV/LDGT1	LDA/LDT1	4	1986 - 1989	92K - 418K
SI_7_2	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1987	162K
SI_7_3	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1989	174K
SI_8_1	CS; WS	LDGV/LDGT1	LDA/LDT1	2	1983 - 1984	197K - 248K
SI_8_2	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1985	212K
SI_8_3[e]	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1984	167K
SI_9_1	CS; WS	LDGV/LDGT1	LDA/LDT1	2	1979 - 1980	159K - 182K
SI_9_2	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1977	158K
SI_9_3	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1979	121K
SI_9_4[e]	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1980	98K
SI_10_1	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1989	421K
SI_10_2	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1990	259K
SI_10_3	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1978	128K
SI_10_4[e]	CS; WS	LDGV/LDGT1	LDA/LDT1	1	1988	149K
LCI-11_1	CS; WS	LDDT12	LDT1	1	1982	162K
CI-10	CCS; HCS; HW	HDDV8	HHDV	3	1992 - 1993	109K - 842K
CI-11	HCS; HW	HDDV8	HHDV	5	1994 - 1997	109K - 602K
CI-11e	HCS; HW; CID; ID	HDDV8	HHDV	1	1995	241K
CI-11n	CCS; HCS; HW; ID	HDDV8	HHDV	1	1994	NA
CI-12	CCS; HCS; HW	HDDV8	HHDV	4	1998 - 2001	145K - 327K
CI-13.1	HCS; MC	HDDBT	UB	1	1992	519K
CI-13.2	HCS; MC	HDDBT	UB	1	1982	103K
CI-4r	HCS	HDDV3	LHDT2	1	2000	45K
CI-5	HCS; HW	HDDV7	MHDT	1	1988	170K
CI-8r	HCS	HDDV5	MHDT	1	1999	15K
CI-9e	CCS; HCS; CSJ; HW; CID; UDDS	HDDV8	HHDT	1	1985	36K
CI-9n	CCS; HCS; HW; ID	HDDV7	MHDT	1	1985	501K
CI-Ia	CCS; HCS; HW	HDDV3	LHDT2	2	1989 - 1990	NA
CI-Ib	CCS; HCS; HW	HDDV2/HDDV3	LHDT1/LHDT2	5	1997 - 2000	NA
CI-II	HCS; HW	HDDV6	MHDT	5	1995 - 1999	15K - 162K
CI-IIb	HCS; HW	HDDV6	MHDT	1	1995	151K

Table 3-1. Continued.

[a] Fujita et al., 2007a; 2007b.

[b] Driving Modes
- CCS (Cold City-Suburban Route);
- CID (Cold Idle);
- CS (Cold Start Unified Driving Cycle [UDC]);
- CSJ (City-Suburban with Jacobs Brake);
- HCS (Hot City-Suburban Route);
- HW (Highway Cycle);
- ID (Idle);
- MC (Manhattan Cycle for Transit buses);
- UDDS (Urban Dynamometer Driving Schedule).
- WS (Warm Start UDC);

c MOBILE Category
- LDGV (Light-Duty Gasoline Vehicle);
- LDGT1 (Light-Duty Gasoline Truck; weight class 1 [0 – 3,000 lbs]);
- LDDT12 (Light-Duty Diesel Truck; combined weight class 1 and 2 [0 – 6,000 lbs]);
- HDDV1 (Heavy-Duty Diesel Vehicle; weight class 1 [0 – 8,500 lbs])
- HDDV2 (Heavy-Duty Diesel Vehicle; weight class 2 [8,501–10,000 lbs])
- HDDV3 (Heavy-Duty Diesel Vehicle; weight class 3 [10,001–14,000 lbs])
- HDDV5 (Heavy-Duty Diesel Vehicle; weight class 4 [14,001–16,000 lbs])
- HDDV5 (Heavy-Duty Diesel Vehicle; weight class 5 [16,001–19,500 lbs])
- HDDV6 (Heavy-Duty Diesel Vehicle; weight class 6 [19,501–26,000 lbs])
- HDDV7 (Heavy-Duty Diesel Vehicle; weight class 7 [26,001–33,000 lbs])
- HDDV8 (Heavy-Duty Diesel Vehicle; weight class 8 [>33,000 lbs]);
- HDDBT (Heavy-Duty Diesel Bus Transit).

[d] EMFAC Category
- LDA (Light-Duty Passenger Vehicle);
- LDT1 (Light-Duty Truck; weight class 1 [0–5,750 lbs]);
- LHDT1 (Light Heavy-Duty Truck; weight class 1 [8,501–10,000 lbs]
- LHDT2 (Light Heavy-Duty Truck; weight class 2 [10,001–14,000 lbs]);
- MHDT (Medium Heavy-Duty Truck; 14,001–33,000 lbs);
- HHDT (Heavy Heavy-Duty Truck; 33,001–60,000 lbs);
- UB (Urban Bus).

[e] High emitting vehicles; smokers.

Table 3-2. Descriptions of vehicle sample composites during the Kansas City Study.[a]

Sample Composite Code	Vehicle Test Cycle[b]	MOBILE Model Vehicle Category[c]	EMFAC Model Vehicle Category[d]	Number of Vehicles Tested	Range of Vehicle Model Year	Odometer Range (miles)
S5-5[d]	FTP (Summer)	LDGV	LDA	1	1980	-
S6-1	FTP (Summer)	LDGV	LDA	1	1989	116K
S6-2	FTP (Summer)	LDGV	LDA	1	1989	209K
S6-3	FTP (Summer)	LDGV	LDA	1	1985	236K
S6-4	FTP (Summer)	LDGV	LDA	1	1986	36K
S7-1	FTP (Summer)	LDGV	LDA	2	1991 - 1994	169K - 214K
S7-2	FTP (Summer)	LDGV	LDA	3	1991 - 1994	32K - 185K
S7-3	FTP (Summer)	LDGV	LDA	1	1994	101K
S7-4	FTP (Summer)	LDGV	LDA	1	1991	226K
S8-1	FTP (Summer)	LDGV	LDA	5	1996 - 1998	45K - 131K
S8-2	FTP (Summer)	LDGV	LDA	5	1996 - 2000	40K - 148K
S8-3	FTP (Summer)	LDGV	LDA	5	1996 - 2003	24K - 146K
S2-1	FTP (Summer)	LDGT1	LDT1	1	1989	161K
S2-2	FTP (Summer)	LDGT1	LDT1	1	1985	30K
S2-3	FTP (Summer)	LDGT1	LDT1	1	1989	132K
S2-4	FTP (Summer)	LDGT1	LDT1	1	1985	47K
S3-1	FTP (Summer)	LDGT1	LDT1	3	1995	74K - 113K
S3-2	FTP (Summer)	LDGT1	LDT1	3	1990 - 1995	73K - 171K
S4-1	FTP (Summer)	LDGT1	LDT1	3	1998 - 2003	19K - 131K
S4-2	FTP (Summer)	LDGT1	LDT1	5	1999 - 2004	11K - 75K
W6-1	FTP (Winter)	LDGV	LDA	1	1988	207K
W6-2	FTP (Winter)	LDGV	LDA	1	1988	287K
W6-3	FTP (Winter)	LDGV	LDA	2	1989 - 1990	168K - 176K
W6-4	FTP (Winter)	LDGV	LDA	1	1989	62K
W7-1	FTP (Winter)	LDGV	LDA	2	1995	146K - 163K
W7-2	FTP (Winter)	LDGV	LDA	3	1991 - 1995	80K - 145K
W7-3	FTP (Winter)	LDGV	LDA	2	1994 - 1995	78K - 112K
W7-4	FTP (Winter)	LDGV	LDA	2	1993 - 1995	140K - 168K
W8-1	FTP (Winter)	LDGV	LDA	4	1996 - 2002	26K - 68K
W8-2	FTP (Winter)	LDGV	LDA	2	1997 - 1998	29K - 63K
W8-3	FTP (Winter)	LDGV	LDA	3	1998 - 2001	56K - 65K
W2-1	FTP (Winter)	LDGT1	LDT1	1	1989	145K
W2-2	FTP (Winter)	LDGT1	LDT1	1	1987	232K
W2-3	FTP (Winter)	LDGT1	LDT1	1	1988	162K
W3-1	FTP (Winter)	LDGT1	LDT1	3	1992 - 1995	85K - 136K
W3-2	FTP (Winter)	LDGT1	LDT1	3	1993 - 1995	47K - 113K
W3-3	FTP (Winter)	LDGT1	LDT1	1	1992	154K
W4-1	FTP (Winter)	LDGT1	LDT1	5	1996 - 2004	14K - 66K
W4-2	FTP (Winter)	LDGT1	LDT1	3	1998 - 2002	0K - 56K
W4-3	FTP (Winter)	LDGT1	LDT1	3	1996 - 1997	125K - 146K

Table 3-2. Continued

[a] U.S. EPA 2008b; 2008c

[b] FTP: Federal Test Procedure, includes the average of three cycles (Cold Start, Hot Start, and Warm Start); tests conducted during summer of 2004 and winter of 2005.

[c] MOBILE Category
  LDGV (Light-Duty Gasoline Vehicle)
  LDGT1 (Light-Duty Gasoline Truck; weight class 1 [0 – 3,000 lbs])

[d] EMFAC Category
  LDA (Light-Duty Passenger Vehicle)
  LDT1 (Light-Duty Truck; weight class 1 [0–5,750 lbs])

Table 3-3. Generator specifications of the off-road diesel emission tests for the SERDP Study.[a]

Generator ID	Generator Model	Engine Year	Serial Number	Rated power (kW)	Hours Used	Test Date	Engine Test Cycle #I	Engine Test Cycle #II
1	MEP803A	1999	FZ30644	10	2618	11/14/2005	10 kW Test #1	10 kW Cold Start
2	MEP803A	1995	RZCO2845	10	3103	11/14/2005	10kW Test #1	10 kW Cold Start
3	MEP803A	1994	RZCO2061	10	2154	11/14/2005	10 kW Test #2	10 kW Cold Start
4	MEP805A	1995	RZH01043	30	1943	11/15/2005	30 kW Test #1	30 kW Cold Start
5	MEP805A	1995	RZH01023	30	3374	11/15/2005	30kW Test #1	30 kW Cold Start
6	MEP805A	1995	RZH00999	30	1641	11/15/2005	NA[b]	30kW Cold Start
7	MEP805B	2002	HX32455	30	636	11/15/2005	NA	30kW Cold Start
8	MEP805B	2002	HX33185	30	85	11/15/2005	NA	30kW Cold Start
9	MEP806B	2002	HX62471	60	1017	11/15/2005	60 kW Test #1	60 kW Cold Start
10	MEP806B	2001	HX62182	60	1084	11/15/2005	60 kW Test #1	60 kW Cold Start
11	MEP806A	1995	RZJ02059	60	947	11/15/2005	60 kW Test #2	60 kW Cold Start
12	MEP806B	2001	HX62178	60	366	11/15/2005	60 kW Test #2	60 kW Cold Start
13	MEP007B	NA	RZ02630	100	1874	11/16/2005	100 kW Test #1	100 kW Cold Start
14	MEP805B	2002	HX33189	30	29	11/16/2005	NA	30 kW Cold Start

[a] Watson et al., (2008a)

[b] NA: not available or not applicable

Table 3-4. Emission factors (EF) for diesel backup generators (BUGs) measured during the SERDP Study in 2005.[a]

					Percent of $PM_{2.5}$			g/kg Diesel Fuel[b]			
Run ID	**Engine Test**	**Engine Test Cycle Number[c]**	**Generator ID(s)**	**Generator Load (%)[d]**	**EC (%)**	**OC (%)**	**OC_{corr} (%)[e]**	**EC EF**	**OC EF**	**OC_{corr} EF[e]**	**$PM_{2.5}$ EF**
1	10kW Test #1	I	1,2	10,25,50, 75,100	8.24	73.85	70.04	0.08	0.76	0.72	1.03
2	10kW Test #2	I	3	10,25,50, 75,100	18.88	19.66	16.53	0.41	0.43	0.36	2.17
3	30kW Test #1	I	4,5	10,25,50, 75,100	20.44	23.19	19.84	0.14	0.16	0.14	0.69
4	60kW Test #1	I	9,10	10,25,50, 75,100	33.93	61.60	55.48	0.15	0.28	0.25	0.45
5	60kW Test #2	I	11,12	10,25,50, 75,100	19.79	23.72	20.69	0.22	0.26	0.23	1.09
6	100kW Test #1	I	13	10,25,50, 75,100	3.56	34.71	29.51	0.53	5.21[e]	4.43[e]	15.02[f]
7	10kW Cold Start	II	1,2,3	0	8.65	60.82	46.77	0.11	0.81	0.62	1.32
8	30kW Cold Start	II	4,5,6,7,8,14	0	10.16	58.18	39.59	0.03	0.19	0.13	0.33
9	60kW Cold Start	II	9,10,11,12	0	22.05	152.54[f,g]	122.86[f,g]	0.05	0.34[g]	0.28[g]	0.23
10	100kW Cold Start	II	13	0	7.69	20.90	14.95	0.23	0.64	0.45	3.04
	Average				**15.34**	**41.85**	**34.82**	**0.20**	**0.43**	**0.35**	**1.15**
	Standard Deviation				**9.24**	**21.51**	**19.41**	**0.16**	**0.25**	**0.21**	**0.93**

[a] Watson et al. (2008a).

[b] Assume a carbon content of 0.856 for the diesel fuel.

[c] See Table 3-3 for Test Cycle specifics.

[d] 0% is equivalent to no load (idle).

[e] Organic sampling artifact corrected by backup filter.

[f] Excluded from average and standard deviation.

[g] OC emission factors exceeded the corresponding $PM_{2.5}$ emission factors.

Table 3-5. Summary of military diesel-fueled vehicles tested during the April 2007 SERDP Study.

Vehicle Type[a]	Engine Specification	Gross Vehicle Weight (lbs)	Range of Vehicle Model Year	Odometer Range (miles)	Vehicle Test Cycle[c]	Number of Vehicles Tested	Vehicle ID (see Table 3-6)[e]	Total Number of Tests[e]
MTVR	Caterpillar C-12 (four stroke)	62,200	2002[b]	5300-6600[b]	Acceleration	10	1,3,4,5,6,7, 8,9,10,11	28
MTVR	Caterpillar C-12 (four stroke)	62,200	2002	5300-6600	Loop driving	2	1,2	8
MTVR	Caterpillar C-12 (four stroke)	62,200	2002	5300-6600	Extended driving	2	1,2	2
LVS	Detroit Diesel 8V92TA (two stroke)	32,000	2006[d]	380[d]	Acceleration	2	12,13	6
LVS	Detroit Diesel 8V92TA (two stroke)	32,000	2006	380	Loop driving	1	12	3
LVS	Detroit Diesel 8V92TA (two stroke)	32,000	2006	380	Extended driving	1	12	1
AAVP7A1	Cummings VT400 (four stroke)	61,200	NA	2332	idle	1	14	1

[a] The **MTVR** (Medium Tactical Vehicle Replacement) is a six-wheel drive all-terrain vehicle used by the U.S. Marine Corps (USMC) and U.S. Navy. It is designed to replace the old M900 series of tactical trucks, and was first fielded in 1998, after the contract was awarded to Oshkosh Truck Corporation. The MTVR comes in several variants, for a wide spectrum of tasks. It offers a major improvement in off-road capability with an advanced suspension, a condition adaptable Central Tire Inflation System (CTIS), and a potent engine/drive train combination utilizing the Caterpillar C-12 engine. The Caterpillar C-12 engine is a turbo-charged, four-stroke, 6-cylinder, 12 l displacement diesel engine. The MTVR is the USMC prime mover for the M777 howitzer, fuel and water assets, troops and a wide variety of equipment.

The **LVS** (Logistics Vehicle System) is a modular assortment of eight-wheel drive all-terrain vehicles used by the USMC. It is powered by a Detroit Diesel 8V92TA engine, which is a turbo-charged, two-stroke, 8-cylinder, 12 l displacement diesel engine. The LVS was fielded in 1985 as the USMC heavy tactical vehicle system. It was designed and manufactured by the Oshkosh Truck Corporation. The U.S. Army has a similar tactical vehicle called the Heavy Expanded Mobility Tactical Truck (HEMTT). The key difference between the two is the LVS' ability to interchange Front Power Units with Rear Body Units. The LVS also steers through both standard wheel pivoting (as on a typical automobile) and hydraulic yaw steering (by articulating the Front Power Unit against the Rear Body Unit). This gives the LVS remarkable maneuverability for its size.

The **AAVP7A1** (Amphibious Assault Vehicle) is a fully tracked amphibious landing vehicle manufactured by FMC Corporation (now BAE Systems Land and Armaments). It is powered by a Cummings VT400 engine, which is a turbo-charged, four-stroke, 8-cylinder, 14.8 l displacement diesel engine. The AAVP7A1 is the current amphibious troop transport of the USMC. It is used by USMC Assault Amphibian Battalions to land the surface assault elements of the landing force and their equipment in a single lift from assault shipping during amphibious operations to inland objectives, conduct mechanized operations, and related combat support in subsequent mechanized operations ashore.

[b] Model year and odometer readings were only available for two vehicles.

[c] **Loop Driving Cycle**: An 1.8 km round-trip loop with driving time of 100 – 130 seconds over paved and concrete surfaces was followed in each of the tests as documented in Watson et al. (2008a). This test loop has an approximately uniform slope resulting in a 1.1° uphill slope on the tank track and a 1.1° downhill slope on Rainbow Canyon Road with fairly level driving on the connector road and Berkeley road.

Extended Driving Cycle (10-21 minutes): More high speed cruising and less frequent acceleration and deceleration.

Accelerated Driving Cycle Description: The vehicles stopped ~10 – 15 meters in front of the testing location and accelerated where the in-plume and cross-plume systems were operating.

[d] Only had model year and odometer reading for one vehicle

[e] Unidentified vehicles in IPETS sampling are not included.

Table 3-6. Emission Factors (EF) for military vehicles measured for the SERDP Study during April 2007.[a]

				Percent of PM[b]			g/kg Fuel[c]			
Vehicle Type[d]	**Vehicle Test Cycle[e]**	**Type of Sampling**	**Vehicle ID**	**EC (%)**	**OC(%)**	**OC_{corr} (%)[f]**	**EC EF**	**OC EF**	**OC_{corr} EF[f]**	**PM EF**
MTVR	Acceleration	On-board	1	NA[g]	NA	NA	NA	NA	NA	0.45[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.86[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.59[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	1.49[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.59[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.86[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.38[h]
MTVR	Acceleration	On-board	1	NA	NA	NA	NA	NA	NA	0.33[h]
MTVR	Loop Driving	On-board	1	21.48	134.14[i]	55.58	0.13	0.84[i]	0.35	0.63
MTVR	Loop Driving	On-board	1	60.43	60.88	26.43	0.12	0.12	0.05	0.20
MTVR	Loop Driving	On-board	1	44.87	64.30	34.35	0.10	0.14	0.08	0.23
MTVR	Loop Driving	On-board	1	64.96	61.98	19.11	0.11	0.10	0.03	0.17
MTVR	Loop Driving	On-board	1	67.62	57.90	28.44	0.13	0.12	0.06	0.20
MTVR	Extended Driving	On-board	1	50.14	32.74	12.35	0.10	0.06	0.02	0.19
MTVR	Loop Driving	On-board	2	61.84	53.15	22.50	0.11	0.10	0.04	0.19
MTVR	Loop Driving	On-board	2	58.71	67.53	20.31	0.09	0.10	0.03	0.15
MTVR	Loop Driving	On-board	2	56.38	67.65	26.49	0.09	0.11	0.04	0.16
MTVR	Extended Driving	On-board	2	66.25	61.17	24.85	0.10	0.10	0.04	0.16
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.37[h]
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.15[h]
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.43[h]
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.67[h]
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.26[h]
MTVR	Acceleration	On-board	3	NA	NA	NA	NA	NA	NA	0.26[h]
MTVR	Acceleration	On-board	4	NA	NA	NA	NA	NA	NA	0.81[h]
MTVR	Acceleration	On-board	4	NA	NA	NA	NA	NA	NA	0.42[h]
MTVR	Acceleration	On-board	4	NA	NA	NA	NA	NA	NA	0.23[h]
MTVR	Acceleration	On-board	4	NA	NA	NA	NA	NA	NA	0.34[h]
MTVR	Acceleration	On-board	4	NA	NA	NA	NA	NA	NA	0.53[h]
MTVR	Acceleration	On-board	5	NA	NA	NA	NA	NA	NA	0.53[h]
MTVR	Acceleration	On-board	5	NA	NA	NA	NA	NA	NA	0.26[h]
MTVR	Acceleration	On-board	6	NA	NA	NA	NA	NA	NA	0.20[h]
MTVR	Acceleration	On-board	6	NA	NA	NA	NA	NA	NA	0.44[h]
MTVR	Acceleration	On-board	7	NA	NA	NA	NA	NA	NA	0.06[h]
MTVR	Acceleration	On-board	8	NA	NA	NA	NA	NA	NA	0.19[h]
MTVR	Acceleration	On-board	9	NA	NA	NA	NA	NA	NA	0.08[h]
MTVR	Acceleration	On-board	10	NA	NA	NA	NA	NA	NA	0.31[h]
MTVR	Acceleration	On-board	11	NA	NA	NA	NA	NA	NA	0.59[h]

Table 3-6. Continued.

				Percent of PM[b]			g/kg Fuel[c]			
Vehicle Type[d]	**Vehicle Test Cycle[e]**	**Type of Sampling**	**Vehicle ID**	**EC (%)**	**OC(%)**	**OC_{corr} (%)[f]**	**EC EF**	**OC EF**	**OC_{corr} EF[f]**	**PM EF**
MTVR, LVS	Acceleration	IPETS	9, others[j]	47.96	78.30	2.57	0.02	0.04	0.00	0.05
MTVR, LVS	Acceleration	IPETS	1,3,4,5,6, 7,8,10,12, 13,others[j]	42.15	64.14	36.14	0.07	0.11	0.06	0.17
LVS	Acceleration	On-board	12	NA	NA	NA	NA	NA	NA	11.03[h]
LVS	Acceleration	On-board	12	NA	NA	NA	NA	NA	NA	5.26[h]
LVS	Acceleration	On-board	12	NA	NA	NA	NA	NA	NA	2.99[h]
LVS	Acceleration	On-board	13	NA	NA	NA	NA	NA	NA	2.52[h]
LVS	Loop Driving	On-board	12	26.27	55.30	52.60	0.36	0.76	0.72	1.38
LVS	Loop Driving	On-board	12	54.93	38.21	32.26	0.61	0.42	0.36	1.11
LVS	Loop Driving	On-board	12	54.66	30.24	25.62	0.64	0.36	0.30	1.18
LVS	Extended Driving	On-board	12	32.81	29.36	24.40	0.37	0.33	0.27	1.13
AAVPA1	Idle	On-board	14	62.20	26.16	17.27	1.04	0.44	0.29	1.67
	Average[k]			**51.39**	**53.06**	**27.13**	**0.25**	**0.21**	**0.16**	**0.53**
	Standard Deviation			**13.90**	**16.30**	**12.95**	**0.28**	**0.20**	**0.19**	**0.54**

[a] Watson et al. (2008a).

[b] No size cut was performed on this study.

[c] Assumed a carbon content of 0.856 for the fuel.

[d] MTVR = Medium Tactical Vehicle Replacement. LVS = Logistics Vehicles System. AAVP7A1 = Amphibious Assault Vehicle.

[e] See Table 3-5 for description of test cycle.

[f] Organic sampling artifact corrected by backup filter.

[g] NA = Not available or not applicable. TSI DustTrak does not differentiate between EC and OC.

[h] PM emission factor measured by the TSI DustTrak and is excluded from the average and standard deviation.

[i] OC emission factor exceeded the corresponding PM emission factor.

[j] Others: unable to identify all of the individual vehicles.

[k] Average includes two IPETS and 15 on-board samples.

Table 3-7. Summary of average $PM_{2.5}$ vehicle engine emission factors measured during recent studies.

	Average $PM_{2.5}$ Emission Factor (g/mile except SERDP in g/kg)					
Study	**Light-Duty Gasoline Vehicle (LDGV)**	**Light-Duty Gasoline Trucks (LDGT1)**	**Medium Heavy-duty (MHDV) Diesel Vehicle**	**Heavy Heavy-duty (HHDV) Diesel Vehicle**	**Urban Bus (UB)**	**Diesel Generator (Diesel BUG)[a]**
Gas/Diesel Split (U.S. EPA 2008b; 2008c)	0.030 ± 0.052		0.70 ± 0.88[b]	0.86 ± 0.62[b]	1.49 ± 0.89[b]	NA
Kansas City (Fujita et al., 2007a; 2007b)	0.021 ± 0.026	0.023 ± 0.023	NA[c]	NA	NA	NA
CRC E55/59 (Phases I and II, Clark et al., 2007)	NA	NA	NA	0.63 ± 0.57[d]	NA	NA
SERDP (Watson et al., 2008a)	NA	NA	NA	0.53 ± 0.54[e]	NA	1.15 ± 0.93[e]

[a] Diesel Backup Generator (BUG)

[b] Hot City-Suburban Route (HCS) cycle

[c] Not Available or Not Applicable

[d] Based on five Urban Dynamometer Driving Schedule (UDDS) tests of three and six HHDVs for the Phase I and Phase II Studies, respectively.

[e] Units: g/kg fuel assuming a fuel carbon content of 85.6%.

Table 3-8. Summary of biomass burned during the FLAME Study.

Biofuel Types	Biofuel Components	Number of Samples	Fuel Moisture (%)	C(%)/N(%)[a]	Phase
Ceanothus		1	24.3	48/1.3	
Chemise	Branches and Leaves Dried	5	11.8 - 19.4	49/1	Flaming; Smoldering
	Branches Dried	2	30.7 - 35.0		
	Branches Fresh	3	23.9 - 50.0		
	Leaves Dried	3	8.7 - 19.6		
	Leaves Fresh	2	52.2 - 60.4		
Dambo Grass	Leaves Dried	2	6.3	49/0.5	Mixed-phase
Excelsior (Shredded Aspen Wood Product)	Dried	2	5.9	48/0.07	Mixed-phase
Lignin		1	17	-	Mixed-phase
Lodgepole Pine	Branches Dried	3	9.0 - 9.3	42-50/0.3-1.2	Mixed-phase
	Needles Fresh	1	76.4 - 90.6		
	Needles Litter	2	13.7 - 15.6		
	Needles Duff	2	20.1 - 24.1		
Manzanita	Branches Fresh	3	62.9 - 70.5	48/0.8	Mixed-phase
	Leaves Dried	2	52.5 - 59.8		
	Leaves Fresh	1	75.4 - 107.0		
Montana Grass	Leaves Dried	1	5.0 - 13.0	44/0.17	Mixed-phase
	Leaves Fresh	5	17.5 - 94.0		
Palmetto	Leaves Fresh	3	5.0 - 7.1	51/1.0	Mixed-phase
Ponderosa Pine	Branches (Large) Dried	3	9.1 - 9.3	46-49/0.04-1.3	Mixed-phase
	Branches (Large) Fresh	3	63.0 - 72.0		
	Branches (Small) Dried	2	9.0 - 9.6		
	Branches (Small) Fresh	3	43.4 - 50.5		
	Needles Dried	2	7.3		
	Needles Fresh	3	57.5 - 60.7		
	Needles Litter	13	9.2 - 10.5		
	Needles and Branches Litter	1	10.3		
	Needles Duff	4	13.9 - 14.7		
Puerto Rico Fern		1	12.8	46/0.4	Mixed-phase
Rice	Straws	5	8.1 - 10.1	39-46/0.6-0.9	Flaming; Smoldering

Table 3-8. Continued

Biofuel Types	Biofuel Components	Number of Samples	Fuel Moisture (%)	C(%)/N(%)[a]	Phase[c]
Sagebrush	Branches and Leaves Dried	2	8.3	47-51/1.5-2.1	Mixed-phase
	Foliage and Sticks	1	9.1		
Tundra	Core Fresh	1	113	31/0.5	Mixed-phase
Juniper	Foliage and Sticks Fresh	1	8.7	49-0.9	Mixed-phase
Wax Myrtle	Branches and Foliage	1	13.6	48-53/1.1-1.4	Mixed-phase
White Pine	Needles Dried	2	8.2	49-0.5	Mixed-phase

[a] Fuel carbon (C) and nitrogen (N) content, with respect to dry fuel mass.

Table 3-9. Summary of the emission factors from DRI's laboratory tests.

				Emission Factors (g/kg fuel)			
Source	**Dilution Ratio**	**Quartz Filter ID**	**Number of Measurements**	**$PM_{2.5}$**	**EC**	**OC**	**OC_{corr}[a]**
Diesel[b] Generator	85	STRQQ184-187	2[c]	0.56±0.02[d]	0.33±0.09	0.09±0.01	0.07±0.01
Diesel Generator	43	STRQQ178-181	2[c]	0.63±0.02	0.36±0.09	0.14±0.01	0.11±0.01
Diesel Generator	19	STRQQ174-177	2[c]	0.67±0.02	0.37±0.10	0.14±0.01	0.11±0.01
Average				0.62±0.02	0.35±0.09	0.12±0.01	0.10±0.01
RWC[e]	105-117	STRQQ122-129	8[f]	1.74±0.21	0.43±0.16	2.41±0.35	1.17±0.18
RWC	40	STRQQ130-136	7[f]	1.48±0.11	0.36±0.12	1.03±0.24	0.69±0.16
RWC	18	STRQQ137-144	8[f]	0.60±0.13	0.22±0.08	0.44±0.34	0.26±0.34
Average				1.28±0.16	0.34±0.12	1.29±0.31	0.71±0.24

[a] Corrected for organic sampling artifact by subtracting backup quartz filter OC.

[b] Onan Cummins diesel generator.

[c] See Appendix_DieselTestSummary.xls on the enclosed CD for detailed test conditions.

[d] Average ± standard deviation of the measurements.

[e] Residential wood combustion with commercial woodstove burning white oak tree wood at the DRI Source Characterization Laboratory.

[f] See Table D-1 of Appendix D in Phase I of this study (Chow et al., 2006d).

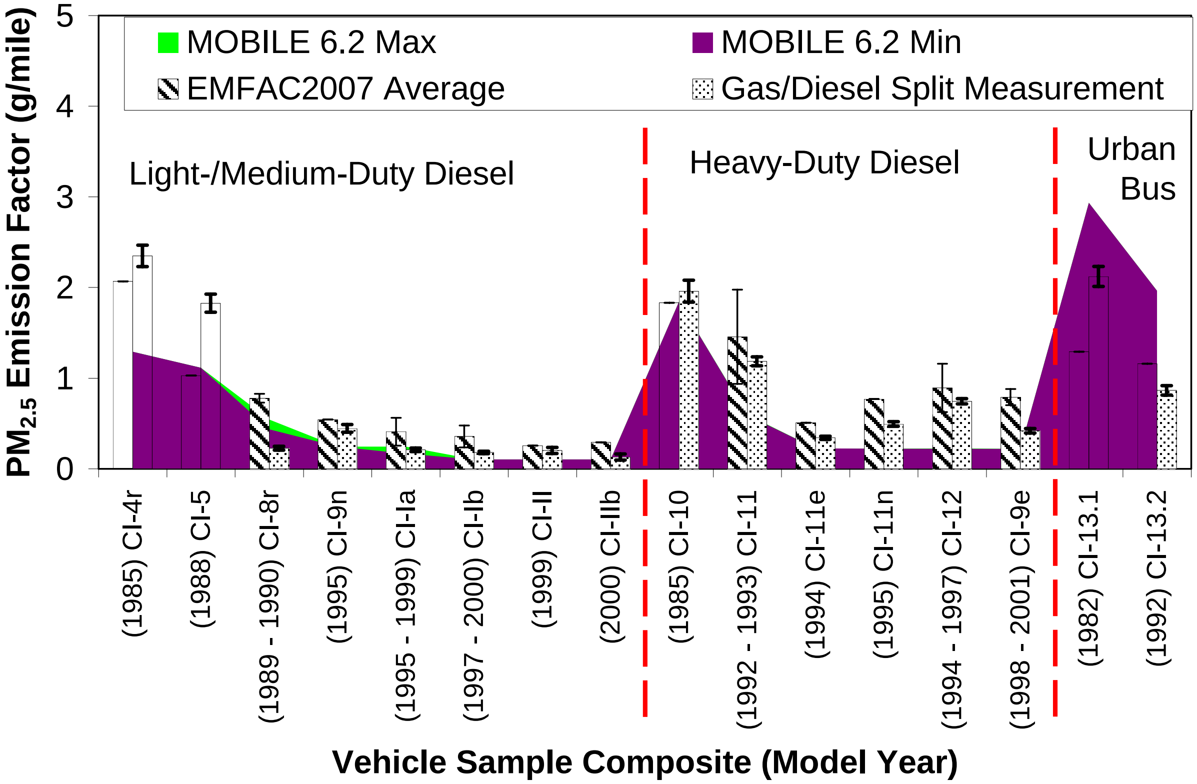


Figure 3-1. Comparisons of diesel-fueled vehicle emission factors of the Hot City-Suburban route (HCS) driving cycle from the Gas/Diesel Split Study with MOBILE 6.2 and EMFAC 2007 emission model estimates for the Federal Test Procedure (FTP) cycle. See Table 3-1 for vehicle identification codes and composite information. Composites in each diesel group (heavy-duty, medium-duty, and bus) are ordered by the average vehicle model year. Error bars associated with the Gas/Diesel Split Study data indicate measurement uncertainties.

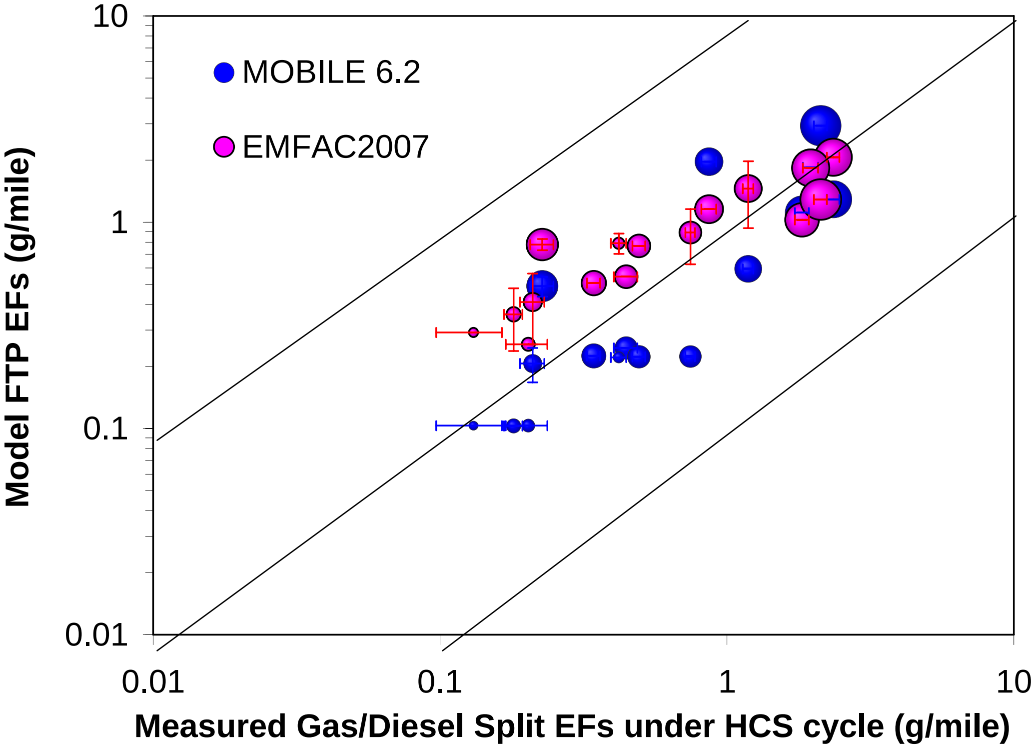
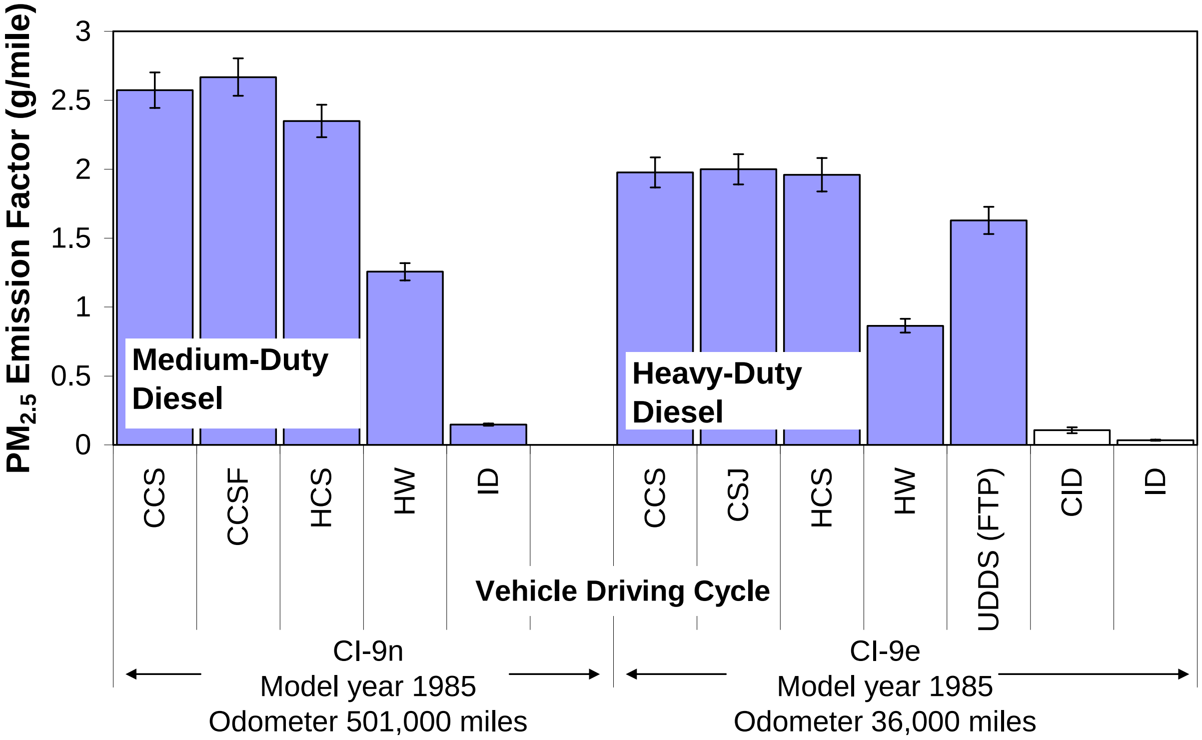


Figure 3-2. Comparison of MOBILE 6.2 and EMFAC2007 modeled and measured $PM_{2.5}$ emission factors (EFs) from the Gas/Diesel Split Study diesel-fueled vehicles under the Hot City-Suburban route (HCS) cycle. Bubble diameter represents mean vehicle age from smallest (zero; i.e., model year 2001) to largest (19; i.e., model year 1982).



Vehicle Driving Cycle:

- CCS (Cold City-Suburban Route)
- CCSF (Cold City-Suburban Route operated with Federal fuel)
- HCS (Hot City-Suburban Route)
- HW (Highway Cycle)
- ID (Idle)
- CSJ (City-Suburban with Jacobs Brake)
- HCS (Hot City-Suburban Route)
- UDDS (Urban Dynamometer Driving Schedule)
- CID (Cold Idle)

Vehicle Classification:

- MOBILE 6.2
  - Medium Heavy-Duty Diesel Vehicle (HDDV7; 26,001 – 33,000 lbs)
  - Heavy Heavy-Duty Diesel Vehicle (HDDV8; >33,000 lbs)
- EMFAC2007
  - Medium Heavy-Duty Diesel Vehicle (MHDV; 14,001 – 33,000 lbs)
  - Heavy Heavy-Duty Diesel Vehicle (HHDV; 33, 001 – 60,000 lbs)

Vehicle Identifier:

- CI-9n (HDDV7 in Mobile 6.2; MHDV in EMFAC2007)
- CI-9e (HDDV8 in Mobile 6.2; HHDV in EMFAC2007)

Unit:

- Unit are in g/mile except for ID, which is in g/min vehicle travelled.

Figure 3-3. Comparison of measured inter-modal emission factors for a medium heavy-duty diesel vehicle (CI-9n) and heavy heavy-duty diesel vehicle (CI-9e). Note that the medium heavy-duty vehicle has much higher mileage.

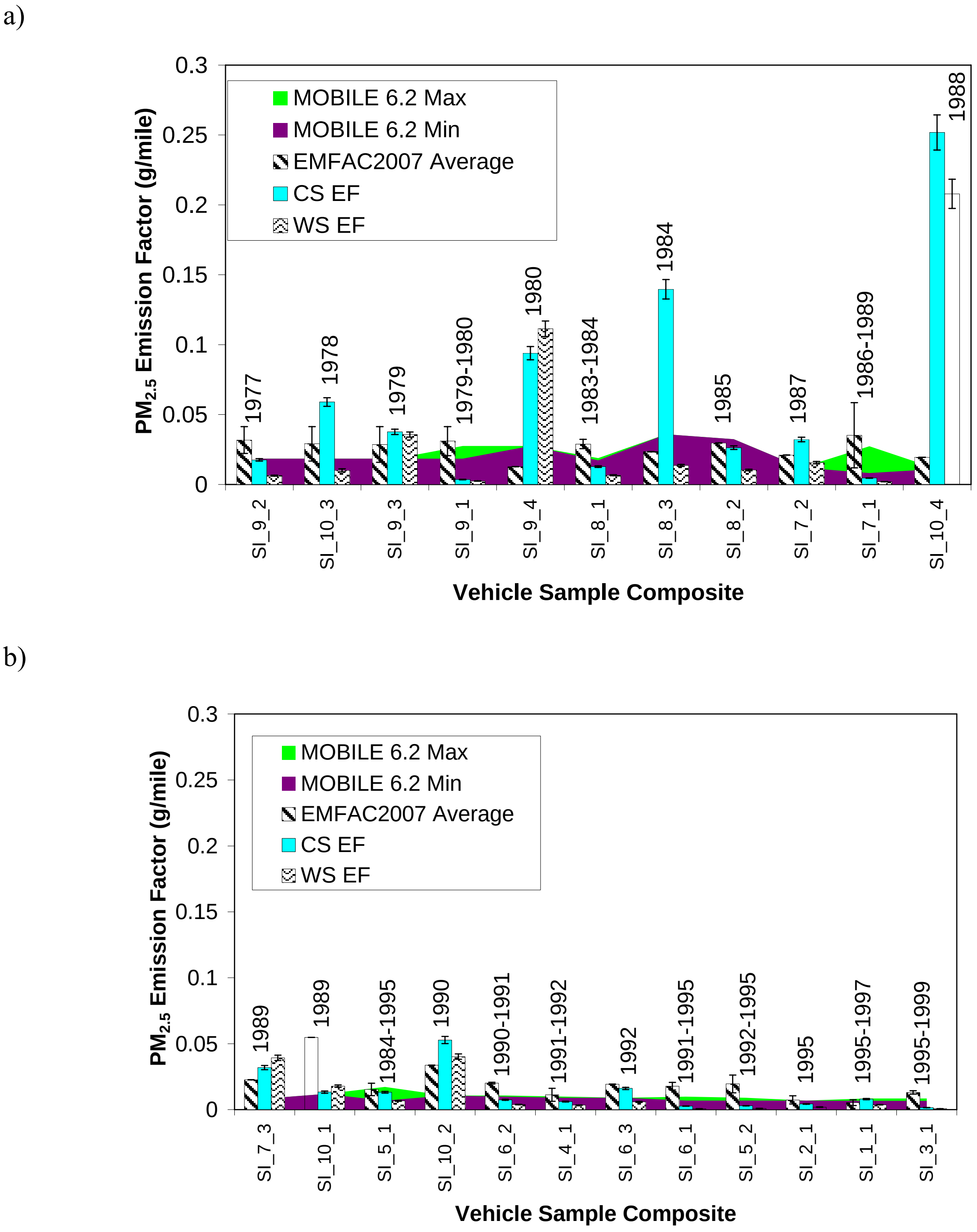


Figure 3-4. Comparisons of gasoline-fueled emission factors from the Gas/Diesel Split Study with MOBILE 6.2 and EMFAC2007 emission model estimates for model years: a) 1977 – 1988; and b) 1989 – 1999. See Table 3-1 for composite information. Composites are ordered by average vehicle model year. Model year(s) are shown above the bar in chronological order. Error bars indicate measurement uncertainties.

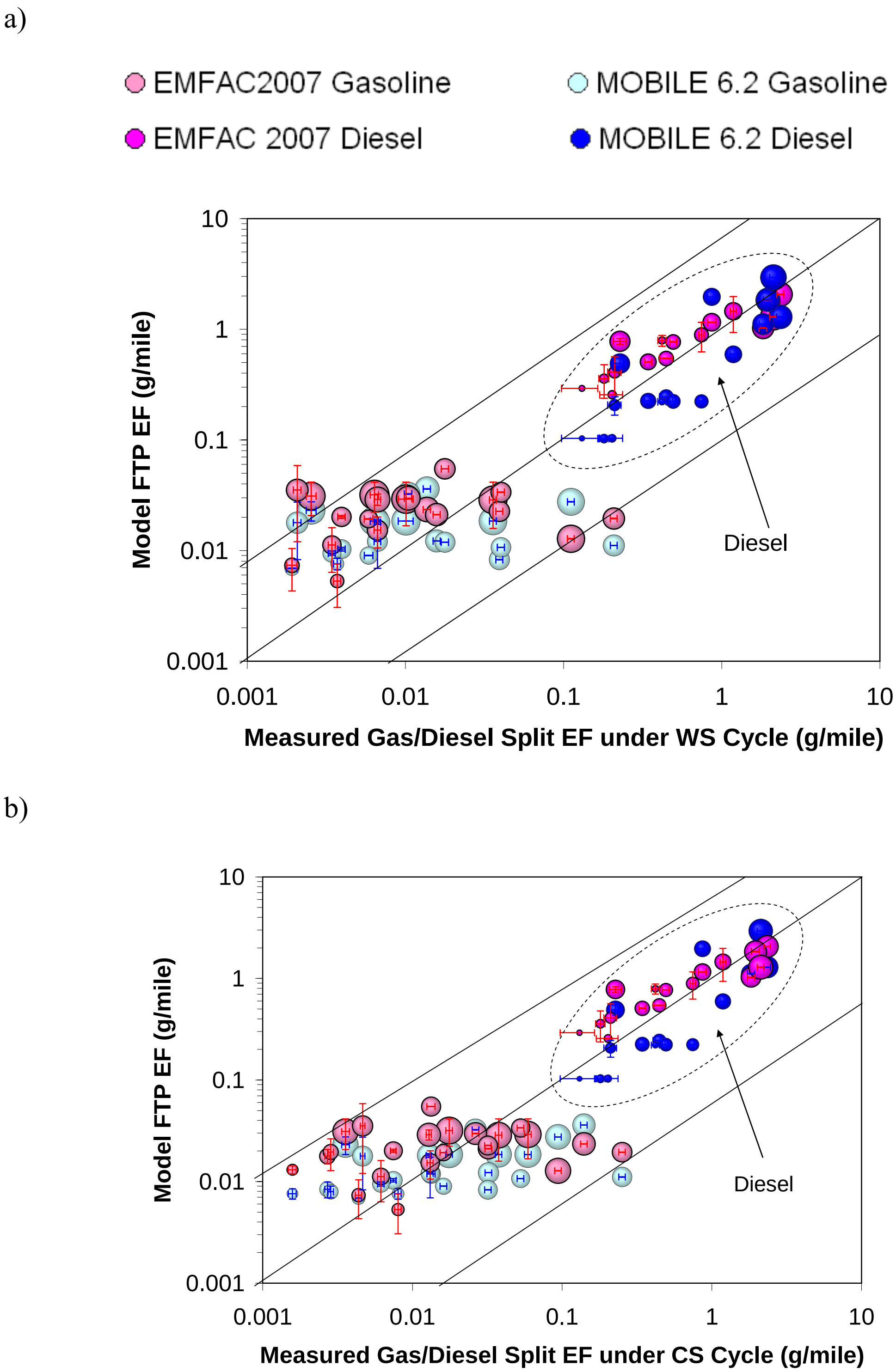


Figure 3-5. Comparison of MOBILE 6.2 and EMFAC2007 modeled and measured $PM_{2.5}$ emission factors (EFs) from Gas/Diesel Split Study under: a) Warm Start (WS); and b) Cold Start (CS) cycles. Bubble diameter represents average vehicle age from smallest (zero; i.e., model year 2001) to largest (19 for diesel-fueled vehicles [model year 1982]; 24 for gasoline-fueled vehicles [model year 1977]).

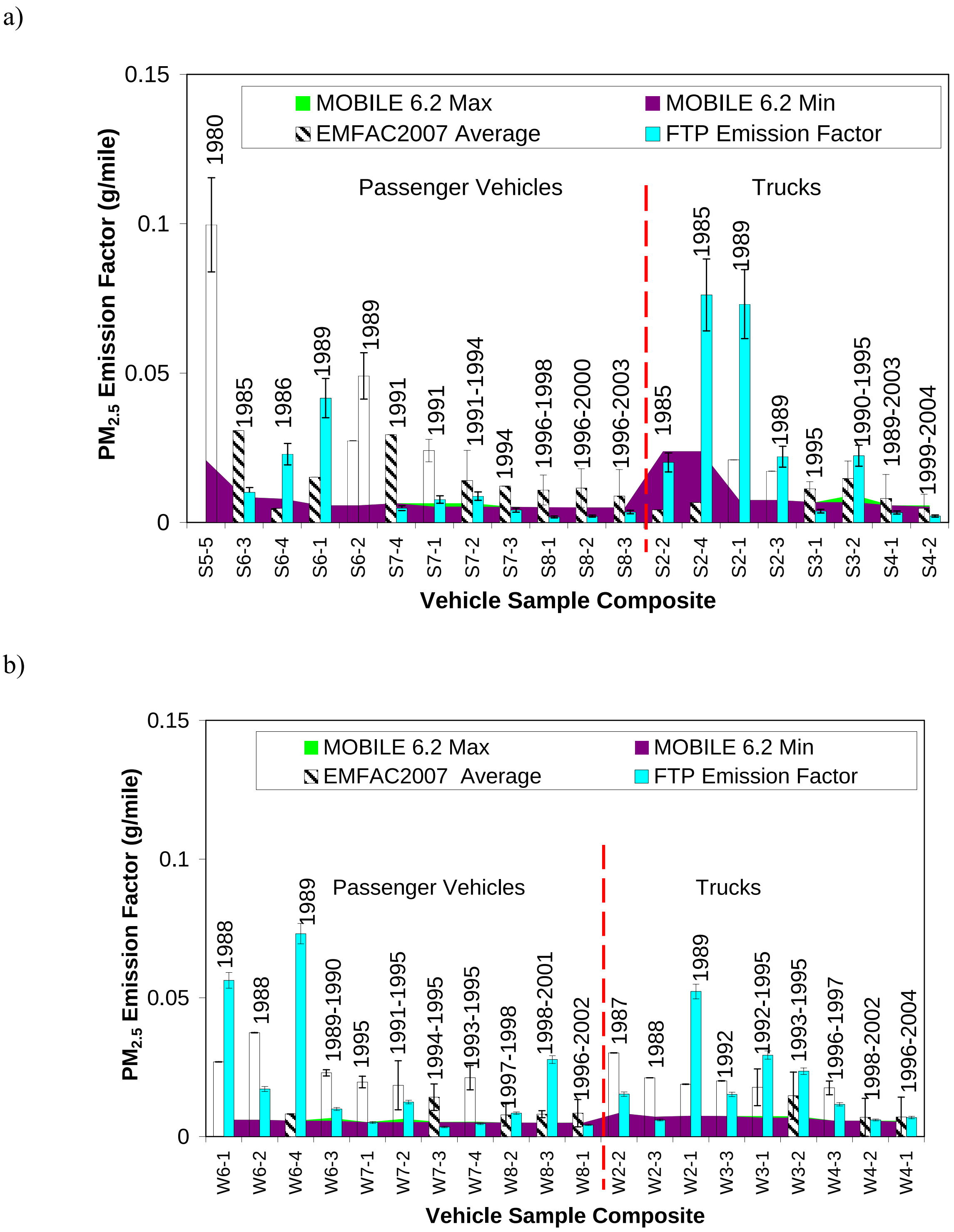
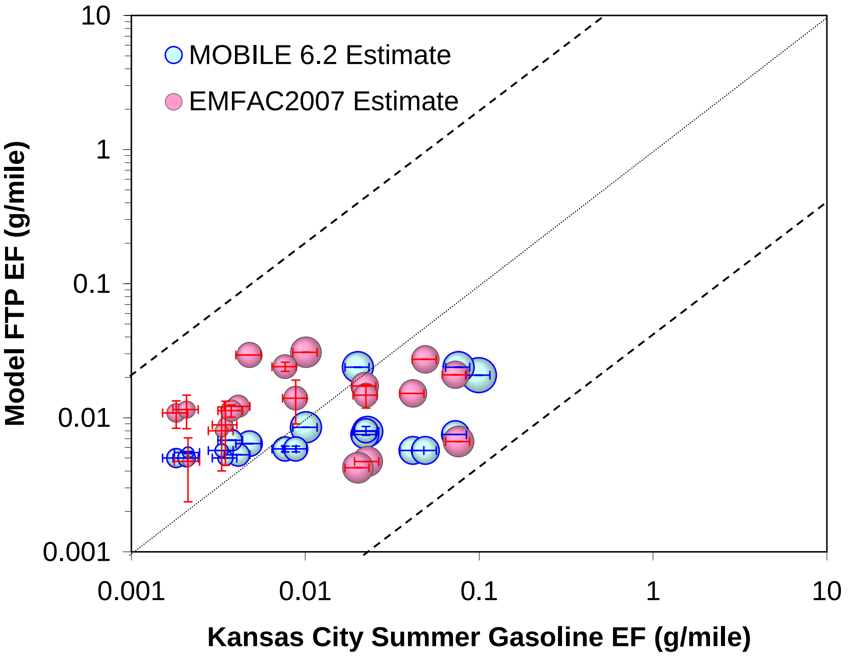


Figure 3-6. Comparisons of: a) summer; and b) winter gasoline-fueled vehicle $PM_{2.5}$ emission factors from the Kansas City Study (U.S. EPA 2008a, 2008b) with emission model estimates. See Table 3-2 for composite information. Composites are ordered by average vehicle model year. Model year(s) are shown above the bar in chronological order. Error bars indicate measurement uncertainties.

a)



b)

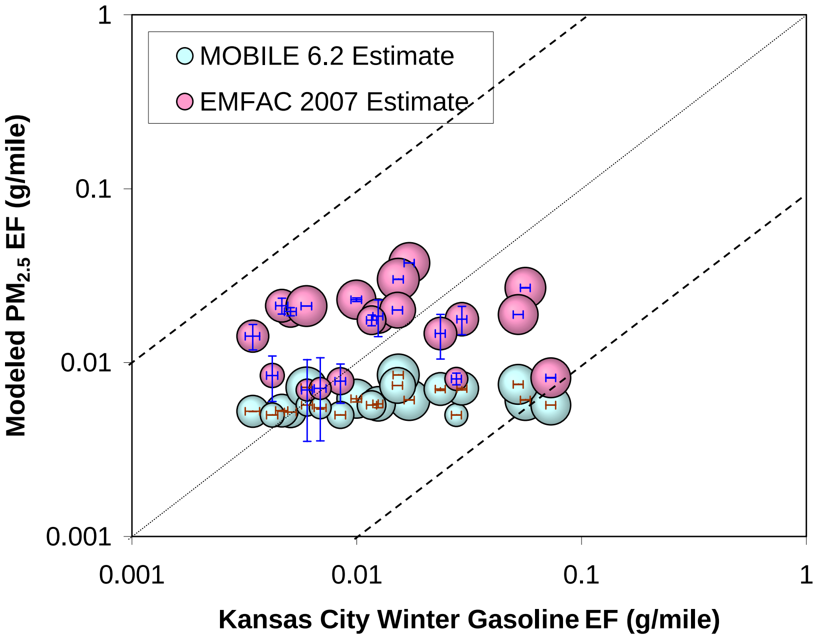
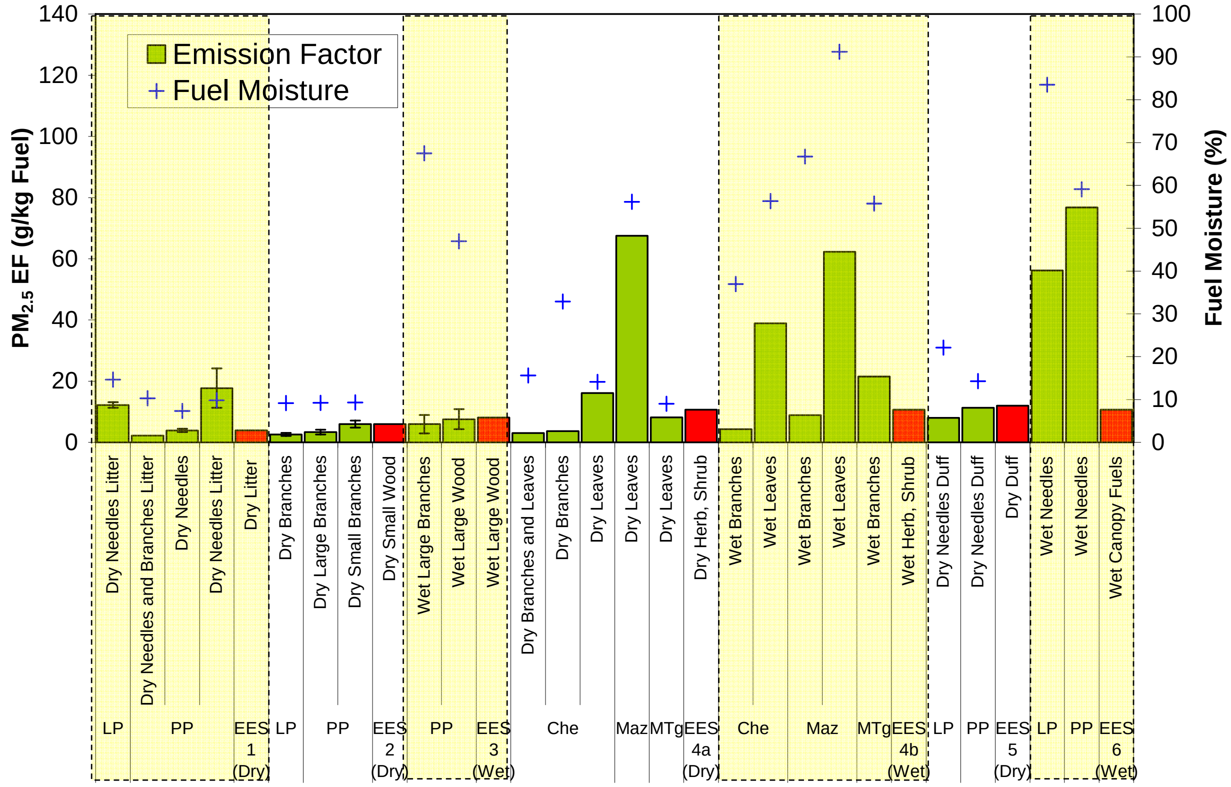


Figure 3-7. Comparison of MOBILE 6.2 and EMFAC2007 modeled and measured $PM_{2.5}$ emission factors for Kansas City Study gasoline vehicles tested in: a) summer of 2004; and b) winter of 2005 under three FTP cycles. Bubble diameter represents mean vehicle age from smallest (zero; i.e., model year 2004) to largest (24; e.g., model year 1980).



EES emission factors are shown by the red bar.

EES Categories:

EES 1: Dry Litter
EES 2: Small Dry Wood
EES 3: Large Wet Wood
EES 4a: Dry Herb and Shrub
EES 4b: Wet Herb and Shrub
EES 5: Dry Duff
EES 6 Wet Canopy Fuels

Biofuel types:

Che: Chemise
Maz: Manzanita
MTg: Montana Grass
PP: Ponderosa Pine
LP: Lodgepole Pine.

Figure 3-8. Comparison of FLAME emission factors (EFs) with those in the California Air Resource Board's Emission Estimation System (EES). FLAME emission factors are classified into the six EES categories and separated by dry and wet moisture content indicated by the boxes in the Figure.

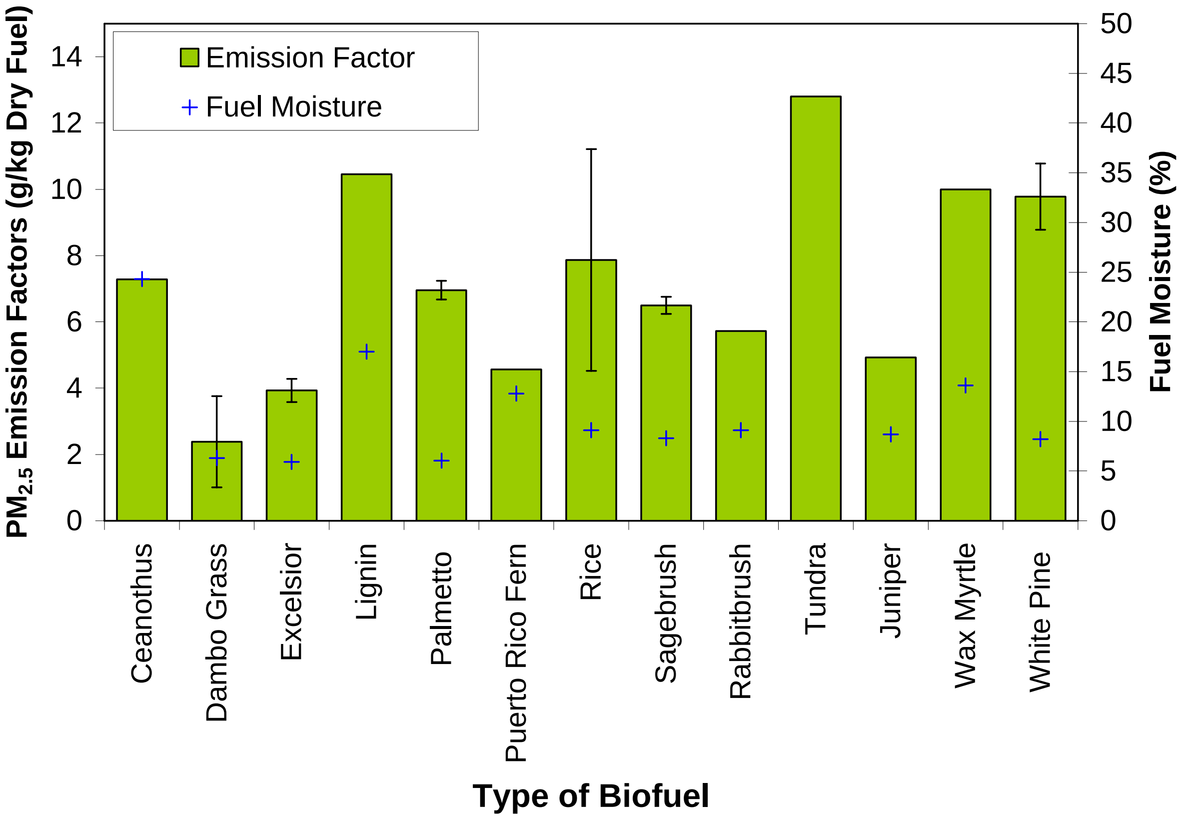


Figure 3-9. Additional FLAME emission factors and corresponding fuel moisture (fuel moisture of fresh tundra cores was not determined; no fuel moisture exceeded 50%).

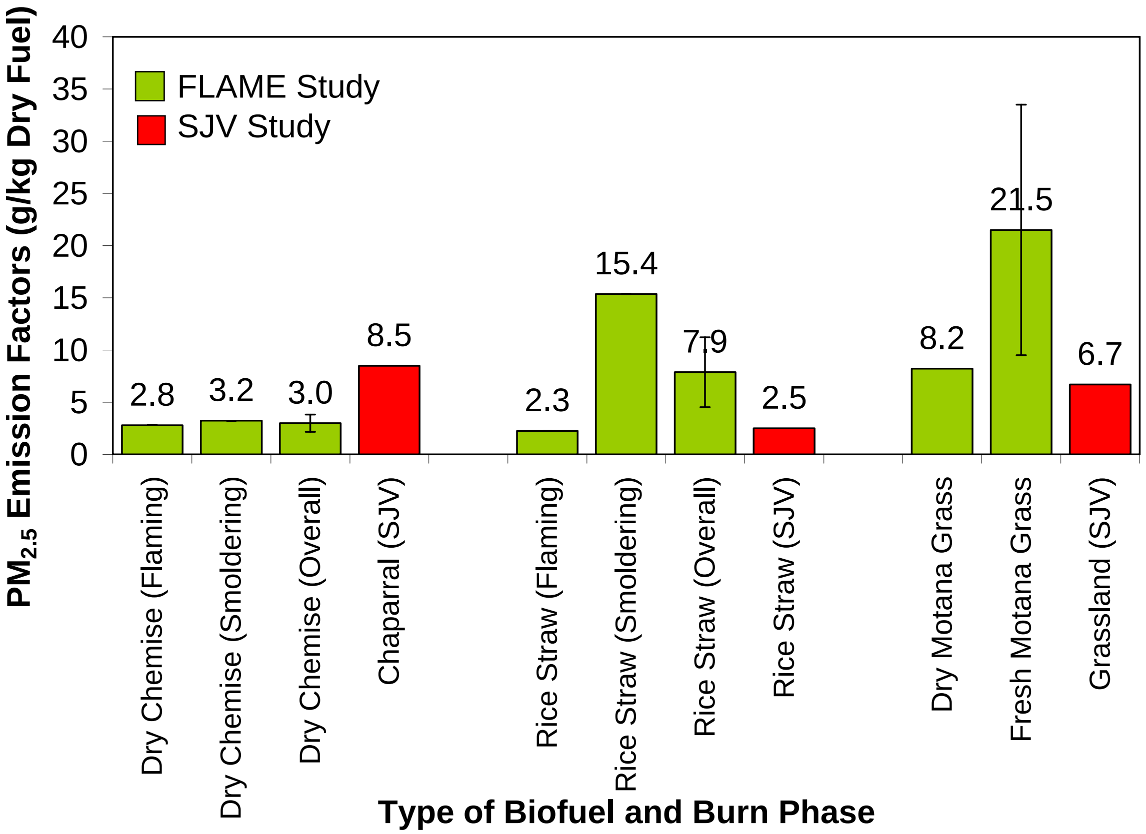


Figure 3-10. Emission factors (shown above each bar in g/kg dry fuel) from different burning phases measured during the FLAME Study and comparisons with emission factors from California's San Joaquin Valley (SJV).

4. SOURCE PROFILES AND OTHER TOOLS FOR DEVELOPING A BC AND OC EMISSION INVENTORY FOR CALIFORNIA

Emission inventories serve as inputs to air quality and global climate models. The NEI, for example, contains estimates of CO, VOC, SO_2, NO_x, ammonia (NH_3), $PM_{2.5}$, and PM_{10} emissions from thousands of individual sources. Chemical models such as the Community Multiscale Air Quality (CMAQ) model (http://www.epa.gov/AMD/CMAQ/; Appel et al., 2007; 2008) are used to estimate ambient concentrations of U.S. EPA criteria pollutants (i.e., CO, SO_2, NO_x, O_3, Pb, and PM). CMAQ simulates photochemical transformations, gas and particle formation, and deposition. Pollutant transport is driven by a meteorological model such as the National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5; http://www.mmm.ucar.edu/mm5/; Grell et al., 1994). Annual average emission rates from an inventory are assigned to geographical grid squares and given a temporal distribution with an emissions model such as Sparse Matrix Operator Kernel Emissions (SMOKE; http://www.smoke-model.org/index.cfm; Houyoux et al., 2000) prior to serving as CMAQ input. The SMOKE-MM5-CMAQ modeling system has been widely used in the U.S. and abroad (e.g., Yu et al., 2008).

EC and OC emissions are estimated by multiplying $PM_{2.5}$ emissions from various sources by the respective fractions of EC and OC in the emitted $PM_{2.5}$. These fractions are commonly referred to as "source profiles," which represent the mass fraction of a chemical component (e.g., EC and OC) in $PM_{2.5}$ or PM_{10} emissions from a specific source type. Source profiles are determined by sampling from a diluted plume (to allow for condensation) onto filters that can be analyzed in the laboratory. Composite profiles are constructed by averaging chemical abundances from several tests of similar sources, using the standard deviation of the average as an estimate of the profile uncertainties. One of the most comprehensive compilations of chemically-speciated source profiles is the U.S. EPA's SPECIATE version 4.0 source profile library (U.S. EPA, 2007). SPECIATE version 4.0 contains 1,215 gaseous and 2,865 particulate source profiles. The NEI and California emission inventories estimate $PM_{2.5}$ emissions for thousands of individual sources. Because the available source profiles are far less comprehensive, it is necessary to aggregate similar sources in an inventory, for example, to separate the diesel fuel combustion from the stationary and area sources.

4.1 SMOKE-MM5-CMAQ Estimates of Ambient EC Concentrations

U.S. EPA STAR Grant RD-83215601-0, “Evaluation of Regional-Scale Receptor Models” is testing the ability of receptor models to determine regional-scale contributions to $SO_4^=$ at remote National Parks. This study created synthetic $PM_{2.5}$ data sets for National Parks in the eastern U.S. using realistic meteorological and aerosol chemistry models. The data sets contain species similar to those measured in the Interagency Monitoring of PROtected Visual Environments (IMPROVE; Eldred, 1988; Malm et al., 2000) network, i.e., EC and OC, ions ($SO_4^=$, nitrate [NO_3^-], chloride [Cl^-], ammonium [NH_4^+]), and trace elements. The synthetic data sets were constructed using: 1) $PM_{2.5}$ emissions from the NEI; 2) speciated source profiles corresponding to sources in the NEI; and 3) high-resolution meteorological fields generated with MM5 by the Visibility Improvement – State and Tribal Association of the Southeast (VISTAS) Regional Planning Organization for the year 2002. The SMOKE model assigns default source profiles consisting of $SO_4^=$, NO_3^-, OC, and EC by source categories in the NEI. The U.S. EPA is developing a means of cross referencing source profiles in its SPECIATE source profile library to sources in the NEI. The biggest challenge in this approach is to relate a relatively small number of available source profiles to a large number of sources in the NEI. The methodology used in this study is directly relevant to the issue of building a carbonaceous aerosol emission inventory for California.

To simplify the modeling problem, NEI sources were aggregated to SCC Level 3, resulting in 895 source categories in the modeling domain (east of the Mississippi River). This number was reduced to 101 source categories by retaining those sources which accounted for at least 95% of the NO_x, SO_2, NH_3, and $PM_{2.5}$ emitted in the modeling domain. Profiles in the DRI and U.S. EPA SPECIATE PM source profile libraries were examined. Many of the profiles in SPECIATE did not contain EC and OC compositions, and many others used carbon analysis methods that were not comparable to the IMPROVE thermal/optical reflectance procedure (Chow et al., 1993; 2007a). Table 4-1 summarizes the list of 101 source categories from the NEI with numerical codes derived from the SCCs and descriptions concatenated to SCC Level 3. Table 4-2 documents the corresponding source profiles (NEI_Profiles.xls on the enclosed CD) chosen to represent the sources in Table 4-1. This set of profiles was assigned to sources in the NEI and appended to the default profiles by SMOKE.

The SMOKE-MM5-CMAQ modeling system was used to generate hourly concentration data sets for IMPROVE monitoring sites at Brigantine National Wildlife Refuge (BRIG), NJ, and Great Smoky Mountains National Park (GRSM), TN, during summer 2002. Measured speciated $PM_{2.5}$ concentrations on a 24-hour average basis are available from IMPROVE (http://vista.cira.colostate.edu/improve/) for both sites during this period. The model underestimated measured EC concentrations at both sites. At the BRIG site, the average measured and model estimated EC concentrations were 0.40 and 0.30 $\mu g/m^3$, respectively. At the GRSM site, the average measured and model estimated EC concentrations were 0.37 and 0.26 $\mu g/m^3$, respectively.

Figure 4-1 compares measured and model estimated 24-hour average EC concentrations at the GRSM site. In this comparison, model estimated EC was based on the appended source profiles described in Tables 4-1 and 4-2. From a modeling perspective, the comparisons are reasonably good with an average difference of -21%. The comparisons help to evaluate the emission inventory and choice of source profiles. Discrepancies between measured and model-estimated concentrations result, in part, from inaccuracies in the simulation of PM transport, chemical change, and removal processes. This example illustrates an approach that can be used to construct a BC/EC emission inventory for California. California's inventory provides $PM_{2.5}$ emissions for a large number of source types. These can be transformed to BC/EC and OC emissions by multiplying the $PM_{2.5}$ emissions for a particular source by the BC/EC and OC fractions of $PM_{2.5}$ in a corresponding source profile.

4.2 Source Profile Compilation for BC/EC and OC

Developing EC and OC emission inventories from $PM_{2.5}$ emission factors/inventories requires reliable source profiles to represent EC and OC mass fractions from source categories contained in the inventory. The most recent version of SPECIATE, version 4.0, was released in 2006. This integrates U.S. EPA, California Institute of Technology (CalTech), ARB, DRI, and Texas Commission on Environmental Quality (TCEQ) speciation data (Chow et al., 2006b; U.S. EPA, 2007). All profiles have gone through uniform QA/QC processes and assigned quality ratings from A (excellent) to E (poor).

Unfortunately, SPECIATE version 4.0 lacks an effective update and documentation feature that allows new source profiles to be submitted by different researchers. Several source characterization studies have been completed since the last update, including the Lake Tahoe (Kuhns et al., 2004) and Las Vegas Carbon Apportionment (Green et al., 2004) Studies, the Gas/Diesel Split Study in southern California (Fujita et al., 2007a; 2007b), and the SERDP off-road diesel emissions Study (Watson et al., 2008a). These recent studies better represent OC and EC abundances in current emissions. Implementation of better burning practices and newer engine/fuel technologies indicates that the EC fraction is decreasing over time.

For this study, a total of 1,869 valid PM (all size ranges), including 810 valid $PM_{2.5}$, source profiles were retrieved with EC and/or OC fractions covering major source categories such as: 1) oil combustion; 2) oil refineries; 3) coal-fired power plants (CFPP); 4) residential coal combustion (RCC); 4) RWC; 5) agricultural burning (AgBurn); 6) open/prescribed burning; 7) forest fires; 8) on-road diesel vehicles; 9) on-road gasoline vehicles; 10) off-road diesel sources; 10) cooking; and 11) California soil (geological dust). There are also profiles representing a wide range of industrial activities.

Based on the 810 valid $PM_{2.5}$ source profiles, Figure 4-2 shows the variability of EC and OC fractions for major source types. Minor source types that are mostly miscellaneous industrial emissions are not presented in this Figure, since OC or EC are missing in some of the profiles provided by other groups. Although the statistics may be uncertain due to unequal numbers of profiles in each source category, the data generally agree with expectations. According to the median value, on-road diesel emissions display the highest EC abundances (50.8 ± 18.8%) of $PM_{2.5}$ mass, followed by off-road diesel (40.7 ± 19.6%), on-road gasoline (22.3 ± 14.1%), and RCC (19.0 ± 13.3%). The median $PM_{2.5}$ EC abundance in RWC emissions is ~9.6 ± 12.2%, in good agreement with that for agricultural and open burning, but substantially higher than that of forest fires (2.9 ± 1.4%). OC fractions are complementary to EC fractions except for oil combustion, refinery emissions, and California soils. California soil is dominated by crustal material while oil combustion and refinery profiles lack good mass closure, reflecting difficulties in characterizing very low emission rates from these sources.

The wide-range of EC and OC fractions within each source category complicates the selection of source profiles for receptor-oriented source apportionment and source-oriented emission inventories and CMAQ modeling. The variability of source emissions can be accounted for to some degree by combining the profiles (Chow et al., 2003). As noted earlier, composite profiles are averages of individual (typically several to a few tens) profiles that are similar with respect to properties of interest. Composite profiles should represent aerosol composition for a particular geographical area (air shed) and time period. Chow et al. (2003) demonstrated a hierarchical compositing scheme for geological profiles acquired from California's central valley. This composite scheme can be applied to other source categories. For example, mobile source exhaust samples from individual vehicles can be composited according to vehicle technology (e.g., diesel, gasoline, etc.), weight (e.g., light-duty, heavy-duty, etc.), model year, odometer mileage, maintenance, and emission (e.g., low emitter, high emitter, etc.). Such profiles are more representative of the "fleet averages".

One hundred and five $PM_{2.5}$ composite profiles representing various source categories selected for potential use in EC and OC emission inventories are presented in Table 4-3. The source categories, SPECIATE ID codes, profile mnemonics from the original report or publication, and the study region and reference(s) in which the profiles were determined are given. Most of the studies reported mobile source emission profiles from different geographical locations, seasons, and/or years.

Substantial variability is observed, even among composited source profiles, from each study. In Figure 4-3, the EC abundances in on-road heavy-duty diesel $PM_{2.5}$ exhaust ranges from 32.9 ± 8.0% (PHDIES) to 73.8 ± 47.2% (HDD). EC and OC in the PHDIES (Watson et al., 1994) and HDD (Fujita et al., 2007a; 2007b) profiles were measured with the same analytical method (the DRI thermal/optical reflectance [TOR] IMPROVE protocol; Chow et al., 1993) but were separated by 12 years. In addition, PHDIES represents average diesel-fueled vehicle emissions sampled at a centralized I/M facility in Phoenix, AZ, during winter 1989, while the HDD profile was determined from dynamometer tests in Southern California during summer 2001 with FTP-compatible test cycles. Such differences explain the different EC fractions since diesel emissions are highly sensitive to operating conditions and emission controls which have been improving over the last two decades. Thus, the higher EC abundance in $PM_{2.5}$ from the HDD profile may better represent emissions from current fleets.

The on-road heavy-duty diesel profile (NWHDc) from the 1997 NFRAQS Study (Watson et al., 1998a; Zielinska et al., 1998) agrees well with the HDD profile from the 2001 Gas/Diesel Split Study in terms of EC (74 – 76%), but the OC fraction differs by over twofold (19.8 ± 7.7% in NWHDc and 47.2 ± 18.7 in HDD). OC abundances can be confounded by the adsorption of organic vapors in quartz fiber filters (positive artifact) and the evaporation of highly volatile organic compounds between sampling and analysis (negative artifact) (Watson and Chow, 2002; Chow et al., 2006d; 2008c; Watson et al., 2008b).

In some studies, backup filters were used to account for the positive artifact. The backup quartz-fiber filter OC is subtracted from the front quartz-fiber filter OC to correct for the VOC adsorption artifact. In Table 4-3, source profiles with mnemonics were determined using the IMPROVE_TOR protocol (Chow et al., 1993). Unfortunately, information regarding the thermal analytical protocol (e.g., TOR or TOT [thermal/optical transmittance]) used to measure EC and OC, or whether correction for sampling artifacts was made, is not available for many of the source profiles in SPECIATE version 4.0. As noted in Section 1.1 and Appendix A of Chow et al. (2006d), the difference between TOR and TOT EC under different temperature protocols could be a factor of seven.

Profiles specific to light-duty and medium-duty diesel vehicles were reported in a few studies. Their EC fractions do not differ much from HDD (Fujita et al., 2007a; 2007b) and NWHDc (Watson et al., 1998a; Zielinska et al., 1998) profiles. The off-road composite diesel profile (LVOffRDIE) was selected from the Las Vegas Carbon Apportionment Study (Green et al., 2004). The LVOffRDIE profile shows 50% lower EC abundance (23.7 ± 11.9%) compared to the on-road diesel profiles of 45.4 ± 12.9% (LVOnRDIE) to 58.3 ± 28.2 % (LVOnRDIEs) during the winter and summer, respectively (Green et al., 2004). On the other hand, the PEN_C profile from the SERDP military diesel generators (Watson et al., 2008a) shows an EC abundance (15.3 ± 9.2%) more comparable to that of off-road diesel-fueled vehicles (LVOffRDIE).

The LVOffRDIE profile (Green et al., 2004) represents off-road vehicles such as forklifts, while PEN_C (Watson et al., 2008a) represents the averages of the fourteen 10 – 100 kW diesel generators operating under various loads. Figure 4-4 shows the EC and OC abundances for selected gasoline-fueled vehicle profiles. $PM_{2.5}$ EC abundances range from 5.93%[c] (SPECIATE ID 312302.5) to 37.5 ± 8.4% (NWLCPC; Zielinska et al., 1998).

EC abundances for gasoline-fueled vehicles are generally lower than those reported for diesel vehicles (Figure 4-3). Fujita et al. (2007b) found a subset of gasoline-fueled vehicles that reported high EC emissions. These are represented in Table 4-3 as the SI_BC (37.4 ± 10.6% EC) and SI_BW (34.6 ± 12.6% EC) profiles, which represent vehicles under cold and warm start condition, respectively. As shown in Figure 4-4, $PM_{2.5}$ EC abundances in the NFRAQS gasoline low-emitter profile (NWLCPC; Zielinska et al., 1998) agree with those of SI_BC and SI_BW. For smoker or high-emitter vehicles, the fraction of EC decreases while the fraction of OC increases. The excess emissions are therefore dominated by OC. Warm and cold start conditions do not appear to influence EC and OC abundances in the gasoline-fueled vehicle profiles.

$PM_{2.5}$ EC and OC abundances for RWC, open burning, forest fires, and agricultural burning are presented in Figure 4-5. Excluding one outlier (SPECIATE profile ID 422012.5 with 33 ± 13% of EC), the EC fraction varied over fivefold ranging from 3.2 ± 1.8% (MZFFIREC; Watson et al., 1996) to 17.5 ± 1.6% (NWFGPDa; Zielinska et al., 1998). There appears to be no difference between softwood and hardwood combustion or between fireplace, woodstove, or open area burning. The variability of OC is smaller than EC (i.e., within a factor of two to three [from 22.3 ± 3.7% for RWC-Woodstove (LTWOODST, Kuhns et al., 2004) to 67.6 ± 5.8% (NWFGPDa, Zielinska et al., 1998)]). This is because OC is the major component of $PM_{2.5}$ in wood smoke emissions.

Owing to well-controlled combustion conditions, most industrial emissions do not contain significant fractions of EC, as shown in Figure 4-6. In many of these profiles, EC was below MDLs and the reported OC might contain sampling artifacts. The low PM carbon content of these emissions may be due to emission controls and the nature of high-temperature combustion in these industrial processes. Sawdust and phosphate industries (SPECIATE profile IDs 222022.5 and 254192.5, respectively) show the highest $PM_{2.5}$ EC abundances at 4 – 5%, followed by cement kiln (3.0 ± 2.5% in BVCEM; Chow et al., 2004b) and pulp and paper manufacturing (2.6 ± 1.8% in SPECIATE profile ID 900152.5).

4.3 Estimation of a BC and OC Emission Inventory for California

ARB's web-based emission inventory tool enables users to calculate criteria pollutant inventories statewide and by air basin. As noted above, the web-based statewide inventory for 2006 contains $PM_{2.5}$ emissions from 1,395 sources (values > 0). However, the short output aggregates individual emitters by source category (e.g., stationary, area, and mobile) and sub-category.

The $PM_{2.5}$ emission inventory for all sources (including natural sources) was estimated statewide for the year 2006. Table 4-4 shows the distinct source categories created by concatenating the category and sub-category descriptions. There were 23 stationary, 11 area, 25 mobile, and 1 natural (i.e., wildfires) sources. Source profiles were compiled corresponding to these categories from those listed in Tables 4-1 and 4-2 and from the ARB source profile library (http://www.arb.ca.gov/ei/speciate/dnldopt.htm#filelist).

ARB source profiles are described by their three-digit numeric codes and source subcategories. Table 4-4 identifies the profiles selected for each of the 60 source categories in the ARB 2006 $PM_{2.5}$ emission inventory and the abundance of EC and OC in $PM_{2.5}$ for each profile. Note that for mobile sources, the EC compositions were based on an average Gas/Diesel Split Study gasoline vehicle profile (28.6 ± 13.8%) derived from tests on 30 spark ignition vehicles (Fujita et al., 2007b) and U.S. EPA SPECIATE heavy-duty diesel vehicle (HDDV) composite profile (50.3 ± 5.0%). RWC ("MISCELLANEOUS PROCESSES RESIDENTIAL FUEL COMBUSTION", see Table 2-3) is a highly significant source in the ARB inventory. The EC abundance (10 ± 3%) for this source was derived from the average of three composite wood and fireplace burning profiles (i.e., SPECIATE IDs 42102, 42303, and 42331) in the U.S. EPA SPECIATE source profile library. There were several ARB source profiles for which OC data were not available (indicated by letter "c" after the profile names in Table 4-4). In these cases, OC was set to twice the EC value.

Table 4-5 presents California (statewide) 2006 annual $PM_{2.5}$, EC, and OC emissions (tons/yr) for anthropogenic sources and natural wildfires, segregated by source category. The estimated total EC emissions were 52,084 tons/yr. The largest single source was wildfires (15,161 tons/yr), followed by miscellaneous sources (12,609 tons/yr, mainly for managed burning and disposal [7,374 tons/yr], mostly for forest management and range improvement) and residential fuel combustion (4,004 tons/yr). The next two largest single sources are off-road mobile sources (12,158 tons/yr), and on-road mobile sources (10,483 tons/yr). State-wide OC emissions (107,979 tons/yr) were about two times higher than EC emissions (52,084 tons/yr). Note that estimates for OC emissions represent only primary emissions, while secondary organics comprise a significant fraction of ambient organic aerosol (Blanchard et al., 2007).

Table 4-1. Source categories from the National Emission Inventory (NEI) including concatenated Source Classification Codes (SCCs) and NEI descriptions to SCC Level 3.

Concatenated SCCs[a]	NEI Description to SCC Level 3
103002	External Combustion Boilers Commercial/Institutional Bituminous/Subbituminous Coal
103006	External Combustion Boilers Commercial/Institutional Natural Gas
101001	External Combustion Boilers Electric Generation Anthracite Coal
101002	External Combustion Boilers Electric Generation Bituminous/Subbituminous Coal
101005	External Combustion Boilers Electric Generation Distillate Oil
101003	External Combustion Boilers Electric Generation Lignite
101006	External Combustion Boilers Electric Generation Natural Gas
101008	External Combustion Boilers Electric Generation Petroleum Coke
101004	External Combustion Boilers Electric Generation Residual Oil
102011	External Combustion Boilers Industrial Bagasse
102002	External Combustion Boilers Industrial Bituminous/Subbituminous Coal
102014	External Combustion Boilers Industrial CO Boiler
102006	External Combustion Boilers Industrial Natural Gas
102007	External Combustion Boilers Industrial Process Gas
102004	External Combustion Boilers Industrial Residual Oil
102009	External Combustion Boilers Industrial Wood/Bark Waste
301005	Industrial Processes Chemical Manufacturing Carbon Black Production
301006	Industrial Processes Chemical Manufacturing Charcoal Manufacturing
301900	Industrial Processes Chemical Manufacturing Fuel Fired Equipment
301999	Industrial Processes Chemical Manufacturing Other Not Classified
301023	Industrial Processes Chemical Manufacturing Sulfuric Acid (Contact Process)
2311020	Industrial Processes Construction: SIC 15 - 17 Industrial/Commercial/Institutional
2311010	Industrial Processes Construction: SIC 15 - 17 Residential
2311030	Industrial Processes Construction: SIC 15 - 17 Road Construction
302007	Industrial Processes Food and Agriculture Grain Millings
2399000	Industrial Processes Industrial Processes: NEC Industrial Processes: NEC
390006	Industrial Processes In-process Fuel Use Natural Gas
305001	Industrial Processes Mineral Products Asphalt Roofing Manufacture
305006	Industrial Processes Mineral Products Cement Manufacturing (Dry Process)
305007	Industrial Processes Mineral Products Cement Manufacturing (Wet Process)
305010	Industrial Processes Mineral Products Coal Mining Cleaning and Material Handling
305012	Industrial Processes Mineral Products Fiberglass Manufacturing
305014	Industrial Processes Mineral Products Glass Manufacture
305016	Industrial Processes Mineral Products Lime Manufacture
305020	Industrial Processes Mineral Products Stone Quarrying - Processing
2325000	Industrial Processes Mining and Quarrying: SIC 14 All Processes

Table 4-1. Continued.

Concatenated SCCs[a]	NEI Description to SCC Level 3
399999	Industrial Processes Miscellaneous Manufacturing Industries Miscellaneous Industrial Processes
310002	Industrial Processes Oil and Gas Production Natural Gas Production
306002	Industrial Processes Petroleum Industry Catalytic Cracking Units
306001	Industrial Processes Petroleum Industry Process Heaters
303001	Industrial Processes Primary Metal Production Aluminum Ore (Electro-reduction)
303003	Industrial Processes Primary Metal Production By-product Coke Manufacturing
303006	Industrial Processes Primary Metal Production Ferroalloy Open Furnace
303008	Industrial Processes Primary Metal Production Iron Production
303010	Industrial Processes Primary Metal Production Lead Production
303009	Industrial Processes Primary Metal Production Steel Manufacturing
307007	Industrial Processes Pulp and Paper and Wood Products Plywood Operations
307008	Industrial Processes Pulp and Paper and Wood Products Sawmill Operations
307001	Industrial Processes Pulp and Paper and Wood Products Sulfate (Kraft) Pulping
304001	Industrial Processes Secondary Metal Production Aluminum
304020	Industrial Processes Secondary Metal Production Furnace Electrode Manufacture
304003	Industrial Processes Secondary Metal Production Grey Iron Foundries
304007	Industrial Processes Secondary Metal Production Steel Foundries
203002	Internal Combustion Engines Commercial/Institutional Natural Gas
201001	Internal Combustion Engines Electric Generation Distillate Oil (Diesel)
201002	Internal Combustion Engines Electric Generation Natural Gas
202002	Internal Combustion Engines Industrial Natural Gas
2801500	Miscellaneous Area Sources Agriculture Production - Crops Agricultural Field Burning - whole field set on fire
2801000	Miscellaneous Area Sources Agriculture Production - Crops Agriculture - Crops
2805001	Miscellaneous Area Sources Agriculture Production - Livestock Beef cattle - finishing operations on feedlots
2805020	Mobile Sources Highway Vehicles - Diesel Heavy-Duty Diesel Buses (School & Transit)
2230071	Mobile Sources Highway Vehicles - Diesel Heavy-Duty Diesel Vehicles (HDDV) Class 2B
2230072	Mobile Sources Highway Vehicles - Diesel Heavy-Duty Diesel Vehicles (HDDV) Class 3 4 & 5
2230073	Mobile Sources Highway Vehicles - Diesel Heavy-Duty Diesel Vehicles (HDDV) Class 6 & 7
2230074	Mobile Sources Highway Vehicles - Diesel Heavy-Duty Diesel Vehicles (HDDV) Class 8A & 8B
2201070	Mobile Sources Highway Vehicles - Gasoline Heavy-Duty Gasoline Vehicles 2B thru 8B & Buses (HDGV)
2201020	Mobile Sources Highway Vehicles - Gasoline Light-Duty Gasoline Trucks 1 & 2 (M6) = LDGT1 (M5)
2201040	Mobile Sources Highway Vehicles - Gasoline Light-Duty Gasoline Trucks 3 & 4 (M6) = LDGT2 (M5)
2201001	Mobile Sources Highway Vehicles - Gasoline Light-Duty Gasoline Vehicles (LDGV)
2267003	Mobile Sources LPG Industrial Equipment

Table 4-1. Continued.

Concatenated SCCs[a]	NEI Description to SCC Level 3
2280002	Mobile Sources Marine Vessels Commercial Diesel
2280003	Mobile Sources Marine Vessels Commercial Residual
2270005	Mobile Sources Off-highway Vehicle Diesel Agricultural Equipment
2270006	Mobile Sources Off-highway Vehicle Diesel Commercial Equipment
2270002	Mobile Sources Off-highway Vehicle Diesel Construction and Mining Equipment
2270003	Mobile Sources Off-highway Vehicle Diesel Industrial Equipment
2270004	Mobile Sources Off-highway Vehicle Diesel Lawn and Garden Equipment
2260004	Mobile Sources Off-highway Vehicle Gasoline 2-Stroke Lawn and Garden Equipment
2265004	Mobile Sources Off-highway Vehicle Gasoline 4-Stroke Lawn and Garden Equipment
2294000	Mobile Sources Paved Roads All Paved Roads
2282005	Mobile Sources Pleasure Craft Gasoline 2-Stroke
2285002	Mobile Sources Railroad Equipment Diesel
2296000	Mobile Sources Unpaved Roads All Unpaved Roads
402999	Petroleum and Solvent Evaporation Surface Coating Operations Miscellaneous
2103002	Stationary Source Fuel Combustion Commercial/Institutional Bituminous/Subbituminous Coal
2103004	Stationary Source Fuel Combustion Commercial/Institutional Distillate Oil
2103006	Stationary Source Fuel Combustion Commercial/Institutional Natural Gas
2103005	Stationary Source Fuel Combustion Commercial/Institutional Residual Oil
2102002	Stationary Source Fuel Combustion Industrial Bituminous/Subbituminous Coal
2102004	Stationary Source Fuel Combustion Industrial Distillate Oil
2102006	Stationary Source Fuel Combustion Industrial Natural Gas
2102005	Stationary Source Fuel Combustion Industrial Residual Oil
2102008	Stationary Source Fuel Combustion Industrial Wood
2104002	Stationary Source Fuel Combustion Residential Bituminous/Subbituminous Coal
2104004	Stationary Source Fuel Combustion Residential Distillate Oil
2104007	Stationary Source Fuel Combustion Residential Liquefied Petroleum Gas (LPG)
2104006	Stationary Source Fuel Combustion Residential Natural Gas
2104008	Stationary Source Fuel Combustion Residential Wood
2601020	Waste Disposal Treatment and Recovery On-site Incineration Commercial/Institutional
2610000	Waste Disposal Treatment and Recovery Open Burning All Categories
2610030	Waste Disposal Treatment and Recovery Open Burning Residential

[a] The SCC1, SCC2, and SCC3 character codes were converted to numerics. These numbers were converted to a unique numerical code, SCC1-3, where: SCC1-3 = 100,000 × SCC1 + 1,000 × SCC2 + SCC3. The corresponding source category descriptions were also concatenated to provide a unique NEI source description.

Table 4-2. Source profiles assigned to the U.S. EPA's source classification codes (SCCs).[a]

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
103002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^=$(CFPP2)
103006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural Gas combustion, EPA, GREER, Denver
101001	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^=$(CFPP2)
101002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^=$(CFPP2)
101005	SPECIATE (U.S. EPA, 2007)	OILCOMB_DISTILLATE	OILCOMB_DISTILLATE	BOILER - #2 FUEL OIL FIRED (12710)
101003	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^=$(CFPP2)
101006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural Gas combustion, EPA, GREER, Denver
101008	CAIRO CAIP (Lowenthal et al., 2001)	COKECOMB	COKE_PLANT	Coke plant
101004	SPECIATE (U.S. EPA, 2007)	OILCOMB_RES	OIL FIRED POWER PLANT	OFPP EPA # 11501-11509 (removed extreme Se, V)
102011	SPECIATE (U.S. EPA, 2007)	BAGASSECOMB	WOODCOMB_INDUSTRIAL	Wood combustion industrial – EPA
102002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^=$(CFPP2)
102014	SPECIATE (U.S. EPA, 2007)	COCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
102006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
102007	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
102004	SPECIATE (U.S. EPA, 2007)	OILCOMB_RES	OIL FIRED POWER PLANT	OFPP EPA # 11501-11509 (removed extreme Se, V)
102009	SPECIATE (U.S. EPA, 2007)	WOODCOMB_IND	WOODCOMB_INDUSTRIAL	Wood combustion industrial – EPA

Table 4-2. Continued.

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
301005	SPECIATE (U.S. EPA, 2007)	BC_PROD	SMUDGEPOT_BC_PROD	Orchard heating smudge pots
301006	SPECIATE (U.S. EPA, 2007)	CHARCOAL_PROD	CHARCOAL_PROD	Charcoal manufacturing
301900	SPECIATE (U.S. EPA, 2007)	CHEMFUELFIREDEQIP_PROD	GASCOMB	Natural gas combustion, EPA, GREER, Denver
301999	SPECIATE (U.S. EPA, 2007)	OTHER_PROD	INDUSTRIAL_MANUFACTURING_AVERAGE	Industrial manufacturing – average
301023	PURE H2SO4	H2SO4_PROD	H2SO4_PROD	Pure H_2SO_4
2311020	CRPAQS TSS12 (Chow et al., 2003)	CONST_INDUSTRIAL	CONST_INDUSTRIAL	TSS12 industrial construction
2311010	CRPAQS TSS12 (Chow et al., 2003)	CONST_RESIDENTIAL	CONST_RESIDENTIAL	TSS12 industrial construction
2311030	ARB 1987 (Cooper et al., 1987; Houck et al., 1989)	CONST_ROAD	CONST_ROAD	Fresno area construction emissions (freeway).
302007	SPECIATE (U.S. EPA, 2007)	GRAINMILLINGS_PROD	GRAINMILLINGS_PROD	EPA vegetative detritus
2399000	SPECIATE (U.S. EPA, 2007)	NEC_PROD	INDUSTRIAL_MANUFACTURING_AVERAGE	Industrial manufacturing – average
390006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
305001	SPECIATE (U.S. EPA, 2007)	ASPHALTROOF_PROD	ASPHALTROOF_PROD	Asphalt roofing production
305006	BRAVO (Chow et al., 2004b), SPECIATE (U.S. EPA, 2007)	CEMENTDRY_PROD	CEMENT_PROD	EPA and BRAVO cement (wet or dry)
305007	BRAVO (Chow et al., 2004b), SPECIATE (U.S. EPA, 2007)	CEMENTWET_PROD	CEMENT_PROD	EPA and BRAVO cement (wet or dry)
305010	COAL COMPOSITION (Kolker et al., 2000)	COALMINECLEAN_PROD	COALMINECLEAN_PROD	Coal composition from web, 2% S
305012	NONE	FIBERGLASS_PROD	FIBERGLASS_PROD	Fiberglass composition from TMO
305014	SPECIATE (U.S. EPA, 2007)	GLASS_PROD	GLASS_PROD	Glass furnace
305016	IMPERIAL VALLEY (Chow and Watson, 1997)	LIME_PROD	LIME PROD	Limestone Imperial Valley
305020	SPECIATE (U.S. EPA, 2007)	STONEQUARRY_PROD	STONE QUARRY IGNEOUS ROCK	Igneous rock composition
2325000	SPECIATE (U.S. EPA, 2007)	MINING_PROD	MINING_PROD	Igneous rock composition
399999	SPECIATE (U.S. EPA, 2007)	MISC_PROD	INDUSTRIAL_MANUFACTURING_AVERAGE	Industrial manufacturing – average

Table 4-2. Continued.

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
310002	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GAS_PROD	GASCOMB	Natural gas combustion, EPA, GREER, Denver
306002	BRAVO (Chow et al., 2004b)	CRACKER_PROD	CATALYTIC CRACKER	Stack emission, Texas petroleum refinery catalytic cracker
306001	SPECIATE (U.S. EPA, 2007)	PROCESSHEATERS_PROD	GASCOMB	Natural gas combustion, EPA, GREER, Denver
303001	SPECIATE (U.S. EPA, 2007)	AL_PROD	AL_PROD	EPA Al Processing
303003	GENEVA STEEL PLANT (OHIO) (Cooper et al., 1989)	COKE_PROD	COKE_STACK	Coke oven stacks - Geneva Steel Plant.
303006	SPECIATE (U.S. EPA, 2007)	FE_PROD	FERROMANGANESE_FURNACE	Ferromanganese furnace
303008	SPECIATE (U.S. EPA, 2007)	FE_PROD	FERROMANGANESE_FURNACE	Ferromanganese furnace
303010	SPECIATE (U.S. EPA, 2007)	PB_PROD	PB_PROD	Lead smelters average
303009	GENEVA STEEL PLANT (OHIO) (Cooper et al., 1989)	STEEL_PROD	STEEL BLAST FURNACE	Blast furnace fugitive - Geneva Steel Plant.
307007	SPECIATE (U.S. EPA, 2007)	PLYWOOD_PROD	PLYWOOD_PROD	Particleboard dryer/direct – fired
307008	SPECIATE (U.S. EPA, 2007)	SAWMILL_PROD	SAWMILL_PROD	Sawmill - EPA
307001	SPECIATE (U.S. EPA, 2007)	KRAFTPULPING_PROD	KRAFTPULPING_PROD	EPA Kraft pulping
304001	SPECIATE (U.S. EPA, 2007)	AL_PROD (SECONDARY)	AL2_PROD	Aluminum production
304020	CAIRO CAIP (Lowenthal et al., 2001)	FURNACEELECTRODE_PROD	COKE_PLANT	Coke plant
304003	SPECIATE (U.S. EPA, 2007)	FE_PROD (SECONDARY)	FERROMANGANESE_FURNACE	Ferromanganese furnace
304007	GENEVA STEEL PLANT (OHIO) (Cooper et al., 1989)	STEEL_PROD (SECONDARY)	STEEL BLAST FURNACE	Blast furnace fugitive - Geneva Steel Plant.
203002	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
201001	SPECIATE (U.S. EPA, 2007)	OILCOMB_DISTILLATE	OILCOMB_DISTILLATE	Boiler - #2 fuel oil fired
201002	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
202002	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver

Table 4-2. Continued.

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
2801500	ARB 1987 (Cooper et al., 1987; Houck et al., 1989), SPECIATE (U.S. EPA, 2007)	AG_BURN	AG_BURN	ARB, EPA Ag burn average
2801000	ARB 1987 (Cooper et al., 1987; Houck et al., 1989)	AG_PROD	AG_SOIL	ARB Ag dust
2805001	CRPAQS TSS12 (Chow et al., 2003)	AG_LIVESTOCKFINISH	FEEDLOT_SOIL	Composite of dairy cattle soil profiles (FDCATDR, FDCATFL)
2805020	SPECIATE (U.S. EPA, 2007)	MOBILEHDDV	MOBILE_DIESEL	EPA Mobile HDDV
2230071	SPECIATE (U.S. EPA, 2007)	MOBILEHDDV	MOBILE_DIESEL	EPA Mobile HDDV
2230072	SPECIATE (U.S. EPA, 2007)	MOBILEHDDV	MOBILE_DIESEL	EPA Mobile HDDV
2230073	SPECIATE (U.S. EPA, 2007)	MOBILEHDDV	MOBILE_DIESEL	EPA Mobile HDDV
2230074	SPECIATE (U.S. EPA, 2007)	MOBILEHDDV	MOBILE_DIESEL	EPA Mobile HDDV
2201070	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILEHDGV	MOBILE_GAS	Gas/Diesel Split gasoline
2201020	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILELDGT	MOBILE_GAS	Gas/Diesel Split gasoline
2201040	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILELDGT	MOBILE_GAS	Gas/Diesel Split gasoline
2201001	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILELDGV	MOBILE_GAS	Gas/Diesel Split gasoline
2267003	ECDIESEL	MOBILELPG	MOBILE_CNG	Bus with CNG
2280002	SPECIATE (U.S. EPA, 2007)	MARINE DIESEL	MOBILE_DIESEL	Diesel – EPA
2280003	SPECIATE (U.S. EPA, 2007)	MARINE DIESEL	MOBILE_DIESEL	Diesel – EPA
2270005	SPECIATE (U.S. EPA, 2007)	MOBILEOFFROADDIESEL	MOBILE_DIESEL	Diesel – EPA
2270006	SPECIATE (U.S. EPA, 2007)	MOBILEOFFROADDIESEL	MOBILE_DIESEL	Diesel – EPA
2270002	SPECIATE (U.S. EPA, 2007)	MOBILEOFFROADDIESEL	MOBILE_DIESEL	Diesel – EPA
2270003	SPECIATE (U.S. EPA, 2007)	MOBILEOFFROADDIESEL	MOBILE_DIESEL	Diesel – EPA
2270004	SPECIATE (U.S. EPA, 2007)	MOBILEOFFROADDIESEL	MOBILE_DIESEL	Diesel – EPA
2260004	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILEGAS2STROKE	MOBILE_GAS	Gas/Diesel Split gasoline
2265004	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MOBILEGAS4STROKE	MOBILE_GAS	Gas/Diesel Split gasoline

Table 4-2. Continued.

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
2294000	CRPAQS TSS12 (Chow et al., 2003), MZ (Watson et al., 1996),NFRAQS (Fujita et al., 1998), BRAVO (Chow et al., 2004b), ARB (Cooper et al., 1987; Houck et al., 1989)	PAVED ROAD DUST	PAVED ROAD DUST	PVRD - BRAVO, ARB, CRPAQS, MZ, NFRAQS
2282005	GAS/DIESEL SPLIT (Fujita et al., 2007b)	MARINE PLEASURE CRAFT	MOBILE_GAS	Gas/Diesel Split gasoline
2285002	SPECIATE (U.S. EPA, 2007)	MOBILE_RAILROAD	MOBILE_DIESEL	Diesel – EPA
2296000	CRPAQS TSS12 (Chow et al., 2003), BRAVO (Chow et al., 2004b), ARB (Cooper et al., 1987; Houck et al., 1989)	UNPAVE ROAD DUST	UNPAVED ROAD DUST	UPVRD - CRPAQS, BRAVO, ARB
402999	PURE OC	SURFACECOAT_PROD	PURE OC	Pure OC to simulate VOC evaporation
2103002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^{=}$(CFPP2)
2103004	SPECIATE (U.S. EPA, 2007)	OILCOMB_DISTILLATE	OILCOMB_DISTILLATE	Boiler - #2 fuel oil fired
2103006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
2103005	SPECIATE (U.S. EPA, 2007)	OILCOMB_RESIDUAL	OIL FIRED POWER PLANT	OFPP EPA # 11501-11509 (removed extreme Se, V)
2102002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^{=}$(CFPP2)
2102004	SPECIATE (U.S. EPA, 2007)	OILCOMB_DISTILLATE	OILCOMB_DISTILLATE	Boiler - #2 fuel oil fired
2102006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
2102005	SPECIATE (U.S. EPA, 2007)	OILCOMB_RES	OIL FIRED POWER PLANT	OFPP EPA # 11501-11509 (removed extreme Se, V)
2102008	SPECIATE (U.S. EPA, 2007)	WOODCOMB_INDUSTRIAL	WOODCOMB_INDUSTRIAL	Wood combustion industrial – PA
2104002	BRAVO (Chow et al., 2004b)	COALCOMB	COALCOMB	Coal - BRAVO, low OC, high Se, high $SO_4^{=}$(CFPP2)
2104004	SPECIATE (U.S. EPA, 2007)	OILCOMB_DISTILLATE	OILCOMB_DISTILLATE	Boiler - #2 fuel oil fired
2104007	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	LPGCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver

Table 4-2. Continued.

Concatenated SCCs	Profile Origin (Reference)	Assigned Profile Mnemonic	Profile Name from the Data Source	Profile Description
2104006	DENVER (Burns et al., 1989), GEEER (England et al., 2007a; 2007b), SPECIATE (U.S. EPA, 2007)	GASCOMB	GASCOMB	Natural gas combustion, EPA, GREER, Denver
2104008	CRPAQS TSS12 (Chow et al., 2003), MZ (Watson et al., 1996), NFRAQS (Fujita et al., 1998), SPECIATE (U.S. EPA, 2007)	WOODCOMB_RESIDENTIAL	WOODCOMB_RESIDENTIAL	Wood combustion residential - CRPAQS, EPA, MZ, NFRAQS
2601020	SPECIATE (U.S. EPA, 2007)	WASTE_INCINERATION	MUNICIPAL INCINERATOR	Municipal incinerator (PA)
2610000	SAFRICA (Annegarn et al., 1992)	WASTE_OPENBURN	PAPER WASTE BURNING	Low-smoke, burning brick-shaped paper waste
2610030	SAFRICA (Annegarn et al., 1992)	WASTE_OPENBURN	PAPER WASTE BURNING	Low-smoke, burning brick-shaped paper waste

[a] The source profile origin, mnemonic, and description are given for each SCC in Table 4-1.

Table 4-3. Selected composite source profiles for $PM_{2.5}$ EC and OC emission inventory development in California.

				Percent of $PM_{2.5}$ Mass	
Source Category	**SPECIATE[a] Source Profile ID**	**Source Profile Mnemonic**	**Study Region (Reference)**	**EC**	**OC**
I. Stationary Sources					
Coal-Fired Power Plants	112022.5	NA	Southern California (Cooper et al., 1987)	NA	0.8±0.12
Coal-Fired Power Plants	3701	MZPPC	Northwestern Colorado (Watson et al., 1996)	4.09±4.41	5.20±10.24
Coal-Fired Power Plants	4373	BVCFPP	Western Texas (Chow et al., 2004b)	1.38±2.23	27.18±25.77
Residential Coal Combustion	3761	MZRCCC	Northwestern Colorado (Watson et al., 1996)	26.08±15.64	69.49±19.19
Oil Combustion	115072.5	NA	Southern California (Cooper et al., 1987)	12.80±9.35	5.00±2.50
Oil Combustion	135052.5	NA	Pacific Northwest (Core et al., 1989)	13.56±9.35	2.28±0.96
Oil Combustion	3253	CHCRUC	California (Houck et al., 1989)	3.01±1.12	1.99±1.33
Oil Refinery	262052.5	NA	Southern California (Cooper et al., 1987)	0.16±0.05	0.28±0.99
Oil Refinery	4375	BVCAT1	Western Texas (Chow et al., 2004b)	0.07±0.05	0.47±0.21
Gas Combustion	421072.5	NA	(Hildemann et al., 1991)	6.70±0	84.90±0
Hogged Fuel Boiler	127062.5	NA	Pacific Northwest (Core et al., 1989)	4.49±1.12	25.38±12.10
Hogged Fuel Boiler	127082.5	NA	Pacific Northwest (Core et al., 1989)	0.27±0.37	7.18±3.01
Hogged Fuel Boiler	127072.5	NA	Pacific Northwest (Core et al., 1989)	1.07±0.67	2.48±3.11
Hogged Fuel Boiler	127092.5	NA	Pacific Northwest (Core et al., 1989)	10.84±1.43	6.73±2.33
Incinerator	3288	SCRRFC	California (Houck et al., 1989)	2.42±2.12	13.37±7.59
Fly Ash	4374	BVCLFA	Western Texas (Chow et al., 2004b)	1.39±1.68	1.53±.90
Industrial - Primary Metal Production	900072.5	NA	NA (Shareef ,1987)	0.34±0.24	3.22±1.46
Industrial – Phosphorus	254212.5	NA	Pacific Northwest (Core et al., 1989)	0.46±0.41	4.34±1.83
Industrial - Lime Kiln	232022.5	NA	Southern California (Cooper et al., 1987)	0.46±0.50	9.28±1.00
Industrial – Mono ammonium Phosphate Dryer	254172.5	NA	Pacific Northwest (Core et al., 1989)	0.59±0.27	1.67±0.89
Industrial - Veneer Dryer	223012.5	NA	Oregon (DeCesar and Cooper 1980)	0.77±0.52	81.65±10.37
Industrial – Manufacturing	900162.5	NA	NA (Shareef, 1987)	0.89±1.86	7.36±3.06
Industrial - Phosphate Fertilizer Calciner	254182.5	NA	Pacific Northwest (Core et al., 1989)	1.11±0.57	2.99±0.60
Industrial - Mineral Products	900132.5	NA	NA (Shareef, 1987)	1.47±3.92	5.26±2.27

Table 4-3. Continued.

Source Category	SPECIATE[a] Source Profile ID	Source Profile Mnemonic	Study Region (Reference)	Percent of $PM_{2.5}$ Mass EC	Percent of $PM_{2.5}$ Mass OC
Industrial - Kraft Recovery Furnace	231042.5	NA	Pacific Northwest (Core et al., 1989)	1.53±1.19	5.23±2.43
Industrial - Phosphorus	254202.5	NA	Pacific Northwest (Core et al., 1989)	1.81±1.02	2.67±1.21
Industrial - Chemical Manufacturing	900022.5	NA	NA (Shareef, 1987)	1.83±0.20	9.18±0.45
Industrial - Phosphate	254162.5	NA	Pacific Northwest (Core et al., 1989)	2.31±9.18	33.68±13.97
Industrial - Pulp And Paper	900152.5	NA	(Shareef, 1987)	2.63±1.82	29.74±7.37
Industrial - Cement Kiln	4378	BVCEM	Western Texas (Chow et al., 2004b)	2.96±2.50	12.78±6.03
Industrial - Phosphate	254192.5	NA	Pacific Northwest (Core et al., 1989)	4.15±2.37	19.60±12.46
Industrial - Sawdust	222022.5	NA	Oregon (DeCesar and Cooper, 1980)	4.60±1.00	50.00±3.50
Industrial - Aluminum	900092.5	NA	NA (Shareef, 1987)	NA	6.50±0
II. Area Sources					
Agricultural Burn	423042.5	NA	Oregon (Watson et al., 1979)	5.80±1.74	35.60±10.75
Agricultural Burn	3258	ELAGBC	California (Houck et al., 1989)	9.59±2.21	38.82±8.93
Agricultural Burn	3453	VIAGBC	California (Houck et al., 1989)	10.90±3.26	34.49±8.03
Agricultural Burn	3243	BAAGBC	California (Houck et al., 1989)	12.29±6.87	44.37±9.85
Agricultural Burn	3448	STAGBC	California (Houck et al., 1989)	13.10±4.16	39.78±10.75
Forest Fire	3766	MZFFIREC	Northwestern Colorado (Watson et al., 1996)	3.23±1.80	46.88±15.67
Open Burn	423202.5	NA	Oregon (Watson et al., 1979; DeCesar and Cooper, 1980)	5.18±2.30	31.62±8.70
Open Burn	4366	BVBURN	Western Texas (Chow et al., 2004b)	15.75±15.45	64.41±16.45
Residential Wood Combustion – All	22073	LTRWCC	Lake Tahoe, NV (Kuhns et al., 2004)	4.94±3.10	40.00±23.60
Residential Wood Combustion – All	3770	MZRWCC	Northwestern Colorado (Watson et al., 1996)	12.39±4.20	51.37±11.72
Residential Wood Combustion – All	423032.5	NA	Oregon (DeCesar and Cooper, 1980)	12.80±8.40	47.50±13.80
Residential Wood Combustion – All	423302.5	NA	Oregon (Muhlbaier, 1981; Dasch, 1982)	15.05±8.49	41.85±8.30
Residential Wood Combustion – Fireplaces	22071	LTFIREPL	Lake Tahoe, NV (Kuhns et al., 2004)	5.66±2.38	57.70±15.24

Table 4-3. Continued.

Source Category	SPECIATE[a] Source Profile ID	Source Profile Mnemonic	Study Region (Reference)	Percent of $PM_{2.5}$ Mass	
				EC	OC
Residential Wood Combustion – Fireplaces	3235	WRWCBC3	Denver (Watson et al., 1988)	15.46±6.57	55.17±15.84
Residential Wood Combustion – Fireplaces	3921	NWFGPDa	Northern Colorado (Zielinska et al., 1998)	17.46±1.59	67.60±5.85
Residential Wood Combustion – Woodstoves	22072	LTWOODST	Lake Tahoe, NV (Kuhns et al., 2004)	4.23±3.68 [b]	22.30±13.59 [b]
Residential Wood Combustion – Woodstoves	421022.5	NA	Residential (Stiles, 1983)	6.40±0	35.90±0
Residential Wood Combustion – Woodstoves	3236	WSTOVEC2	Denver (Watson et al., 1988)	12.62±4.27	58.01±18.38
Residential Wood Combustion – Softwoods	22069	LTRWSC	Lake Tahoe (Kuhns et al., 2004)	4.19±2.42 [b]	29.80±24.21 [b]
Residential Wood Combustion – Hardwoods	22070	LTRWHC	Lake Tahoe (Kuhns et al., 2004)	5.69±3.65 [b]	50.19±25.85 [b]
Residential Wood Combustion – Hardwoods	422022.5	NA	Residential (Dasch, 1982)	8.00±7.00	46.00±7.00
Residential Wood Combustion – Softwoods	422012.5	NA	Residential (Dasch, 1982)	33.00±13.00	38.00±6.00
Industrial Wood Combustion	221032.5	NA	Pacific Northwest (Core et al., 1989)	6.15±1.76	62.63±12.93
Industrial Wood Combustion	4704	NA	United States (EPA National Risk Management Research laboratory, 2001)	13.80±3.10	32.60±8.00
Cooking	3915	NMc	Northern Colorado (Zielinska et al., 1998)	2.25±1.32	81.00±6.58
Cooking	4383	BVCOOK	Western Texas (Chow et al., 2004b)	10.17±6.29	86.63±16.31
Cooking	4020	CET	Mexico City	0.65±0.05	80.06±4.25
Cooking - Charcoal Chicken	4380	CHCHICK	Western Texas (Chow et al., 2004b)	3.62±1.17	95.03±10.85
Cooking - Propane Chicken	4381	PRCHICK	Western Texas (Chow et al., 2004b)	12.72±4.93	84.31±23.36
Cooking - Smoke Chicken	4379	SMCHICK	Western Texas (Chow et al., 2004b)	17.21±3.73	76.30±8.52
Soil	413532.5	NA	Oregon	0.36±1.25	6.28±2.92
Soil	3717	MZSOILC	Northwestern Colorado (Watson et al., 1996)	0.94±1.48	6.06±2.58
Soil	4353	BVSOIL2	Western Texas (Chow et al., 2004b)	0.01±0.48	4.70±3.16
Soil	4351	BVSOIL1	Western Texas (Chow et al., 2004b)	0.35±1.03	7.76±4.08
Soil	413502.5	NA	Iowa (Core et al., 1982)	0.09±0.16	0.69±0.68
Soil - Agriculture	3497	PHOVERAG	Phoenix (Chow et al., 1991)	0.15±0.88	3.33±1.49
Soil - Agriculture	3488	PHBAREAG	Phoenix (Chow et al., 1991)	0.00±0.93	4.30±1.84

Table 4-3. Continued.

				Percent of $PM_{2.5}$ Mass	
Source Category	**SPECIATE[a] Source Profile ID**	**Source Profile Mnemonic**	**Study Region (Reference)**	**EC**	**OC**
Soil - Construction	3491	PHCONSTR	Phoenix (Chow et al., 1991)	0.00±0.71	4.62±1.58
Soil - Desert	3494	PHDSSOIL	Phoenix (Chow et al., 1991)	0.00±0.94	3.66±1.28
Soil - Desert	3512	TUDSSOIL	Phoenix (Chow et al., 1991)	0.16±0.76	4.16±0.86
Soil and Dust	3709	MZGEOLC	Northwestern Colorado (Watson et al., 1996)	0.78±0.84	6.49±2.55
Tar Pot	255002.5	NA	NA	0.01±0	60.30±0
III. Mobile Sources					
On-Road - All	330092.5	NA	Southern California (Cooper et al., 1987)	38.12±4.91	38.59±5.55
On-Road - All	330202.5	NA	Oregon (Pierson and Brachaczek, 1983; DeCesar and Cooper, 1980)	15.03±6.70	28.84±6.38
On-Road - Light-Duty Gasoline	312302.5	NA	Southern California (Cass and McRae, 1981)	5.93±0.00	23.73±0.00
On-Road - Light-Duty Leaded Gasoline	311052.5	NA	NA	8.19±0.00	41.61±0.00
On-Road - Gasoline	3517	PHAUTO	Phoenix (Chow et al., 1991)	13.50±8.02	30.08±12.30
On-Road - Gasoline BC-Emitters Warm Start	NA	SI_BW	Gas/Diesel Split (Fujita et al., 2007a;2007b)	34.58±12.57[c]	30.91±11.36[c]
On-Road - Gasoline BC-Emitters Cold Start	NA	SI_BC	Gas/Diesel Split (Fujita et al., 2007a;2007b)	37.38±10.60[c]	32.36±9.34[c]
On-Road - Gasoline Smokers Summer	3959	NSSCPC	Northern Colorado (Zielinska et al., 1998)	9.24±8.70	74.97±7.30
On-Road - Gasoline Smokers Winter	3904	NWSCPC	Northern Colorado (Zielinska et al., 1998)	14.92±16.23	69.56±13.93
On-Road - Gasoline High-Emitters Cold Start	NA	SI_HC	GD Split (Fujita et al., 2007a;2007b)	13.29±7.37[c]	62.24±27.09[c]
On-Road - Gasoline High-Emitters Warm Start	NA	SI_HW	Gas/Diesel Split (Fujita et al., 2007a;2007b)	14.77±10.58[c]	71.59±32.44[c]
On-Road - Gasoline High-Emitters Winter	3892	NWHCPC	Northern Colorado (Zielinska et al., 1998)	34.03±20.34	51.92±16.90
On-Road - Gasoline Low-Emitters Cold Start	NA	SI_LC	Gas/Diesel Split (Fujita et al., 2007a;2007b)	24.84±8.49[c]	54.27±15.22[c]
On-Road - Gasoline Low-Emitters Warm Start	NA	SI_LW	Gas/Diesel Split (Fujita et al., 2007a;2007b)	28.26±12.97[c]	63.49±22.99[c]
On-Road - Gasoline Low-Emitters Winter	3884	NWLCPC	Northern Colorado (Zielinska et al., 1998)	37.46±8.45	43.35±9.16

Table 4-3. Continued.

				Percent of $PM_{2.5}$ Mass	
Source Category	**SPECIATE[a] Source Profile ID**	**Source Profile Mnemonic**	**Study Region (Reference)**	**EC**	**OC**
On-Road - Gasoline Non-Smokers Winter	3900	NWnSPC	Northern Colorado (Zielinska et al., 1998)	35.91±12.84	47.54±11.90
On-Road - Diesel Winter	23050	LVOnRDIE	Las Vegas, NV (Green et al., 2004)	45.41±12.91[b]	52.82±14.20[b]
On-Road - Diesel Summer	23075	LVOnRDIEs	Las Vegas, NV (Green et al., 2004)	58.26±28.18[b]	36.48±15.65[b]
On-Road - Heavy-duty Diesel	3518	PHDIES	Phoenix (Chow et al., 1991)	32.92±7.97	40.10±6.60
On-Road - Heavy-duty Diesel	322062.5[d]	NA	NA	52.06±0	36.05±0
On-Road - Heavy-duty Diesel	322072.5[d]	NA	Pacific Northwest (Core et al., 1989)	52.06±4.64	36.05±3.41
On-Road - Heavy-duty Diesel Winter	3913	NWHDc	Northern Colorado (Zielinska et al., 1998)	73.51±10.14	19.81±7.74
On-Road - Heavy-duty Diesel	NA	HDD	Gas/Diesel Split (Fujita et al., 2007a;2007b)	73.76±28.19[c]	47.16±18.71[c]
On-Road - Medium Duty Diesel	NA	MDD	Gas/Diesel Split (Fujita et al., 2007a;2007b)	75.63±31.61[c]	82.59±32.89[c]
On-Road - Light-duty Diesel Winter	3912	NWLDCPC	Northern Colorado (Zielinska et al., 1998)	61.46±16.13	30.73±13.66
On-Road - Light-duty Diesel	321042.5	NA	NA	64.30±0	33.50±0
Off-Road - Diesel Vehicle	23051	LVOffRDIE	Las Vegas, NV (Green et al., 2004)	23.72±11.89[b]	64.30±19.56[b]
Off-Road - Diesel Generator	NA	PEN_C[e]	SERDP (Watson et al., 2008a)	15.34±9.24[e]	41.85±21.51[e]
Tire Wear	340022.5	NA	Oregon (Watson, 1979; Pierson and Brachaczek, 1983)	60.90±0	21.75±0
Tire Wear	340032.5	NA	Southern California (Cooper et al., 1987)	28.70±0	58.30±0

[a] U.S. EPA SPECIATE version 4.0 (web: http://www.epa.gov/ttn/chief/software/speciate/index.html)

[b] Special study, profiles not included in U.S. EPA SPECIATE version 4.0; uncertainties listed in DRISourceProfilesv5.mdb (see enclosed CD).

[c] Percent $PM_{2.5}$ mass and uncertainties based on Table 1 of Fujita et al., 2007a.

[d] Profiles 322062.5 and 322072.5 have the same EC and OC in the SPECIATE database. This is suspect. The Total (sum of species) is slightly different for the two profiles: profile 322062.5 is 88.76% and profile 322072.5 is 89.06%. Profile 322062.5 SPECIATE notes field states, “Profile representing a composite of profiles 32203 and 32204” and has a quality of “0”. Profile 322072.5 notes field states, “Represents composite of several sampling runs, tests limited to PM_{10} measurements, vehicles operated over the Federal Test Cycle” and has a quality of “4”.

[e] Special study, profiles not included in U.S. EPA SPECIATE version 4.0; composite of profiles 24027 – 24036 for EC and profiles 24027 – 24031 and 24033 – 24036 for OC in DRISourceProfilesv5.mdb (see enclosed CD). Uncertainties based on standard deviation of averaged profiles.

NA: Not available or not applicable

Table 4-4. Source categories for stationary, area, and mobile sources in the ARB 2006 $PM_{2.5}$ emission inventory.[a]

Source Type	Source[b]	Source Profile Origin	% of $PM_{2.5}$ Mass	
			EC	OC
STATIONARY	FUEL COMBUSTION COGENERATION	ARB356[c],ARB111,ARB112-Electric Arc Furnace[d]	13.67	27.33
STATIONARY	FUEL COMBUSTION ELECTRIC UTILITIES	ARB356, ARB111, ARB112-Electric Arc Furnace[d]	13.67	27.33
STATIONARY	FUEL COMBUSTION FOOD AND AGRICULTURAL PROCESSING	EPA[e] HDDV Average	50.30	32.33
STATIONARY	FUEL COMBUSTION MANUFACTURING AND INDUSTRIAL	EPA 90016-Avg: Industrial Manufacturing	0.89	7.36
STATIONARY	FUEL COMBUSTION OIL AND GAS PRODUCTION (COMBUSTION)	ARB112-Fuel Combustion – Distillate	15.00	30.00
STATIONARY	FUEL COMBUSTION OTHER (FUEL COMBUSTION)	ARB356, ARB111, ARB112-Electric Arc Furnace	13.67	27.33
STATIONARY	FUEL COMBUSTION PETROLEUM REFINING (COMBUSTION)	ARB331-Petroleum Refining[d]	4.00	8.00
STATIONARY	FUEL COMBUSTION SERVICE AND COMMERCIAL	EPA 90016-Avg: Industrial Manufacturing	0.89	7.36
STATIONARY	INDUSTRIAL PROCESSES CHEMICAL	EPA 90012-Avg: Chemical Manufacturing	1.83	9.18
STATIONARY	INDUSTRIAL PROCESSES ELECTRONICS	EPA 90016-Avg: Industrial Manufacturing	0.89	7.36
STATIONARY	INDUSTRIAL PROCESSES FOOD AND AGRICULTURE	ARB1 (OMNI) AG_Prod	1.01	6.05
STATIONARY	INDUSTRIAL PROCESSES GLASS AND RELATED PRODUCTS	EPA 27102-Glass Melting Furnace	0.06	0.71
STATIONARY	INDUSTRIAL PROCESSES METAL PROCESSES	EPA 90007-Avg: Primary Metal Production	0.34	3.22
STATIONARY	INDUSTRIAL PROCESSES MINERAL PROCESSES	EPA 90013-Avg: Mineral Production	1.47	5.26
STATIONARY	INDUSTRIAL PROCESSES OTHER (INDUSTRIAL PROCESSES)	EPA 90016-Avg: Industrial Manufacturing	0.89	7.36
STATIONARY	INDUSTRIAL PROCESSES WOOD AND PAPER	EPA 90015-Avg: Pulp and Paper Industry	2.63	29.74
STATIONARY	PETROLEUM PRODUCTION AND MARKETING OIL AND GAS PRODUCTION	ARB112-Fuel Combustion – Distillate[d]	15.00	30.00
STATIONARY	PETROLEUM PRODUCTION AND MARKETING PETROLEUM MARKETING	ARB112-Fuel Combustion – Distillate[d]	15.00	30.00
STATIONARY	PETROLEUM PRODUCTION AND MARKETING PETROLEUM REFINING	ARB331-Petroleum Refining	4.00	8.00
STATIONARY	WASTE DISPOSAL INCINERATORS	ARB161, ARB162-Incineration	32.50	65.00
STATIONARY	WASTE DISPOSAL LANDFILLS	ARB421-Landfill Dust	0.62	6.77
STATIONARY	WASTE DISPOSAL OTHER (WASTE DISPOSAL)	ARB462-Waste Burning	19.32	37.63
STATIONARY	WASTE DISPOSAL SOIL REMEDIATION	EPA 17108-Waste Incineration	3.50	0.57
AREA	MISCELLANEOUS PROCESSES CONSTRUCTION AND DEMOLITION	ARB420-Construction Dust	0.62	6.77
AREA	MISCELLANEOUS PROCESSES COOKING	BRAVO Cooking Composite[f]	10.17	86.63
AREA	MISCELLANEOUS PROCESSES FARMING OPERATIONS	ARB417-Agricultural Tilling	0.35	3.43

Table 4-4. Continued.

Source Type	Source[b]	Source Profile Origin	% of $PM_{2.5}$-Mass	
			EC (%)	OC (%)
AREA	MISCELLANEOUS PROCESSES FIRES	ARB460-Grass/Woodland Fires	19.32	37.63
AREA	MISCELLANEOUS PROCESSES FUGITIVE WINDBLOWN DUST	ARB416-Unpaved Road Dust	0.11	4.53
AREA	MISCELLANEOUS PROCESSES MANAGED BURNING AND DISPOSAL	ARB463-Forest Management Burning	20.26	54.00
AREA	MISCELLANEOUS PROCESSES OTHER (MISCELLANEOUS PROCESSES)	EPA 90016-Avg: Industrial Manufacturing	0.89	7.36
AREA	MISCELLANEOUS PROCESSES PAVED ROAD DUST	ARB71-Paved Road Dust	0.77	5.97
AREA	MISCELLANEOUS PROCESSES RESIDENTIAL FUEL COMBUSTION	EPA (42303,42331,42102)-Residential Wood Combustion	10.00	43.51
AREA	MISCELLANEOUS PROCESSES UNPAVED ROAD DUST	ARB416-Unpaved Road Dust	0.11	4.53
AREA	SOLVENT EVAPORATION ASPHALT PAVING / ROOFING	EPA 25402-Asphalt Roofing Manufacture	1.00	23.00
MOBILE	ON-ROAD MOTOR VEHICLES HEAVY-DUTY DIESEL URBAN BUSES (UB)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES HEAVY-DUTY GAS URBAN BUSES (UB)	Gas/Diesel Split Gasoline[g]	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES HEAVY HEAVY-DUTY DIESEL TRUCKS (HHDV)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES HEAVY HEAVY-DUTY GAS TRUCKS (HHDV)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT-DUTY PASSENGER (LDA)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT-DUTY TRUCKS - 1 (LDT1)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT-DUTY TRUCKS - 2 (LDT2)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT HEAVY-DUTY DIESEL TRUCKS - 1 (LHDV1)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT HEAVY-DUTY DIESEL TRUCKS - 2 (LHDV2)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT HEAVY-DUTY GAS TRUCKS - 1 (LHDV1)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES LIGHT HEAVY-DUTY GAS TRUCKS - 2 (LHDV2)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES MEDIUM DUTY TRUCKS (MDV)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES MEDIUM HEAVY-DUTY DIESEL TRUCKS (MHDV)	EPA HDDV Average	50.30	32.33
MOBILE	ON-ROAD MOTOR VEHICLES MEDIUM HEAVY-DUTY GAS TRUCKS (MHDV)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES MOTOR HOMES (MH)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES MOTORCYCLES (MCY)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES OTHER BUSES (OB)	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	ON-ROAD MOTOR VEHICLES SCHOOL BUSES (SB)	Gas/Diesel Split Gasoline	28.56	58.77

Table 4-4. Continued.

Source Type	Source[b]	Source Profile Origin	% of $PM_{2.5}$ Mass EC (%)	 OC (%)
MOBILE	OTHER MOBILE SOURCES AIRCRAFT	DRI Aircraft Jet Fuel C-130 McMurdo[h]	76.10	38.35
MOBILE	OTHER MOBILE SOURCES FARM EQUIPMENT	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	OTHER MOBILE SOURCES OFF-ROAD EQUIPMENT	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	OTHER MOBILE SOURCES OFF-ROAD RECREATIONAL VEHICLES	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	OTHER MOBILE SOURCES RECREATIONAL BOATS	Gas/Diesel Split Gasoline	28.56	58.77
MOBILE	OTHER MOBILE SOURCES SHIPS AND COMMERCIAL BOATS	EPA HDDV Average	50.30	32.33
MOBILE	OTHER MOBILE SOURCES TRAINS	EPA HDDV Average	50.30	32.33
NATURAL	NATURAL SOURCES WILDFIRES	ARB460-Grassland/Wood Fires	19.32	37.63

[a] The ARB emission inventory does not include uncertainties.

[b] The name (mnemonic) in the Source column is automatically generated by the ARB database rather than assigned by DRI. As such, acronyms such as “UB”, “HHDV”, and “LDA” may not correspond to their use elsewhere in this report. HHDV includes gasoline and diesel vehicles.

[c] ARB source profile.

[d] No OC data were available. OC was set to twice the EC value.

[e] From the U.S. EPA SPECIATE version 4.0 source profile library.

[f] Chow et al. (2004b).

[g] Fujita et al. (2007a; 2007b).

[h] Mazzera et al. (2001).

Table 4-5. $PM_{2.5}$ mass, OC, and EC emissions for California in 2006 (http://www.arb.ca.gov/).

	Emissions (tons/yr)		
Source	$PM_{2.5}$	EC	OC
Fuel Combustion			
ELECTRIC UTILITIES	2,108	288	576
COGENERATION	1,475	202	403
OIL AND GAS PRODUCTION	660	99	198
PETROLEUM REFINING	1,215	49	97
MANUFACTURING AND INDUSTRIAL	2,040	18	150
FOOD AND AGRICULTURAL PROCESSING	1,065	536	344
SERVICE AND COMMERCIAL	1,833	16	135
OTHER	1,331	182	364
Total	11,727	1,389	2,268
Waste Disposal			
LANDFILLS	148	1	10
INCINERATORS	40	13	26
SOIL REMEDIATION	27	1	0
OTHER	15	3	6
Total	230	18	42
Petroleum Production			
OIL AND GAS PRODUCTION	21	3	6
PETROLEUM REFINING	757	30	61
PETROLEUM MARKETING	3	0	1
Total	781	34	68
Industrial Processes			
CHEMICAL	1,305	24	120
FOOD AND AGRICULTURE	2,533	0	2,533
MINERAL PROCESSES	7,419	109	390
METAL PROCESSES	269	1	9
WOOD AND PAPER	2,960	78	880
GLASS AND RELATED PRODUCTS	518	0	4
ELECTRONICS	2	0	0
OTHER	2,172	19	160
Total	17,178	231	4,096
Solvent Evaporation			
ASPHALT PAVING / ROOFING	13	0	3
Miscellaneous			
RESIDENTIAL FUEL COMBUSTION	40,042	4,004	17,422
FARMING OPERATIONS	14,473	51	496
CONSTRUCTION AND DEMOLITION	7,461	46	505
PAVED ROAD DUST	21,475	166	1,283
UNPAVED ROAD DUST	18,874	20	854
FUGITIVE WINDBLOWN DUST	16,390	17	742
FIRES	399	77	150

Table 4-5. Continued.

	Emissions (tons/yr)		
Source	**$PM_{2.5}$**	**EC**	**OC**
Miscellaneous, continued			
MANAGED BURNING AND DISPOSAL	36,396	7,374	19,652
COOKING	8,380	852	7,259
OTHER	221	2	16
Total	164,111	12,609	48,381
Mobile (On-Road)			
LIGHT-DUTY PASSENGER	3,357	959	1,973
LIGHT-DUTY TRUCKS	3,412	975	2,005
MEDIUM DUTY TRUCKS	1,097	552	354
LIGHT HEAVY-DUTY GAS TRUCKS	142	40	83
MEDIUM HEAVY-DUTY GAS TRUCKS	21	6	12
HEAVY HEAVY-DUTY GAS TRUCKS	15	4	9
LIGHT HEAVY-DUTY DIESEL TRUCKS	220	111	71
MEDIUM HEAVY-DUTY DIESEL TRUCKS	1,450	729	469
HEAVY HEAVY-DUTY DIESEL TRUCKS	13,731	6,907	4,439
MOTORCYCLES (MCY)	122	35	72
HEAVY-DUTY DIESEL URBAN BUSES	176	88	57
HEAVY-DUTY GAS URBAN BUSES	3	1	2
SCHOOL BUSES	167	48	98
OTHER BUSES	68	19	40
MOTOR HOMES	34	10	20
Total	24,014	10,483	9,703
Mobile (Other)			
AIRCRAFT	3,107	2,364	1,191
TRAINS	1,557	783	503
SHIPS AND COMMERCIAL BOATS	8,917	4,485	2,883
RECREATIONAL BOATS	2,319	662	1,363
OFF-ROAD RECREATIONAL VEHICLES	205	59	121
OFF-ROAD EQUIPMENT	10,939	3,124	6,429
FARM EQUIPMENT	2,382	680	1,400
Total	29,427	12,158	13,890
Natural Sources			
WILDFIRES	78,479	15,161	29,530
Grand Total	**325,959**	**52,084**	**107,979**

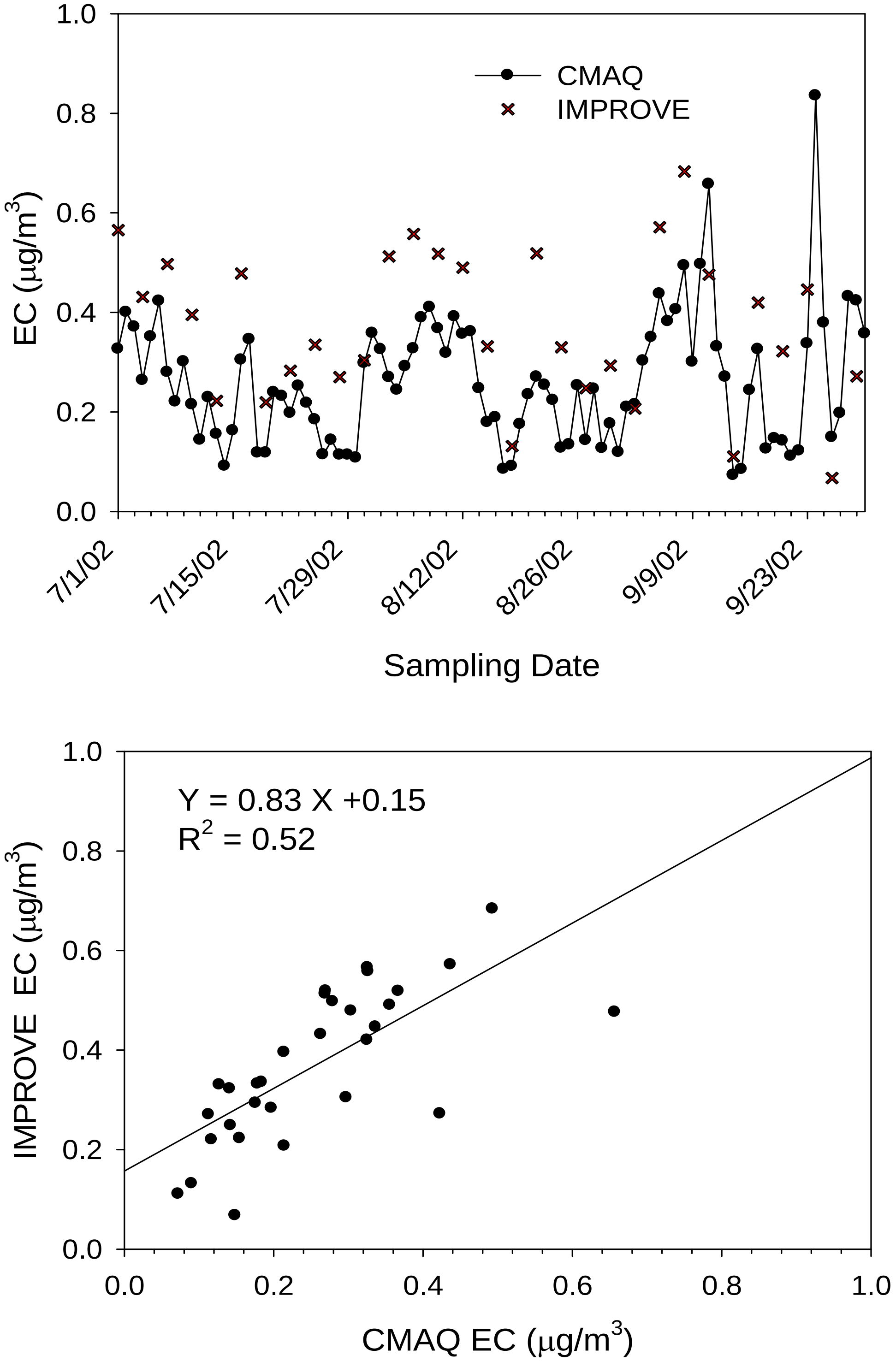


Figure 4-1. Community Multi-Scale Air Quality (CMAQ) model comparison of estimated and measured 24-hour average EC concentrations (μg/m^3) using the IMPROVE protocol (Chow et al., 2007a) based on DRI source profiles (Chow et al., 2006b) at Great Smoky Mountains National Park (GRSM), TN, during summer 2002.

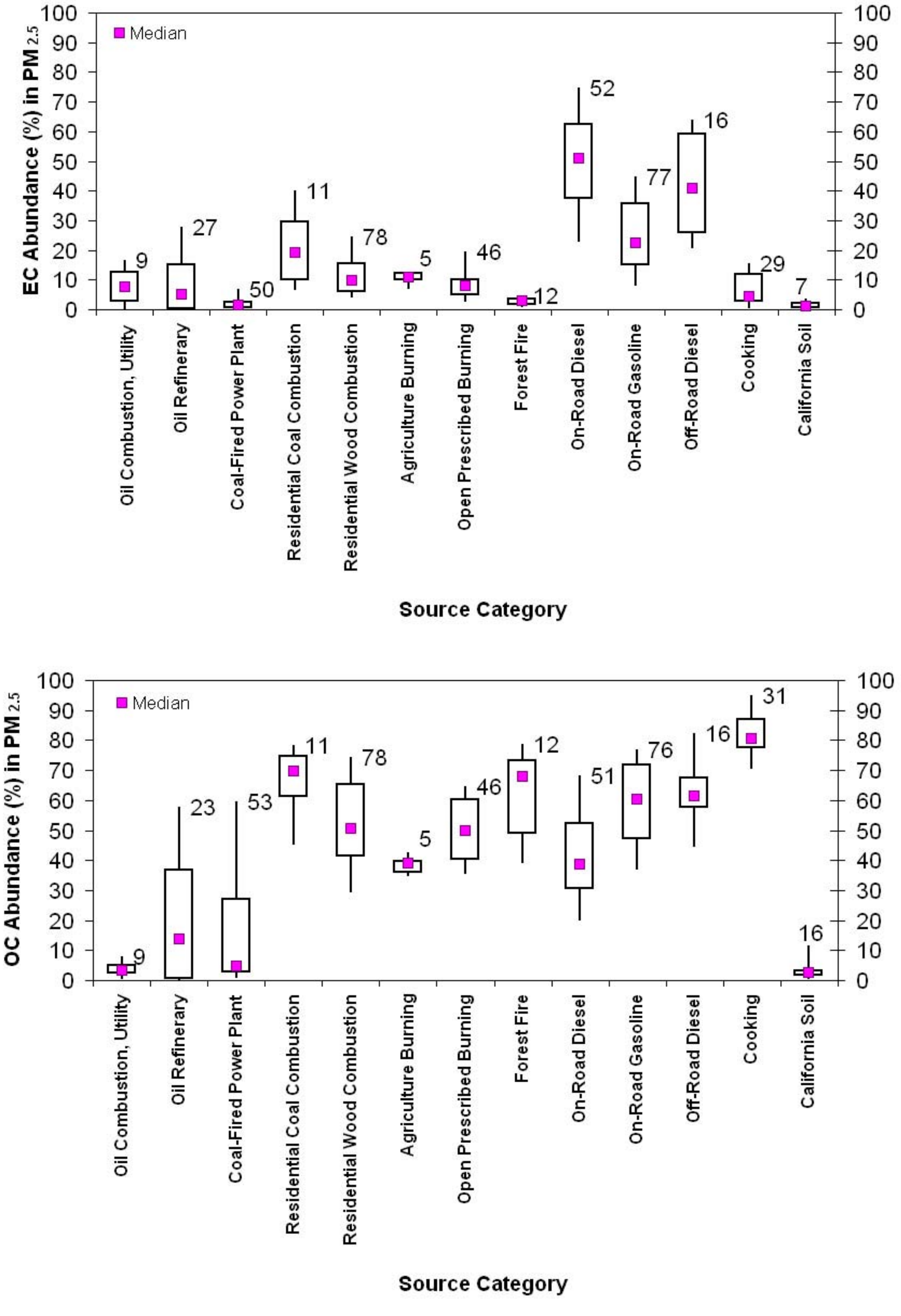


Figure 4-2. Distribution statistics of EC and OC abundances in specific $PM_{2.5}$ source profiles. (The lower and upper bar indicate the 10th and 90th percentile, respectively, and the box spans the 25th to 75th percentile. The pink square indicates the median value. The number next to the box indicates the number of profiles used for the average. Not every OC measurement has a corresponding EC measurement.)

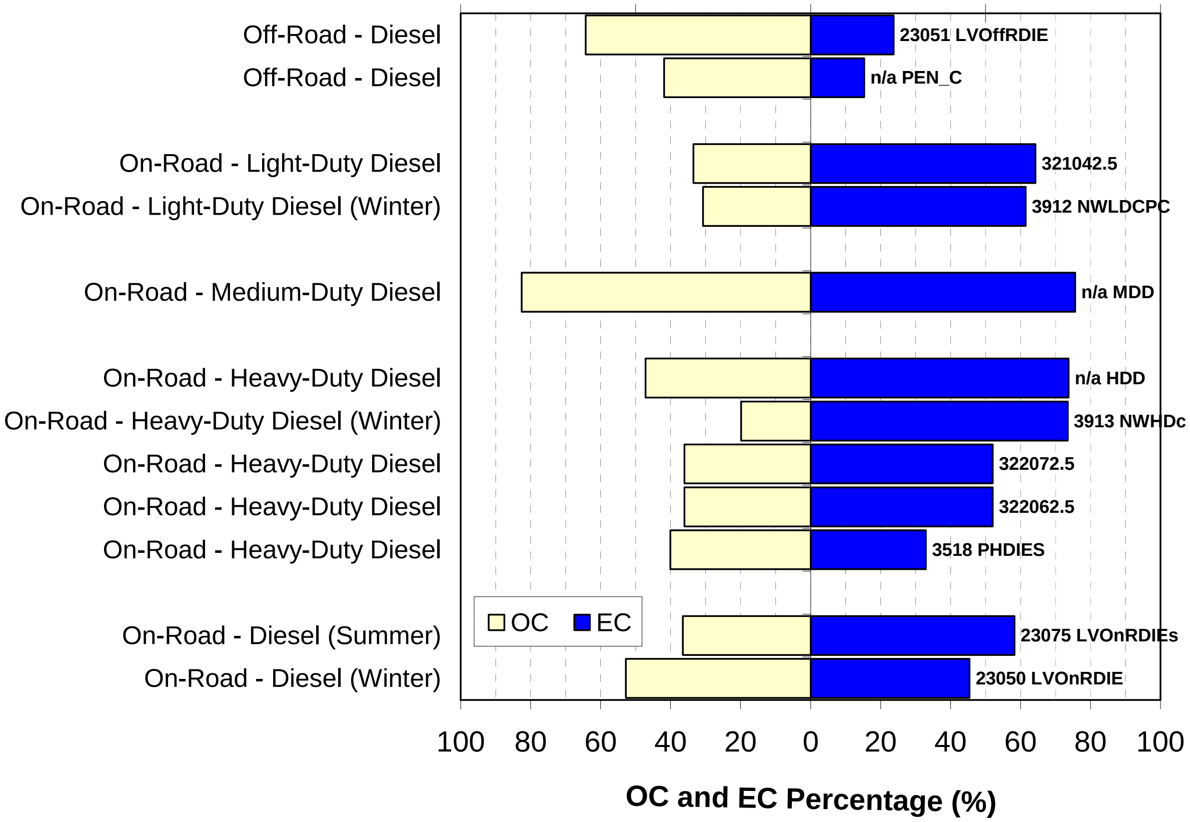


Figure 4-3. OC and EC abundances in selected composite $PM_{2.5}$ source profiles representing diesel-fueled vehicle emissions. See Table 4-3 to match profile IDs/mnemonics to the right of the blue (EC) bar. (Note that SPECIATE profile IDs 322072.5 and 322062.5 reported identical OC and EC abundances with different PM sum of species [89.06 and 88.71%, respectively] and have different references in the SPECIATE database.)

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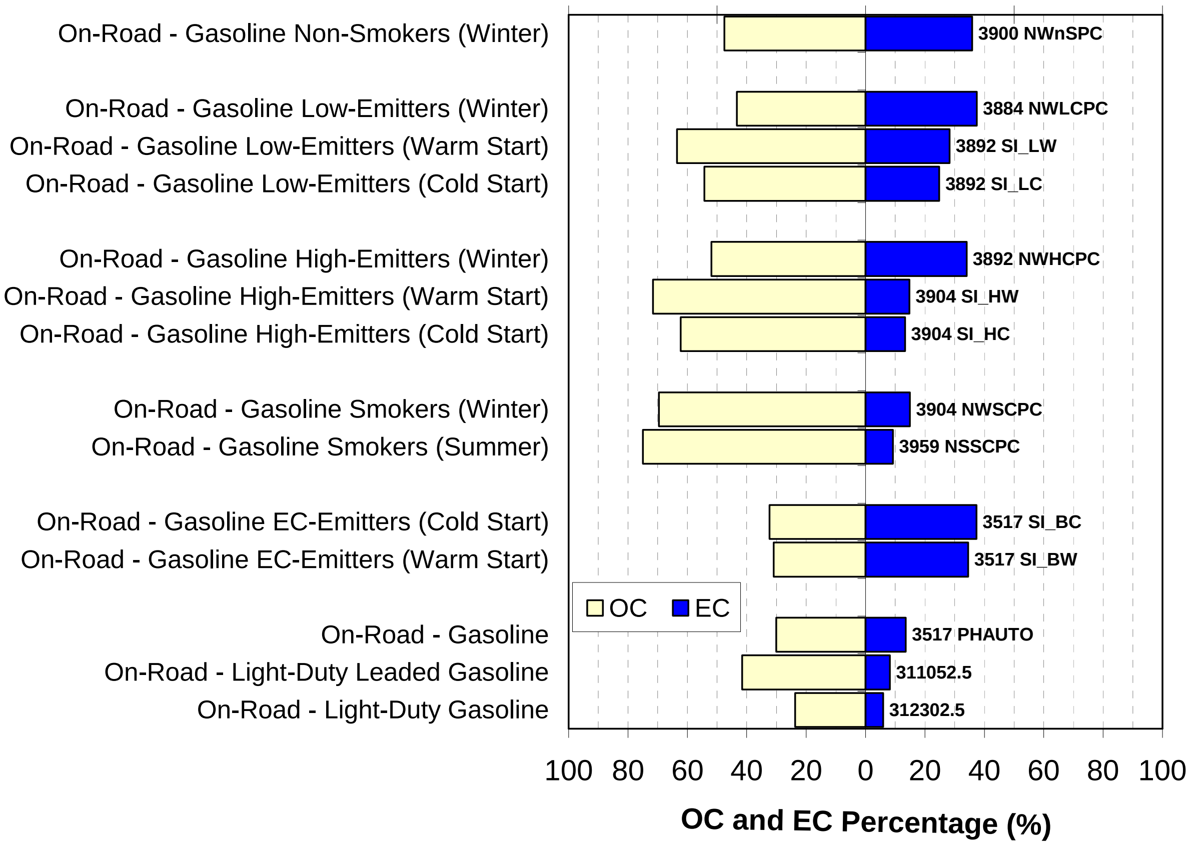


Figure 4-4. OC and EC abundances in selected composite $PM_{2.5}$ source profiles representing gasoline-fueled vehicle emissions. See Table 4-3 to match profile IDs/mnemonics to the right of the blue (EC) bar.

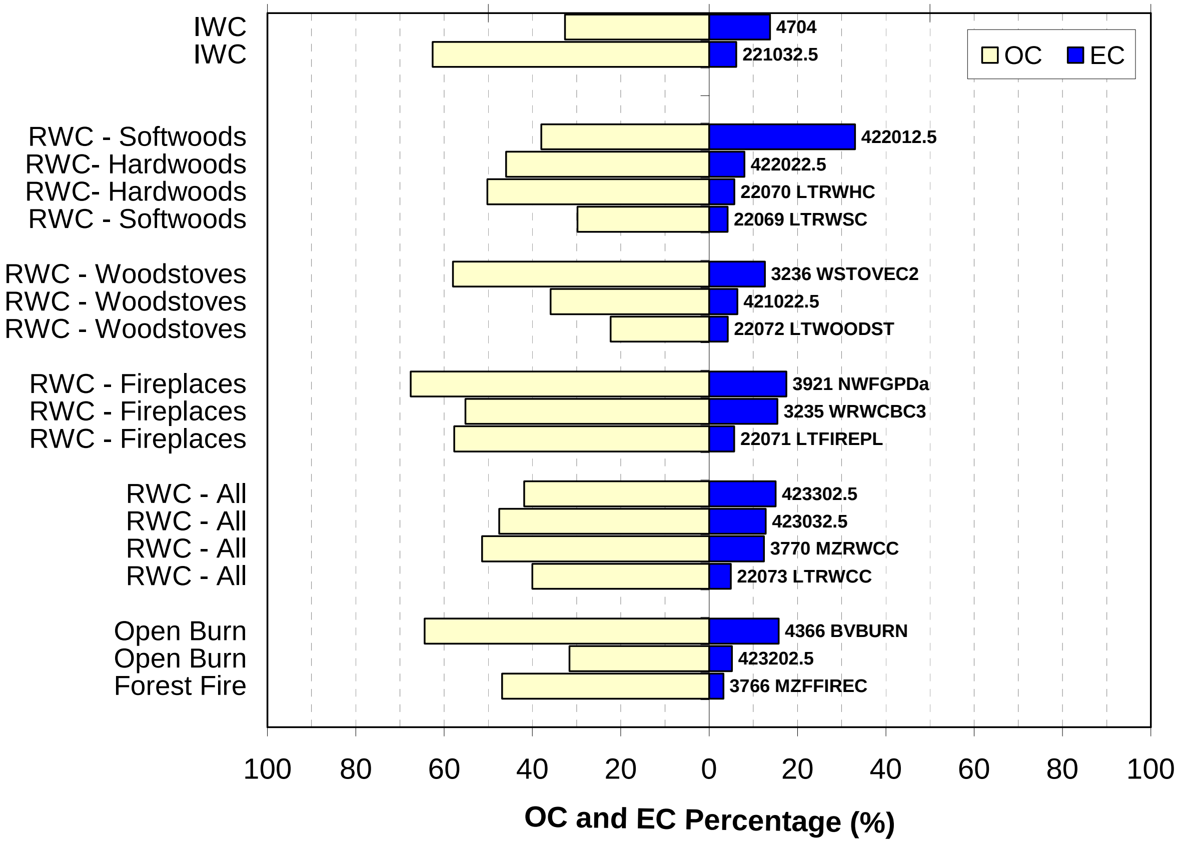


Figure 4-5. OC and EC abundances in selected composite $PM_{2.5}$ source profiles representing wood burning emissions. See Table 4-3 to match profile IDs/mnemonics to the right of the blue (EC) bar. IWC: Industrial Wood Combustion. RWC: Residential Wood Combustion.

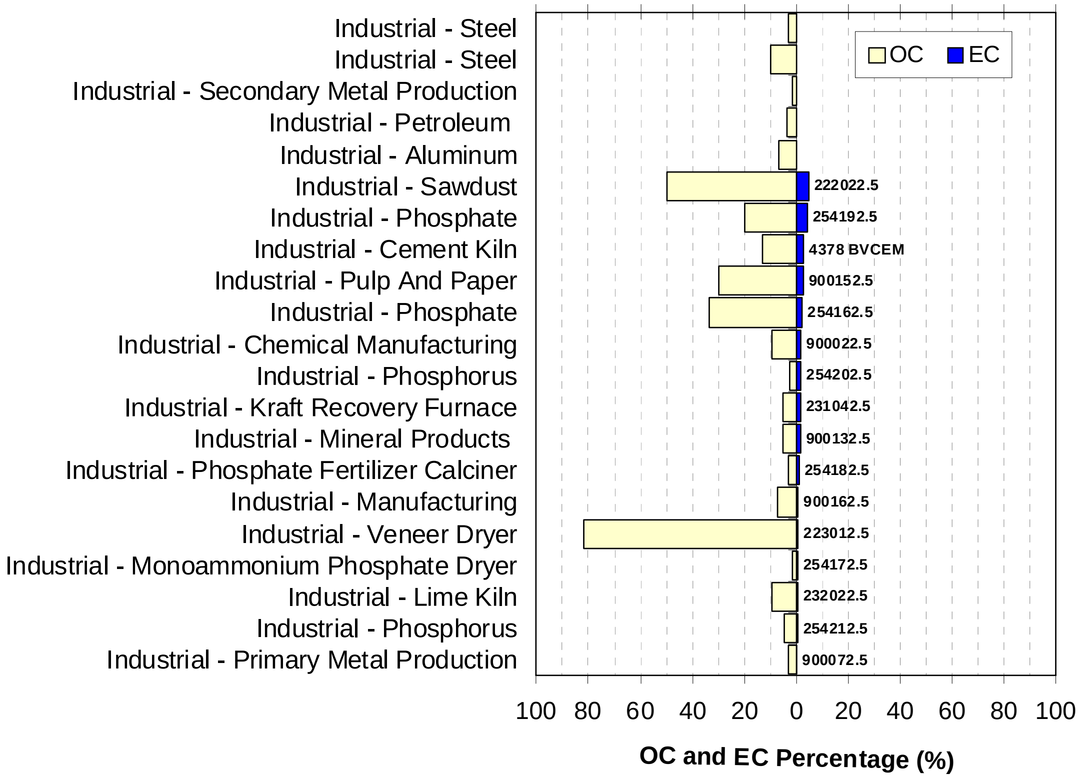


Figure 4-6. EC and OC abundances in selected composite $PM_{2.5}$ source profiles representing industrial emissions. See Table 4-3 to match profile IDs/mnemonics to the right of the blue (EC) bar.

5. UNCERTAINTY OF BLACK CARBON EMISSIONS

Emission inventories of all sorts usually provide annual estimates to three significant digits or more. This implies a precision on the order of less than ±1%, which is unjustified given the poor precision of most input data. Emission rate uncertainty has been addressed by several methods and to various levels of detail. Streets et al. (2001) presented central and high estimates for BC emissions in China based on the range of values available for BC emission factors. Bond et al. (2004) applied a statistical approach that assumed statistical distributions for the components in the emission inventory (i.e., emission factors and activities) and propagated these errors and their covariances. The end-product was an overall uncertainty in the global BC emissions of a factor of two, with a range of 4.3 to 22 Tg BC/yr. It is unclear whether this is a statistically meaningful quantity or simply represents large variability in measurements made at different locations under different conditions with different methodologies. Mobile source emission factors applied in China (Streets et al., 2001; Cao et al., 2006) are not necessarily relevant to emission factors for on-road vehicles in California estimated with the EMFAC2007 model.

The individual components used to calculate the emissions in the ARB emission inventory are not readily available. The responsibility of each district in California is limited to reporting emissions for point and area sources but not the corresponding emission factors or activities the emissions were based on. It is not feasible to take a purely statistical approach to evaluating uncertainties in ARB emission estimates. It is unlikely that major sources of error in these variables are random; much of the error is related to systematic bias, but the bias is unknown. For example, agricultural burning activity could be low-biased due to incomplete reporting of unscheduled events.

The level of uncertainty of estimated BC emissions in California can be examined by: 1) comparing the ARB EC inventory with a global BC inventory; 2) comparing modeled EC based on the NEI inventory with ambient EC measurements; 3) comparing measured emission factors with those estimated with models used in the ARB emission inventory; and 4) determining the sensitivity of EC emission estimated with the ARB emission inventory to source profiles used to convert $PM_{2.5}$ mass to EC emissions.

5.1 Comparison of BC/EC and OC Emission Inventories between ARB (1995) and Bond (1996)

The best understanding of the uncertainties of global or other inventories is the repeatability of estimates by different investigators using independent methodologies. Statistically, this is referred to as the standard error of the mean or in this case, the sum. A potential limitation of this method is that these methodologies may not be independent if they use the same emission factors and/or activities as input (i.e., same input = same output).

Global BC emissions from the Speciated Pollutant Emissions Wizard (SPEW) are available (http://cee.uiuc.edu/research/bondresearch/) for 1850 and every ten years up to 2000. As noted above, the Bond et al. (2004) estimate for California BC emissions was 33,281 tons/yr in 1996, which is denoted as the "current year." Following the approach used in Section 4.3, statewide California EC and OC emissions were estimated by applying the same set of source profiles (Table 4-4) to $PM_{2.5}$ emission for 1995 estimated with the ARB emission inventory tools.

Results are presented in Table 5-1 and are compared with Bond's estimates for the biofuel, fossil fuel, and open burning emissions for BC/EC and OC. Based on the ARB inventory, 1995 EC emissions were 38,781 tons/yr (implying less than ±0.01% precision by the significant digits), 16% higher than the Bond et al. (2004) estimate of 33,281 tons/yr for 1996. For practical purposes, these independent estimates based on different approaches agree. While this agreement may be fortuitous, the Bond et al. (2004) stated inventory uncertainty of a factor of two seems high, at least for California.

The Bond et al. (2004) inventory is based on fuel use by technology sector and distributed according to population. In the ARB inventory, EC emissions were summed for Bond et al.'s (2004) three fuel use categories: 1) biofuel (RWC and cooking); 2) fossil fuel (fuel combustion, industrial activities, petroleum production, miscellaneous processes, and on-road and off-road mobile sources); and 3) biomass burning (agricultural waste burning, forest management, and wildfires). Table 5-1 gives the absolute (tons/yr) and relative (percent of total) BC/EC and OC estimates from the 1995 ARB and 1996 Bond inventories. Agreement on a percentage basis for EC abundances of 26 – 28% is good for the open burning category. As a percentage of total EC from biofuel burning, the Bond estimate (24%) is twice the ARB estimate

(12%). Conversely, for the fossil fuel burning category, the ARB EC estimate (62% of total EC emissions) is higher than the corresponding Bond estimate (48% of total EC emissions).

Table 5-1 also compares OC emissions from the 1995 ARB and 1996 Bond inventories. The aggregated OC emissions from the Bond inventory (179,101 tons/yr) are 2.2 times OC emissions from the ARB inventory (82,596 tons/yr). On a percentage basis, the Bond OC open burning emissions (66% of total OC) are more than twice the ARB OC estimate (30%). On a percentage basis, the ARB and Bond estimates for the biofuel burning category are similar: 29 and 24% of total OC, respectively. For fossil fuel combustion, ARB OC emissions constitute 37% of the total OC emissions while the corresponding Bond estimate is 10%.

The largest difference is for open burning OC emissions: 24,336 tons/yr from the 1995 ARB inventory versus 118,968 tons/yr from the 1996 Bond inventory. The large open burning OC estimate in the Bond inventory appears high for several reasons. Table 2-3 of Section 2.2 shows that managed burning and disposal (33,725 tons/yr) along with wildfires (15,901 tons/yr) accounted for 19% of estimated $PM_{2.5}$ emissions (266,581 tons/yr) in the 1995 ARB inventory. The Bond open burning OC emissions (118,968 tons/yr) alone accounted for 45% of the ARB $PM_{2.5}$ emissions. Assuming an OM to OC ratio of 1.5, the Bond OM emissions would account for 67% of the ARB $PM_{2.5}$ emissions. The ratios of OC/BC in the Bond global and California inventories for 1996 are 4.2 and 5.4, respectively. The OC/BC ratio for California by Bond et al. (2004) is 2.5 times the 1995 ARB emission inventory OC/BC ratio of 2.1.

During the 2000/2001 California Regional Air Quality Study (CRPAQS), $PM_{2.5}$ and its chemical components were measured on the U.S. EPA's every-sixth-day sampling schedule at 32 urban and rural sites in Central California (Chow et al., 2006e; 2006f; 2006g). The ratio of average OC to EC was 2.9. OC constituted 32% of $PM_{2.5}$, half the 67% ratio based on the Bond OC estimate (179,101 tons/yr) divided by the ARB $PM_{2.5}$ estimate (266,581 tons/yr). This discrepancy could be attributed to low-biased OC fractions in the managed burning (54% in the ARB463 profile) and wildfire (38% in the ARB460 profile) profiles in Table 4-4. However, if the OM/OC ratio is assumed to be 1.5, OM + EC in these two profiles would be 101 and 76% of $PM_{2.5}$, respectively. While OC in the wildfire profile is lower than that in the managed burning profile, the difference cannot account for the large OC emission estimates from open burning in the 1996 Bond inventory.

5.2 Comparison between Measured and NEI Modeled EC Concentrations

Section 4.1 described simulated speciated $PM_{2.5}$ concentrations at eastern U.S. national parks during summer, 2002, using the NEI and source profiles representing major source categories. Source profiles were associated with the emission inventory sources using the SMOKE model. Two sets of source profiles were used: 1) default profiles, including EC and OC, derived by U.S. EPA from its SPECIATE version 4.0 source profile library; and 2) a set of source profiles chosen by DRI from past studies (now incorporated into the SPECIATE database) and profiles derived from recent studies. Since EC is chemically inert, it is appropriate to use modeled EC concentrations to evaluate the emission inventory and source profiles used to generate them.

Figure 5-1 compares SMOKE-MM5-CMAQ model estimated six-hour average EC at the BRIG, NJ and GRSM, TN sites using the U.S. EPA default source profiles and the ones selected in Section 4 for this study. There is a near one-to-one correspondence ($y = 0.91x - 0.001$ $\mu g/m^3$) and a high correlation ($r^2 = 0.92$) at the BRIG site. While the correlation is high ($r^2 = 0.90$) at the GRSM site, the non-default profiles result in higher EC concentrations ($y = 1.53x + 0.001$ $\mu g/m^3$).

The effect of using different source profiles to estimate EC concentrations is illustrated in Figure 5-2, which shows lower model-estimated EC with the default profiles. As noted in Section 4.1, model-estimated EC concentrations with the non-default (DRI) profiles were systematically lower than the corresponding measured values. At the GRSM site, the average measured EC concentration was 0.36 $\mu g/m^3$ compared to 0.26 $\mu g/m^3$ based on the non-default profiles. However, model estimated EC based on the default profiles was 50% lower than measured EC, on average (0.17 $\mu g/m^3$). Thus, the non-default profiles fit the measured data better than the defaults. This exercise illustrates the importance of choosing representative source profiles in the derivation of an EC emission inventory from a $PM_{2.5}$ emission inventory.

5.3 Comparison between Measured and Modeled Emission Factors

$PM_{2.5}$ emission factors summarized in Sections 3.1 and 3.2 are compared with modeled and/or empirical emission factors currently used in California's $PM_{2.5}$ emission inventory in Table 5-2. Comparisons are first evaluated using the average of the absolute differences (AAD), i.e., the average of the percent differences between the non-default and default emission factors divided by the default factors for specific source categories. For the 16 sets of on-road diesel-fueled vehicle emission factors obtained under the hot city-suburban route (HCS) cycle (Fujita et al., 2007a; 2007b), the AAD with respect to EMFAC2007 predictions is 37.6% (Table 5-2).

The Kansas City Study (U.S. EPA 2008a; 2008b) was conducted 3-4 years after the Gas/Diesel Split Study (Fujita et al., 2007a; 2007b). Gasoline-fueled vehicle emission factors in the Gas/Diesel Split Study were classified into WS and CS cycles, while the Kansas City emission factors were classified according to the seasons (summer vs. winter) based on the three FTP cycles (i.e., cold start, hot start, and warm start). The AADs for gasoline-fueled vehicle emission factors ranged from 65.9% (Kansas City Gasoline [FTP winter]) to 163.9% (Kansas City Gasoline [FTP summer]), which are two to four times the diesel exhaust AAD of 37.6%. This suggests that gasoline exhaust emissions in the current inventory are uncertain.

Removing two outliers (i.e., SI_9_4 and SI_10_4; high-emitting smoker vehicles; see Figure 3-4 and footnotes in Table 5-2) from the Gas/Diesel Split Study reduces the AADs from 136.1% to 66.3 and from 150.3 to 77.7% for the Gas/Diesel Split WS and CS categories, respectively. Similarly, removing outliers (i.e., S2_1, S2_2, W6_1, and W6_4; see outliers shown in Figure 3-6 and footnotes in Table 5-2) from the Kansas City Study reduces the AADs from 163.9 to 107.1% and from 103.5 to 65.9% during summer and winter, respectively. Even with outliers excluded, the AADs are much higher for the gasoline- than for the diesel-fueled vehicles. The best agreement for gasoline-fueled vehicles is found for the Kansas City winter Study, which represents the most recent data (February - March, 2005).

California biomass burning emission factors were acquired from the EES model and the SJV measurements, as described in Section 3.3. These emission factors are based on fewer measurements than are the on-road mobile source emission factors, so the comparisons with the FLAME biomass burning emission factors are probably less statistically significant. The largest AAD is 524.3% for wet fresh canopy fuels followed by 245% for rice straw (Table 5-2). The combustion and fuel conditions (e.g., moisture content) are more variable for biomass burning than for motor vehicle operating conditions. Emission models do not appear to accurately simulate the full complexity of biomass burning.

Considering the large variability of individual measurements and the fact that modeled emission factors should represent an "average" for similar sources, modeled average emission factors were compared with the measured average for each subcategory. This was achieved by calculating the regression slope of measured (y) against modeled (x) emission factors with the intercept constrained to zero. The results in Table 5-2 are presented for ordinary least-squares (OLS) regressions and for “robust” regressions (RR). RR reduces the influence of outliers using an iterative feedback algorithm developed by Huber (1981). The standard error of the slope is reported for both cases.

The OLS and RR slopes of 103 ± 9% and 87 ± 7%, respectively, for the Gas/Diesel Split Study diesel-fueled emission factors in Table 5-2 suggest that the EMFAC2007 model overestimates diesel emissions for vehicles that are not high-emitters. The error is small (within 10%) in terms of category averages. EMFAC2007 also overestimates gasoline-fueled vehicle emissions, according to the RR slopes $< 100\%$. When high-emitting gasoline vehicles are not downweighted in the regression analysis, the measured emission factors attain or exceed the EMFAC2007 model estimates (i.e., OLS slopes are $\geq 100\%$). The only exception is for the Gas/Diesel Split Study WS vehicles (i.e., OLS slope of 80 ± 40%), in which emission factors are smaller than the EMFAC2007 estimates. EMFAC2007 estimates are based on the FTP cycle which contains CS conditions. This study shows that gasoline-fueled vehicles under WS conditions emit only 36 ± 11% (RR slope) of the EMFAC2007 estimates in terms of the category average.

For biomass burning, Table 5-2 shows that the RR slopes indicate that the EES and SJV emission factors are lower than measured emission factors for dry litter (229 ± 91%), wet herb and shrub (253 ± 129%), wet canopy fuels (624 ± 97%), rice straw (339 ± 152%), and grass (222 ± 99%). The results are not statistically significant because the standard errors of the RR slopes are large compared to those associated with mobile source emissions. However, measured and model estimated SJV emission factors for dry herb, dry duff, and wet wood burning are similar with RR slope of 81 – 97%. For biomass burning, the OLS and RR slopes are similar, but with a limited number of data points (i.e., two to five data pairs). Considering the variability of biomass burning emission factors, future studies need to focus on more comprehensive sampling and analysis to obtain statistically meaningful results.

5.4 Sensitivity of the ARB EC Emission Inventory to Choice of Source Profiles

Table 4-5 summarizes California’s 2006 $PM_{2.5}$, EC, and OC emissions. The base-case source profiles are presented in Table 4-4. This serves as a basis for examining the sensitivity of the EC emissions to the choice of source profiles that convert $PM_{2.5}$ to EC emissions. Table 5-3 presents EC emissions from the major source categories in California's inventory (see Table 4-5). For the base case, summarized in the first column of Table 5-3, the U.S. EPA HDDV source profile (see Table 4-4) was applied to the "FOOD AND AGRICULTURAL PROCESSING" source in the fuel combustion category and to sub-categories in Mobile (On-road; i.e., light heavy-duty gasoline trucks, medium-duty trucks, medium heavy-duty gasoline and diesel trucks, heavy heavy-duty gasoline and diesel trucks, and buses) and Mobile (Other; e.g., aircraft, ships, commercial boats, and trains). Compared with the higher EC values used for gasoline- (28.6 ± 13.8%) and diesel- (50.3 ± 5.0%) fueled vehicle source profiles in the base case (Table 4-4), the EC abundances of the ARB gasoline and diesel vehicle profiles (profile numbers ARB400 and ARB425, respectively) are 20 and 26.4%, respectively. The uncertainty of the U.S. EPA HDDV EC composition is only ±5% so the EPA HDDV and ARB diesel profiles are significantly different. The effects of substituting these profiles on the EC emission inventory are shown in the second column of Table 5-3. Mobile On-Road emissions decrease by 44% from 10,483 to 5,876 tons EC/yr and the Mobile Off-Road emissions decrease by 32% from 12,158 to 8,302 tons EC/yr. Overall, the 2006 statewide EC emissions decreases 17% from 52,084 to 43,367 tons EC/yr.

The "RESIDENTIAL FUEL COMBUSTION" (RWC in woodstoves and fireplaces) in the "Miscellaneous" category is an important EC source (4,004 tons EC/yr in 2006, see Table 4-5). The EC abundance in the composite U.S. EPA SPECIATE profile (profile numbers 42303, 42331, and 42102 averaged into one profile) is 10 ±3% (Table 4-4). Chow et al. (2007b) used a hardwood combustion source profile (BURN-H) with a $PM_{2.5}$ EC composition of 5.2 ± 0.8% for a source apportionment study in Fresno during CRPAQS. The results of substituting this profile for the U.S. EPA RWC source profile composite used in the base case are given in the third column of Table 5-3. The decrease in RWC emissions from 4,004 to 2,078 tons EC/yr results in a decrease in emissions from the "Miscellaneous" source category from 12,609 to 10,684 tons EC/yr. However, the overall decrease in statewide EC emissions is only 4.2% with respect to the base case.

These examples illustrate the sensitivity of estimated EC emissions to variations of source profiles used to convert estimated $PM_{2.5}$ emissions to EC emissions. With 1,326 $PM_{2.5}$

sources in the ARB 1995 emission inventory (http://www.arb.ca.gov/app/emsinv/ fcemssumcat2007.php), there is clearly a dearth of available source profiles. When profiles are available, they need to be justified as representing the category, especially for the highest emitting source types. ARB profile numbers ARB114 and ARB116 represent stationary internal combustion engines burning diesel or distillate/diesel fuels, respectively. The $PM_{2.5}$ EC abundances in these profiles are 15 and 4%, respectively. These abundances are much lower than recent and older profile measurements of diesel exhaust. This is why the U.S. EPA HDDV profile with an EC abundance of 50.3% is used to represent the "FUEL COMBUSTION FOOD AND AGRICULTURAL PROCESSING" source, which includes stationary diesel engines that power irrigation pumps.

The ARB residential natural gas combustion profile (i.e., profile number ARB121) has a $PM_{2.5}$ EC abundance of 50%. This value seems high compared to published gas combustion profiles. U.S. EPA SPECIATE profile number 42107 (natural gas home appliances) has an EC abundance of 6.7%, almost one-tenth of the ARB121 profile. The composite profile for gas-fired co-generation plants has an EC abundance of 2.5 ± 2.0% (England et al., 2007b). The ARB documentation shows that the residential gas combustion profile number ARB121 was based on measurements of an industrial boiler.

Both the U.S. EPA and ARB have made efforts to cross-reference codes (i.e., SCC and EIC, respectively) for inventory sources with source profile libraries. Automating complex inventory calculations may seem desirable but the choice of accurate and representative source profiles is ultimately the responsibility of the individual investigator.

Table 5-1. Comparison of $PM_{2.5}$ emission inventory for BC/EC and OC between 1995 ARB[a] and 1996 Bond et al. (2004).

		BC/EC Tons/yr (% of Total)			
Emission Inventory	**Base Year**	**Biofuel Burning**[b]	**Fossil Fuel**[c]	**Open Burning**[d]	**Total**
ARB (1995)	1995	4,741 (12%)	24,017 (62%)	9,978 (26%)	38,781
Bond et al. (2004)	1996	7,884 (24%)	16,109 (48%)	9,288 (28%)	33,281
		OC Tons/yr (% of Total)			
ARB (1995)	1995	23,691 (29%)	30,332 (37%)	24,336 (30%)	82,596
Bond et al. (2004)	1996	42,991 (24%)	17,142 (10%)	118,968 (66%)	179,101

[a] http://www.arb.ca.gov/app/emsinv/fcemssumcat2007.php.

[b] Biofuel Burning includes: residential wood combustion (RWC) and cooking.

[c] Fossil Fuel includes: fuel combustion, industrial activities, petroleum production, miscellaneous processes, and on-road and off-road mobile sources.

[d] Open Burning includes: agricultural waste burning, forest management, and wildfires.

Table 5-2. Comparability of measured (y) and modeled (x) emission factors for PM.

Study and source category for measured emission factors (y)	**Number of data pairs**	**Average Absolute Difference (AAD) %[a]**	**100 × Ordinary Least Squares Regression Slope ± σ (%)[b]**	**100 × Robust Regression Slope ± σ (%)[c]**
Gas/Diesel Split Diesel (Hot City-Suburban route [HCS] mode)	16	37.6	103±9	87.2±7.2
Gas/Diesel Split Gasoline (Warm Start [WS])	23	136.1	80.1±39.7	36.2±10.5
Gas/Diesel Split Gasoline (Warm Start [WS])	21[d]	66.3		
Gas/Diesel Split Gasoline (Cold Start [CS])	23	150.3	128±49	80.1±20.3
Gas/Diesel Split Gasoline (Cold Start [CS])	21[e]	77.7		
Kansas City Gasoline (FTP Summer)	19	163.9	111±34	86.8±25.6
Kansas City Gasoline (FTP Summer)	17[f]	107.1		
Kansas City Gasoline (FTP Winter)	20	103.5	92.9±24.7	72.7±16.5
Kansas City Gasoline (FTP Winter)	18[g]	65.9		
FLAME Dry Herb, Shrub	5	149	185±114	97.1±67.1
FLAME Dry Litter	4	151	229±91	**229±91**
FLAME Dry Wood	3	33.3	66.7±17.0	63.7±24.6
FLAME Dry Duff	2	18.9	81.1±13.9	81.1±13.9
FLAME Wet Herb, Shrub	5	186	255±100	**253±129**
FLAME Wet Canopy Fuels	2	524.3	624±97	**624±97**
FLAME Wet Wood	2	16.8	83.2±10.0	83.2±10.0
FLAME Chaparral (Chemise)	3[h]	64.6	35.4±1.5	35.4±1.5
FLAME Rice Straw	3[h]	245	339±152	**339±152**
FLAME Grass	2[i]	122	222±99	**222±99.4**

[a] AAD = $(100\times\overline{|\mathrm{Y}-\mathrm{X}|/\mathrm{X}})$, where Y and X are the measured and modeled (2006 California Emission Inventory) emission factors, respectively. Emission factors for mobile sources were estimated with EMFAC2007. Emission factors for biomass burning were based on the Emission Estimation System (EES) model except for chaparral, rice straw and grass, which were based on SJV emission factors.

[b] Based on ordinary least square regression with zero intercept; σ is the standard error of the slope.

[c] Based on robust regression with zero intercept to reduce the influence of outliers; σ is the standard error of the slope.

[d] Two outliers, SI_9_4 and SI_10_4 for warm start, were removed from the comparison (see Figure 3-4).

[e] Two outliers, SI_9_4 and SI_10_4 for cold start, were removed from the comparison (see Figure 3-4).

[f] Two outliers, S2_1 and S2_4, were removed from the comparison (see Figure 3-6).

[g] Two outliers, W6_1 and W6_4, were removed from the comparison (see Figure 3-6).

[h] Emission factors represent both flaming and smoldering phases.

[i] Emission factors represent dry and wet fuels.

Table 5-3. Sensitivity of the ARB EC emission inventory to selected major source profiles.

	2006 EC Emissions in tons/yr		
Source Category	**Base Case**[a]	**ARB Diesel**	**Fresno CMB RWC**
Fuel Combustion	1,389	1,135[b]	1,389
Industrial Processes	231	231	231
Miscellaneous	12,609	12,609	10,684[c]
Natural (Wildfires)	15,161	15,161	15,161
Mobile (On-road)	10,483	5,876[b]	10,483
Mobile (Other)	12,158	8,302[b]	12,158
Petroleum Production	34	34	34
Waste Disposal	18	18	18
Total	52,084	43,367[b]	49,885[c]

[a] From Table 4-5, $PM_{2.5}$ mass, OC, and EC emissions for California in 2006 (http://www.arb.ca.gov/)..

[b] Substituted ARB gasoline and diesel profiles (i.e., profiles ARB400 and ARB425, respectively) for corresponding base case profiles (i.e., Gas/Diesel Split Gasoline and HDDV, respectively) for the Fuel Combustion, Food and Agricultural Processing, Mobile (On-road), and Mobile (Other) categories.

[c] Substituted hardwood burning profile (i.e., BURN-H) from Chow et al. (2007b) for base case RWC profile (U.S. EPA [42303,42331,42102]-Residential Wood Combustion) for the Miscellaneous category.

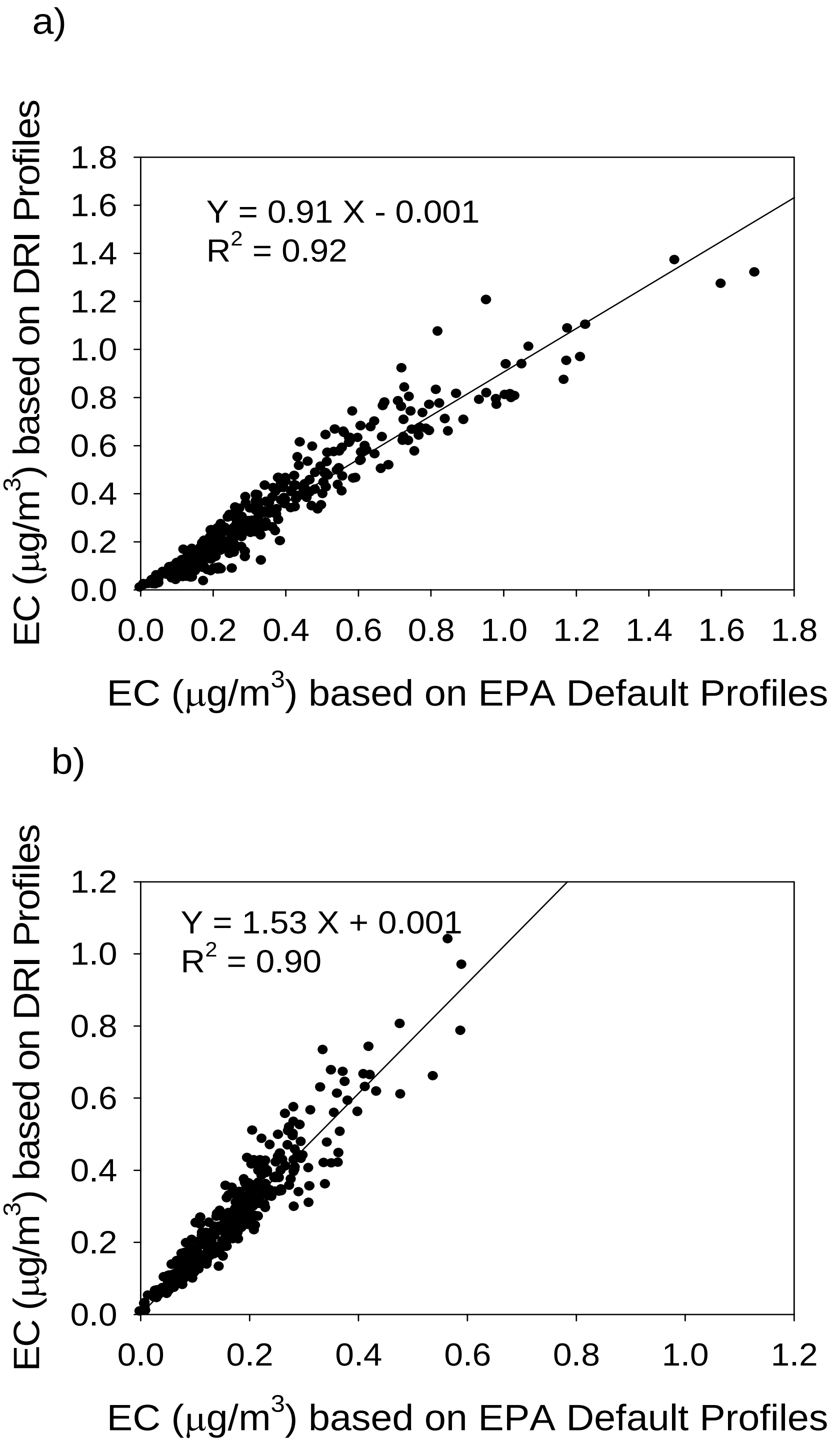


Figure 5-1. Comparison of SMOKE-MM5-CMAQ model estimated six-hour average EC based on default National Emission inventory (NEI) and DRI-selected non-default EC source profiles for the: a) Brigantine National Wildlife Refuge, NJ; and b) Great Smoky Mountains National Park, TN, during summer 2002..

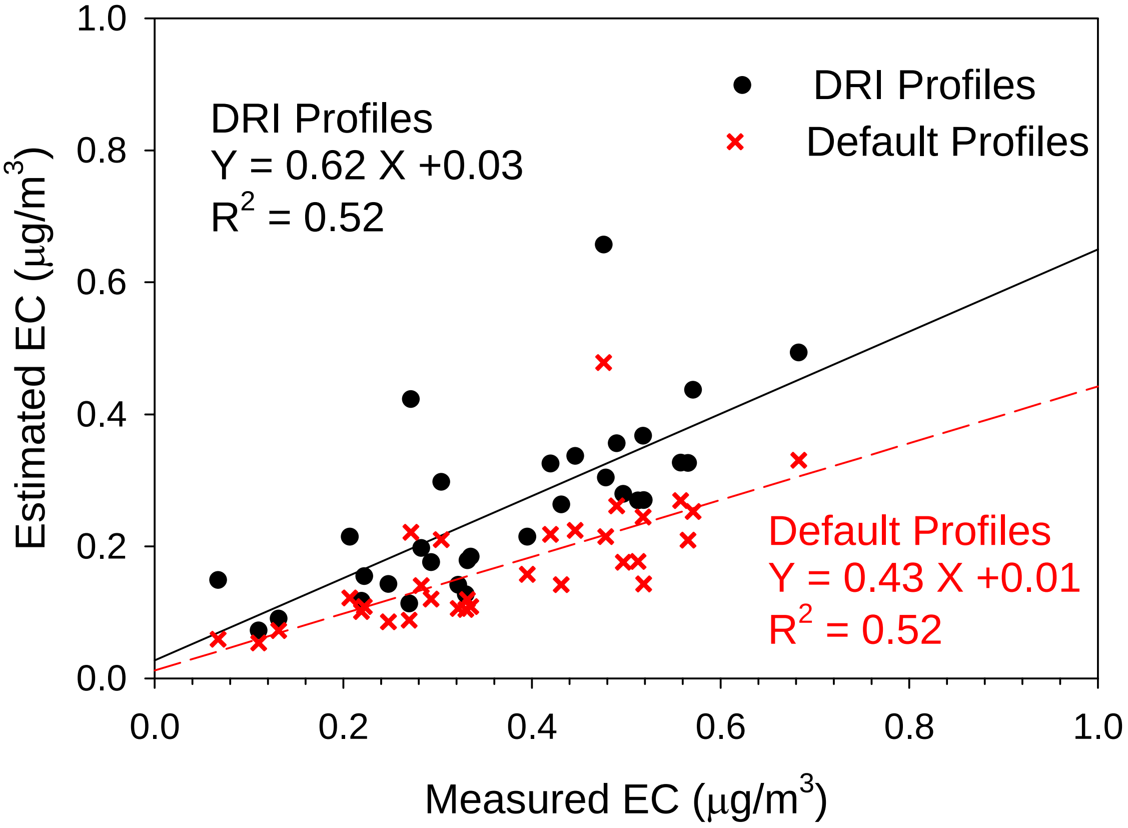


Figure 5-2. Comparison of measured (IMPROVE) EC at the Great Smoky Mountain National Park (GSMN), TN, site with EC estimated from DRI-selected non-default source profiles (red) and U.S. EPA default source profiles (black).

6. EMISSION FACTOR DATABASE QUALITY ASSURANCE

As described in Section 3, recent emission factors for gasoline- and diesel-fueled vehicles were systematically measured in the following nine studies: 1) Gas/Diesel Split Study (Fujita et al., 2007a; 2007b); 2) Coordinating Research Council (CRC) E55/59 Phase I Study (Clarke et al., 2007); 3) CRC E55/59 Phase II Study (Clarke et al., 2007); 4) Kansas City summer Study (U.S. EPA 2008a; 2008b); 5) Kansas City winter Study (U.S. EPA 2008a; 2008b); 6) SERDP Non-Road Diesel Generator Study (Watson et al., 2008a); 7) SERDP Military Vehicle Study (Watson et al., 2008a); 8) JFSP Pilot Study (Chen et al., 2006a; 2006b; McMeeking et al., 2008); and 9) FLAME I and II Study (Chen et al., 2006a; 2006b; McMeeking et al., 2008). Emission factors for biomass burning were measured in the joint FLAME study (Chen et al., 2006a; 2006b). The results of individual tests are presented in a Microsoft Access database that accompanies this report. Table 6-1 summarizes the measurements for each of the source characterization studies, including the laboratory tests during Phase I of this study (Chow et al., 2006d).

PM mass and chemical data from these source characterization studies were evaluated for their precision, accuracy, and validity. This section defines the analytical specifications and documents measurement attributes.

6.1 Quality Assurance/Quality Control for Emission Factor Measurements

Emission factors were derived from continuous monitors and filter-based samples in the field, followed by laboratory analysis of the filters and data processing/validation of both gas and particulate measurements. A Quality Assurance Program Plan (QAPP) was developed as part of this study which includes 49 standard operating procedures (SOPs; Chow et al., 2006d). Detailed analytical specifications, data validation, and QA/QC for both the in situ continuous gaseous and particulate instruments and laboratory filter-based chemical analyses were documented by Chow et al. (2006d). These QA/QC procedures were applied to both the laboratory generated combustion source emissions for Phase I of the study (Chow et al., 2006d) and field studies included in this report. Databases for the U.S. EPA SPECIATE version 4.0 and ARB source profiles were acquired and inconsistencies found are noted in this report.

Many of the profiles in the U.S. EPA SPECIATE and ARB databases lack detailed traceability and are sometimes incomplete (e.g., missing carbon data or lack of documentation with respect to carbon analysis protocol that determines the abundances of OC and EC in a given

PM size fraction). The ARB source profile library does not provide uncertainty estimates associated with the measured OC and EC fractions. Although uncertainty measurements are given in the U.S EPA SPECIATE version 4.0 source profile library, it lacks documentation on the derivation of those uncertainties. As can be seen in Table 4-3, some of the uncertainties of OC and EC exceed their corresponding fractions. In some cases zero was reported in place of an uncertainty.

The ARB source profile library assigns a three-digit code for each source profile, where the U.S. SPECIATE IDs vary from four to seven digits with one decimal place. Only some of the source profiles are associated with a profile mnemonic. Varying numbers of characteristics are assigned as profile mnemonics by different studies. Consistent standard operating procedures need to be developed for the U.S. in terms of source sampling method, naming convention, chemical analysis specifications, data validation, data quality evaluation criteria, uncertainty estimates, and reporting formats, so that a consistent quality of emission factor databases can be used for future emission estimates.

6.2 Database Structure

Emission factor data have been compiled into a database (EFDatabase.mdb) with comparable variable names and units for this study. This integrated and documented database provides a resource for this and other studies of $PM_{2.5}$ mass, BC, and OC emissions. The database format was modeled after the FIRE data file format with some modifications. Data properties were concatenated and stored in the Microsoft Access database as separated columns.

Table 6-2 lists the data tables, descriptions, and variables in EFDatabase.mdb, which is designed to allow easy comparison and integration with the U.S. EPA's FIRE System. The "Emission_Sources" table in the EFDatabase.mdb contains 2,700 records from the nine studies cited above. The database is organized into tables with linked fields that allow queries based on selected parameters. The field relationships are shown in Figure 6-1. The "Emission_Sources" table lists the general information of each emission factor record, while the actual emission factor values are stored in the "Emission_Factors" table. These tables are linked through the Emission Factor ID (EF_ID) field. The units follow the standard EPA Emission Factor FIRE model. For example, emission factor ID (EF_ID) #5091 is reported in units of "g/kg per fuel carbon burned" where the field "unit" is "g", "measure" is "kg", "material" is "fuel carbon", and "action" is "burned". More detailed information on the fuel burned or vehicle tested is available in the “Material_Properties” table linked to the “Emission_Sources” table through the common identifier field “Material_ID”.

The “Species_Properties” table describes species measured based on U.S. EPA acronyms. These properties are linked to individual emission factors through the common identifier field “Species_ID”. Some of the emission factors are composites from individual emission factors, and information describing the compositing is stored in the “Composite_Info” table linked to the “Emission_Factors” table through the “Emissions_Sources” table. A summary of the mobile source emission factors for the Gas/Diesel Split Study can be found in the table “G/D Split Mobile EF.” There are also several queries that retrieve subgroups of the emission factors.

Fuel-based emission factors such as those acquired from the SERDP (Watson et al., 2008a) and FLAME (Chen et al., 2006a; 2006b) Studies are derived from coupling continuous and filter-based measurements. Typically, $PM_{2.5}$ mass, EC, and OC are collected on filters sampled directly from diluted emission plumes, while CO_2, CO, and total hydrocarbon (THC) are quantified continuously. The analysis method for each species is recorded in the “AnalysisMethod” column of the “Emission_Factors” table. Average CO_2, CO, and THC concentrations with baselines subtracted are then calculated to match the filter sampling periods. The development of emission factors follows Equations 3-1 through 3-5 in Section 3.2. In the emission factor database, the unit of fuel-based emission factors is g/kg fuel burned, which can be converted to mg/g fuel carbon burned when the fuel carbon content (i.e., CM_{fuel} in Equation 3-2) is known. For example, the CM_{fuel} of diesel fuel is assumed to be 0.856 for diesel combustion sources. All available CM_{fuel} of biomass fuel are recorded in the “Material_Properties” table. $PM_{2.5}$ mass was not measured during the FLAME II study, though the emission factors of EC and OC from FLAME II constitute most of the mass emissions. EC and OC from FLAME II are derived only by the NIOSH/STN_TOT method.

Table 6-3 lists the data tables, descriptions, and variables in the source profile database (DRISourceProfilesv5.mdb). The database contains source profile information for geological material, motor vehicle exhaust, vegetative burning, cooking, and industrial sources. The database is organized into tables with linked fields that allow queries based on selected parameters. The field relationships are shown in Figure 6-2. The “PM_Profile” table contains the profile list and variables associated with each profile. This table is linked to the profile mnemonic table (“MNEMONIC”) through the unique identifier “number” field, and linked to a description of the species in the “SPECIES_PROPERTIES” table through the “name” field. The “PM_Species” table lists the fractional abundances of the PM components and is linked to the “PM_SPECIES” table through the “ID” field.

These abundances were normalized mostly to the measured PM mass with a few exceptions where the sum of species was used (noted in the database) as sum of species exceeded its measured mass. Reference tables include “KEYWORD” and “REFERENCE” and are linked to the “SPECIES_PROPERTIES” and “PM_SPECIES” through the profile type (“P_TYPE”) and profile number (“P_NUMBER”), respectively. These tables are used to map additional metadata to each source profile during analysis and modeling. A sample table was created listing only the profiles for Phoenix called “PhoenixProfiles”. Detailed descriptions of each table and field can be found in the design view of the database object. Queries and reports have been developed and included to retrieve subgroups of the source profiles. Databases are self-contained and self-documented. Additional explanatory material and queries can be added to facilitate subsequent use of the data.

Table 6-1. Summary of measurements for the source characterization studies that acquired $PM_{2.5}$ emission factors from the combustion sources.

Instrument	Model	Observables (Concentration Unit)	Averaging Time (sec)	ARB Phase I: Laboratory Testing[a]	JFSP Pilot, FLAME Phase I & II[b]	Gas/ Diesel Split[c]	Kansas City (Summer & Winter)[d]	SERDP Diesel Backup Generators[e]	SEDRP Military Vehicles[e]
TSI Scanning Mobility Particle Sizer (SMPS)	3936	Particle size distribution between 0.003 and 0.08 µm in 97 bins (Number of particles/cm^3)	150	√					
Grimm Scanning Mobility Particle Sizer plus Optical Particle Counter (SMPS+C)	5.503	Particle size distribution between 0.05 and 0.33 µm in 43 bins (Number of particles/cm^3)	230	√					
MSP Wide-range Particle Spectrometer (WPS)	1000XP	Particle size distribution between 0.1 and 10 µm in 67 bins (Number of particles/cm^3)	150	√					
Dekati Electical Low Pressure Impactor (ELPI)	NA	Particle size distribution between 0.007 and 10 µm in 12 bins (Number of particles/cm^3)	1					√	√
Grimm DustMonitor	1.108	Particle size distribution between 0.2 and >20 µm in 16 bins (Number of particles/cm^3)	1					√	√
TSI DustTrak	8520	Particle mass concentration (mg/m^3)	60	√	√	√	√	√	√
Rupprecht & Patashnick Tapered Element Oscillating Microbalance (TEOM)	1105	Particle mass concentration (µg/m^3)	10		√	√			
Magee Aethalometer	AE-31	Black carbon mass concentration (µg/m^3)	120	√					

Table 6-1. Continued.

Instrument	Model	Observables (Concentration Unit)	Averaging Time (sec)	ARB Phase I: Laboratory Testing[a]	JFSP Pilot, FLAME Phase I & II[b]	Gas/ Diesel Split[c]	Kansas City (Summer & Winter)[d]	SERDP Diesel Backup Generators[e]	SEDRP Military Vehicles[e]
DRI Photoacoustic Analyzer (PA)	PA	Black carbon mass concentration (μg/m^3)	1	√	√	√	√	√	√
EcoChem Analytics Photoelectric Aerosol Sensor (PAS)	2000	PAH mass concentration (ng/m^3)	60	√					
Cavity Ring Down Spectrometer	NA	Particle extinction (1/Mm)	10		√				
Midac Fourier Transform Infrared Spectrometer (FTIR)	Illuminator	Gas (CO, CO_2, SO_2, NO, NO_2, NH_3) concentrations (ppm)	1.5					√	√
LiCor CO_2/H_2O	Li-840	CO_2 and water vapor concentration (ppm)	1	√				√	√
Dilution Sampling System with Filter Packs	NA	$PM_{2.5}$ mass, 51 elements, ions (Cl^-, $SO_4^=$, NO_3^-, NH_4^+, Na^+, K^+), EC, OC, carbon fractions, SO_2, NH_3	1200 - 18700	√	√	√	√	√	√

[a] Chow et al. (2006d)

[b] Chen et al. (2006a; 2006b); McMeeking et al. (2008)

[c] Fujita et al. (2007a; 2007b)

[d] U.S. EPA (2008a; 2008b)

[e] Watson et al. (2008a)

Table 6-2. Summary of the database for the mobile source and biomass burning emission factors.

EMISSION FACTOR DATABASE (EFDatabase.mdb)

Table Name	Description	Number of Data Records
Composite_Info	Sample composite summary	654
G/D Split Mobile EF	Summary of mobile emission factors	922
Emission_Factors	Emission factor data	84,079
Emission_Sources	Sources of emission data	2,700
Material_Properties	Sample description and metadata	299
Species_Properties	Detailed properties of individual chemical species	626

Query Name	Description
BB_cateory_avg	Biomass burning category average query
BB_Composite	Biomass burning composite query
CategoryEF	Subcategory query
GasolineProfiles	Profiles of gasoline-fueled engine exhaust samples query
MobileEF	Individual and composite mobile emission factor query
MobileEF_Vinfo	Mobile source emission factor query with vehicle information
MobileEF2	Query to make G/D Split mobile source $PM_{2.5}$ emission factor only table
ProfileClass	Input to MatLab source classification program
ProfileQuery	Simple profile query without material information

Table 6-3. Source profile database contents.

SOURCE PROFILE DATABASE (DRISourceProfilesv5.mdb)

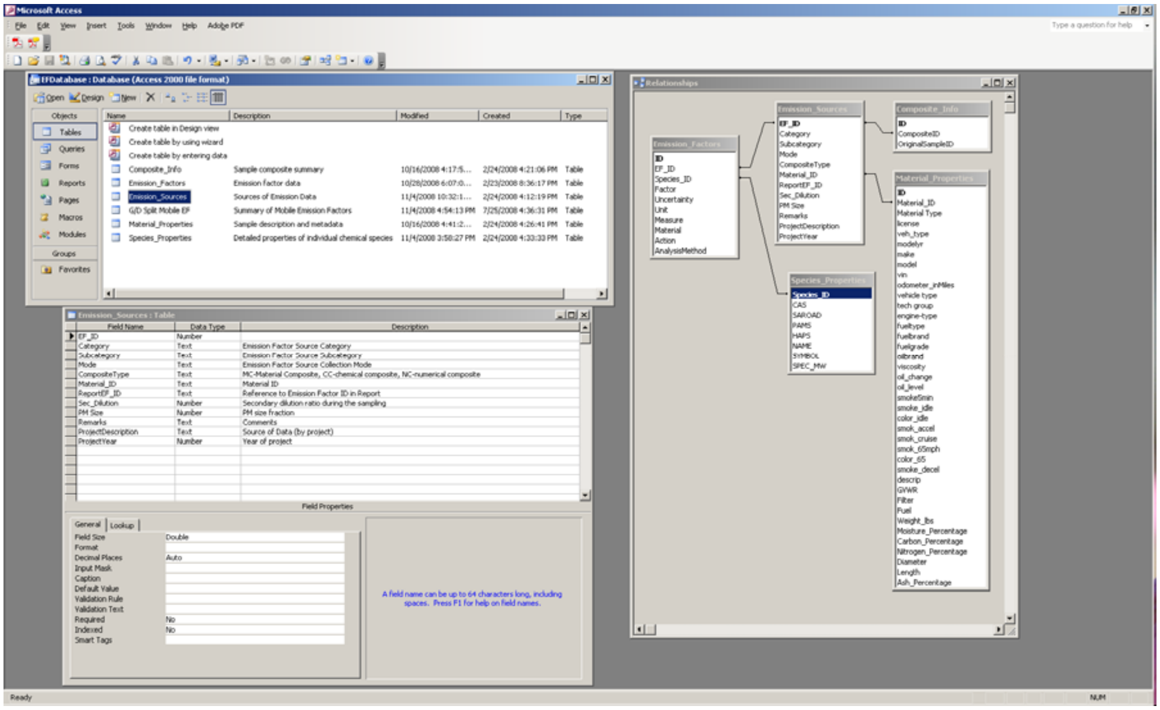
Table Name	**Description**	**Number of Data Records**
PM_PROFILE	Profile list and sample information	1,326
MNEMONIC	Mnemonic of source profiles	1,311
SPECIES_PROPERTIES	Detailed properties of individual species	745
PM_SPECIES	PM species in percentage, normalized to measured mass or sum of species as noted	109,714
PhoenixProfiles	Profiles for phoenix samples	1,512
KEYWORD	Profile keywords	1,311
REFERENCE	Table with links to DRI references	1,312

Query Name	**Description**
UpdateSpecies	Query to update the PM species table
qryOrig_Compo	Queries original composite profiles
OrganicQuery	Queries by species
Analytical Method	Query to extract data by analytical method
MasterTable	Query to link all tables into single output
ExtractProfiles_Tables	Query to make table by profile
Extract_Profiles	Query to extract data by profile

Report Name	**Description**
rptPM_PROFILE	Profile user report of original samples

Table 6-4. Summary of data files included on the enclosed CD.

File Path including File Name	File Type	Related Section in this Report
\Databases\DRISourceProfilesv5.mdb	Access Database	Section 6
\Databases\EFDatabase.mdb	Access Database	Section 6
\DatafilesforFiguresandTables\Appendix_DieselTestSummary.xls	Excel Spreadsheet	Section 3
\DatafilesforFiguresandTables\DRIspeciated emissions profiles_data in mass percent_sum.xls	Excel Spreadsheet	Section 4
\DatafilesforFiguresandTables\nei_profiles.xls	Excel Spreadsheet	Section 4
\DatafilesforFiguresandTables\Figures3-1to3-5b.xls	Excel Spreadsheet	Section 3
\DatafilesforFiguresandTables\Figure3-6and3-7.xls	Excel Spreadsheet	Section 3
\DatafilesforFiguresandTables\Figure3-8to3-10.xls	Excel Spreadsheet	Section 3
\DatafilesforFiguresandTables\Figure4-1to4-6.xls	Excel Spreadsheet	Section 4
\DatafilesforFiguresandTables\pmprof_07_19_07.xls	Excel Spreadsheet	Section 7



Name	Description	Modified	Created	Type
Create table in Design view				
Create table by using wizard				
Create table by entering data				
Composite_Info	Sample composite summary	10/16/2008 4:17:5...	2/24/2008 4:21:06 PM	Table
Emission_Factors	Emission factor data	10/28/2008 6:07:0...	2/23/2008 8:36:17 PM	Table
Emission_Sources	Sources of Emission Data	11/4/2008 10:32:1...	2/24/2008 4:12:19 PM	Table
G/D Split Mobile EF	Summary of Mobile Emission Factors	11/4/2008 4:54:13 PM	7/25/2008 4:36:31 PM	Table
Material_Properties	Sample description and metadata	10/16/2008 4:41:2...	2/24/2008 4:26:41 PM	Table
Species_Properties	Detailed properties of individual chemical species	11/4/2008 3:58:27 PM	2/24/2008 4:33:33 PM	Table

Field Name	Data Type	Description
EF_ID	Number	
Category	Text	Emission Factor Source Category
Subcategory	Text	Emission Factor Source Subcategory
Mode	Text	Emission Factor Source Collection Mode
CompositeType	Text	MC-Material Composite, CC-chemical composite, NC-numerical composite
Material_ID	Text	Material ID
ReportEF_ID	Text	Reference to Emission Factor ID in Report
Sec_Dilution	Number	Secondary dilution ratio during the sampling
PM Size	Number	PM size fraction
Remarks	Text	Comments
ProjectDescription	Text	Source of Data (by project)
ProjectYear	Number	Year of project

Field Size	Double
Format	
Decimal Places	Auto
Input Mask	
Caption	
Default Value	
Validation Rule	
Validation Text	
Required	No
Indexed	No
Smart Tags	

A field name can be up to 64 characters long, including spaces. Press F1 for help on field names.

Emission_Factors
- ID
- EF_ID
- Species_ID
- Factor
- Uncertainty
- Unit
- Measure
- Material
- Action
- AnalysisMethod

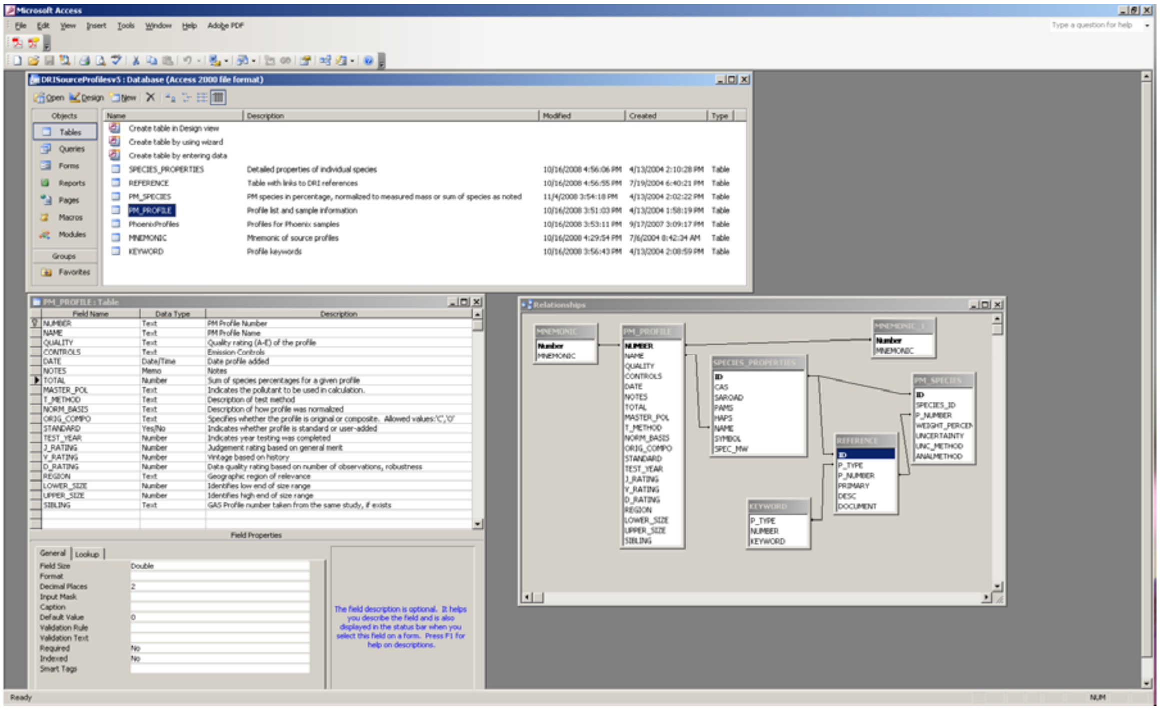
Emission_Sources
- EF_ID
- Category
- Subcategory
- Mode
- CompositeType
- Material_ID
- ReportEF_ID
- Sec_Dilution
- PM Size
- Remarks
- ProjectDescription
- ProjectYear

Composite_Info
- ID
- CompositeID
- OriginalSampleID

Species_Properties
- Species_ID
- CAS
- SAROAD
- PAMS
- HAPS
- NAME
- SYMBOL
- SPEC_MW

Material_Properties
- ID
- Material_ID
- Material Type
- license
- veh_type
- modelyr
- make
- model
- vin
- odometer_inMiles
- vehicle type
- tech group
- engine-type
- fueltype
- fuelbrand
- fuelgrade
- oilbrand
- viscosity
- oil_change
- oil_level
- smoke5min
- smoke_idle
- color_idle
- smok_accel
- smok_cruise
- smok_65mph
- color_65
- smoke_decel
- descrip
- GVWR
- Filter
- Fuel
- Weight_lbs
- Moisture_Percentage
- Carbon_Percentage
- Nitrogen_Percentage
- Diameter
- Length
- Ash_Percentage

Figure 6-1. Example of table descriptions, field descriptions, table relationships, and field relationships in the emission factor database (EFDatabase.mdb).



Name	Description	Modified	Created	Type
Create table in Design view				
Create table by using wizard				
Create table by entering data				
SPECIES_PROPERTIES	Detailed properties of individual species	10/16/2008 4:56:06 PM	4/13/2004 2:10:28 PM	Table
REFERENCE	Table with links to DRI references	10/16/2008 4:56:55 PM	7/19/2004 6:40:21 PM	Table
PM_SPECIES	PM species in percentage, normalized to measured mass or sum of species as noted	11/4/2008 3:54:18 PM	4/13/2004 2:02:22 PM	Table
PM_PROFILE	Profile list and sample information	10/16/2008 3:51:03 PM	4/13/2004 1:58:19 PM	Table
PhoenixProfiles	Profiles for Phoenix samples	10/16/2008 3:53:11 PM	9/17/2007 3:09:17 PM	Table
MNEMONIC	Mnemonic of source profiles	10/16/2008 4:29:54 PM	7/6/2004 8:42:34 AM	Table
KEYWORD	Profile keywords	10/16/2008 3:56:43 PM	4/13/2004 2:08:59 PM	Table

Field Name	Data Type	Description
NUMBER	Text	PM Profile Number
NAME	Text	PM Profile Name
QUALITY	Text	Quality rating (A-E) of the profile
CONTROLS	Text	Emission Controls
DATE	Date/Time	Date profile added
NOTES	Memo	Notes
TOTAL	Number	Sum of species percentages for a given profile
MASTER_POL	Text	Indicates the pollutant to be used in calculation.
T_METHOD	Text	Description of test method
NORM_BASIS	Text	Description of how profile was normalized
ORIG_COMPO	Text	Specifies whether the profile is original or composite. Allowed values:'C','O'
STANDARD	Yes/No	Indicates whether profile is standard or user-added
TEST_YEAR	Number	Indicates year testing was completed
J_RATING	Number	Judgement rating based on general merit
V_RATING	Number	Vintage based on history
D_RATING	Number	Data quality rating based on number of observations, robustness
REGION	Text	Geographic region of relevance
LOWER_SIZE	Number	Identifies low end of size range
UPPER_SIZE	Number	Identifies high end of size range
SIBLING	Text	GAS Profile number taken from the same study, if exists

Field Properties

General | Lookup

Field Size	Double
Format	
Decimal Places	2
Input Mask	
Caption	
Default Value	0
Validation Rule	
Validation Text	
Required	No
Indexed	No
Smart Tags	

The field description is optional. It helps you describe the field and is also displayed in the status bar when you select this field on a form. Press F1 for help on descriptions.

Figure 6-2. Example of table descriptions, field descriptions, table relationships, and field relationships for the source profile database (DRISourceProfilesv5.mdb).

7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary and Conclusions

California BC/EC and OC emissions can be estimated by several methods: 1) extract emissions from an existing global inventory; 2) create a b_{ap} inventory; 3) apply BC source profiles to existing PM emission factors; 4) combine NEI with SMOKE default source profiles; and 5) combine the ARB inventory with selected source profiles. Based on the investigation and documentation of this study, recommendations are given for future work.

Global BC emission estimates can be obtained from SPEW (http://cee.uiuc.edu/research/bondresearch/) for periods of 1850 to 2000 (Bond et al., 2004). These values would need to be updated for future use. This emission inventory is based on fuel use by technology sector. The coarse spatial resolution of 1º x 1° grids permits only an approximate correspondence with California's boundaries. Emission factors vary by country; emission factors for various technology sectors in the U.S. are lower than those in developing countries. Technology sector activities use proxies such as urban and rural population and agricultural land cover (Bond et al., 2004). According to the 1996 estimates, California accounted for 6.7% of U.S. BC emissions (based on a combination of the Bond et al. [2004] estimate for U.S. BC emissions and calculations derived for this study using Bond's data for California), even though California contains 12% of the U.S. population. While this emission inventory may be useful from a global perspective, it doesn't make use of the available extensive activity data specific to California.

Expressing emissions directly in terms of particle light absorption (b_{ap}) does not appear to be a physically reasonable approach. The particle absorption cross section and mass absorption efficiency are not conserved after emission; they depend on particle mixing state, hydration history, and interactions with cloud and precipitation particles.

Converting PM to BC emission factors is feasible but impractical for a number of reasons. Currently used PM emission factors are based on measurements. Models like EMFAC2007 created weighted averages of specific emission factors to account for variations in operating conditions, vehicle model year, etc. Translating directly measured or modeled PM emission factors to BC or EC could involve new measurements on a great number of source emissions. This is essentially a recommendation to develop speciated (EC and OC) emission factors for sources in the current PM emission inventories.

Using the NEI $PM_{2.5}$ emission inventory with SMOKE default EC and OC profiles would require gridding the NEI for California and relying on default source profiles. NEI estimates exist for 1996, 1999, and 2002. An NEI is planned which will incorporate 2005 emissions for mobile and power generation sources in an updated 2002 emission inventory. Longer-term plans exist for updating the NEI on a yearly basis (http://www.epa.gov/ttn/chief/net/eis.html). The U.S. EPA is developing software tools to cross-reference sources in the NEI with source profiles in its SPECIATE library. This approach benefits from a large EPA investment, but it is not specific to California's situation.

The most accurate and practical approach is to apply EC and OC source profiles to PM emissions for specific source categories from the existing ARB $PM_{2.5}$ emission inventory. The remaining challenge is to improve ARB's collection, evaluation, and management of appropriate source profiles and assigning these to the different source categories. This is especially a challenge for future emissions from transportation sources, such as diesel engines, as new technology and fuels are penetrating the fleet with expected future BC emission reductions. Off-cycle operating conditions (e.g., cold start) and non-road (e.g., aircraft, ships, military vehicles, agricultural and construction equipment) source profiles are poorly characterized with respect to their $PM_{2.5}$ compositions. Biomass burning profiles show the largest variability and deviations from current emission models.

7.2 Recommendations

ARB can adapt its existing $PM_{2.5}$ emission inventory to estimate BC/EC and OC emissions by applying relevant source profiles. The data base of source profiles created for this study is a starting point, but it requires more real-world emission tests that include BC measurements. These measurements should be acquired with a dilution sampling system that brings exhaust plumes to temperatures near ambient levels. Light absorption measurements at various wavelengths should be obtained in conjunction with filter measurements whenever possible during these tests. More complete chemical profiles, including organic marker compounds, would enhance the value of these profiles for other applications such as receptor modeling.

Uncertainties associated with emission factors, activity levels, and source profiles need to be estimated and propagated to the annual emission estimate for each source category.

Comparison of ARB and recently measured mobile and biomass burning emission factors show large differences that should be further studied and reconciled. EMFAC2007 underestimated recently measured high-emitting gasoline-fueled vehicle emission factors. While measurements are necessarily limited with respect to emission sources, efforts should continue to characterize these emissions and update their emission factors, activities, and source profiles.

There will never be enough representative measured emission factors and source profiles. The best that can be achieved are representative profiles for broad source categories. A review of source profile libraries such as the U.S. EPA SPECIATE version 4.0 should eliminate profiles that are outdated, biased, or irrelevant to California emissions. Chow et al. (2001) found that EC analyzed using the NIOSH thermal/optical transmittance analytical protocol (NIOSH, 1999) was typically less than half that measured with the IMPROVE protocol (Chow et al., 1993). This difference has important implications for estimating EC emissions. Source profile development should focus on the major EC and OC emitters in California: mobile and other transportation sources, RWC, agricultural burning, and wildfires. A cross-referencing tool to relate source profiles to individual source codes (e.g., emission inventory code [EIC]) should be developed.

ARB has developed a PM source profile library (http://www.arb.ca.gov/ei/speciate/dnldopt.htm#filelist). The file, pmprof_07_19_07.xls, contains 93 speciated source profiles in $PM_{2.5}$, PM_{10}, and total suspended particulate size fractions but does not include uncertainties associated with these profiles. Source profile uncertainties are required for application of the U.S. EPA's CMB source apportionment model (Watson et al., 1998b; 2008c). Source profile uncertainties are also needed to evaluate uncertainties in BC/EC and OC emission inventories in California. Uncertainties reported in the U.S. EPA SPECIATE library should be evaluated and incorporated into the ARB profile library.

Traceability of ARB's $PM_{2.5}$ emissions should be improved, especially for data submitted by local air quality management districts. Districts are not required to provide emission factors and activities for point and area sources. Ideally, the ARB emission inventory tools would provide emission factors and activities along with $PM_{2.5}$ emissions for each EIC source code and geographical area. Of the more than 500 area source categories established by ARB, each district is only responsible for estimating emissions from ~100 categories, and the remaining ~400 categories are estimated by ARB based on statewide data. Area sources will be better estimated if each air district can submit estimates on the majority of the area sources.

Terminology needs to be consistent among the inventories. For example, ARB inventory classifies transportation-related sources as Mobile (On-road) and Mobile (Other). Other inventories classify them as off-road or non-road. Wildfire is considered a natural source in the ARB inventories, but forest fire is considered an area source in the U.S. EPA inventory. This creates difficulties in intercomparison among the different inventories.

$PM_{2.5}$, EC, and OC emission inventories can be evaluated by comparing measured concentrations with those estimated with air quality models such as the SMOKE-CMAQ-MM5 modeling system. California has several chemically speciated $PM_{2.5}$ ambient data sets, including the San Joaquin Valley Air Quality Study/ Atmospheric Utility Signatures, Predictions and Experiments (SJVAQS/AUSPEX; Chow et al., 1992; Start and Olson, 1992; Solomon and Thuillier, 1995), Integrated Monitoring Study (IMS95; Chow and Egami, 1997), and California Regional PM_{10}/$PM_{2.5}$ Air Quality Study (CRPAQS) (Chow et al., 2005) that could be used for this purpose. For example, Ying et al. (2008) applied the UCD/CIT (University of California at Davis/California Institute of Technology) air quality model for pollution episodes in the San Joaquin Valley during CRPAQS. The IMPROVE network is also extensive and has a long-term data record (since 1988) for many of California’s national parks and wilderness areas.

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9. LIST OF ABBREVIATIONS AND LIST OF WEBSITES

9.1 List of Abbreviations

Abbreviation	**Definition and Description**
AAD	Average of the Absolute Deviations
AAVP7A1	Amphibious Assault Vehicle
AgBurn	Agricultural Burning
AP-42	Compilation of Air Pollutant Emission Factors, Volume I, Stationary, Point, and Area Sources
ARB	Air Resources Board
b_{ap}	Particle light absorption
BC	Black Carbon
BRAVO	Big Bend Regional Aerosol and Visibility Observational Study
BRIG	Brigantine National Wildlife Refuge
BTU	British Thermal Unit
BUG(s)	Backup Generator(s)
C	Carbon
CalTech	California Institute of Technology
CCS	Cold City-Suburban Route
CEI	California Emissions Inventory for Criteria Pollutants
CFPP	Coal-Fired Power Plant
CH_4	Methane
Che	Chemise
CID	Cold Idle
Cl^-	Chloride
CMAQ	Community Multiscale Air Quality Model
CMB	Chemical Mass Balance
CMF(s)	Carbon Mass Fraction(s)
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COH	Coefficient of Haze
CRPAQS	California Regional Air Quality Study
CS	Cold Start
CSJ	City-Suburban with Jacobs Brake
CVS	Constant Volume Sampling System for estimating source emissions
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DRI	Desert Research Institute
EAF	Environmental Analysis Facility

Abbreviation	**Definition and Description**
EC	Elemental Carbon
ECHAM4	European Centre Hamburg Climate Model
EES	ARB Emission Estimation System to estimate burning emissions; analogous and cross-referenced with the Source Clarification Code(s) in the U.S. EPA National Emissions Inventory
EF(s)	Emission Factor(s)
EF_ID	Emission Factor ID
EIA	U.S. Energy Information Administration
EIC	ARB Emission Inventory Code
EMFAC(s)	EMission FACtor(s)
f_{BC}	BC Fraction
FEPS	Fire Emission Produce Simulator
FIRE	Factor Information Retrieval Data System
FLAME	Fire Laboratory at Missoula Experiment
FOFEM	First Order Fire Effects Model
FSL	U.S. Forest Service Fire Science Laboratory
FTP(s)	Federal Test Procedure(s)
GCM	Global Climate Model
GEIA	Global Emissions Inventory Activity
GHG(s)	Greenhouse Gas(es)
GRSM	Great Smoky Mountains National Park
H_2	Hydrogen
HAP(s)	Hazardous Air Pollutant(s)
HC	Hydrocarbon
HCS	Hot City-Suburban Route
HDD	Heavy-Duty Diesel
HDDV	Heavy-Duty Diesel Vehicles
HEPA	High Efficiency Particulate Air
HHDV	Heavy Heavy-Duty Vehicle
HW	Highway Cycle
I/M	Inspection and Maintenance Program
IC	Ion Chromatography
ID	Idle
IEA	International Energy Agency
IMPROVE	Interagency Monitoring of PROtected Visual Environments
IMS95	Integrated Monitoring Study
IPCC	Intergovernmental Panel on Climate Change

Abbreviation	**Definition and Description**
IPETS	DRI In-Plume Emission Test Stand for vehicle emission testing
IPM	"Integrating Plate" Method
JFSP	Joint Fire Science Project
K^+	Potassium
LAC	Light-Absorbing Carbon
LDA	Passenger Vehicles
LDD	Light-Duty Diesel
LDG	Light-Duty Gasoline
LDGV	Light-Duty Gasoline Vehicle
LDT	Light-Duty Trucks
LDV	Logistics Vehicle System
LP	Lodgepole Pine
LPG	Liquefied Petroleum Gas
LVOffRDIE	Las Vegas Off-road Composite Diesel Profile
LVOnRDIE	Las Vegas On-road Composite Diesel Profile
MAAP	Multi-Angle Absorption Photometer
Maz	Manzanita
MC	Manhattan Cycle
MDL(s)	Minimum Detectable Limit(s)
MHDV	Medium Heavy-Duty Vehicle
MM5	NCAR / Pennsylvania State Mesoscale Model
MOVES	MOtor Vehicle Emission Simulator
MTg	Montana Grass
MTVR	Medium Tactical Vehicle Replacement
MW	Megawatts
N	Nitrogen
N_2O	Nitrous Oxide
NA	Not Available or Not Applicable
NCAR	National Center for Atmospheric Research
NEI	U.S. National Emission Inventory for criteria pollutants
NH_3	Ammonia
NH_4^+	Ammonium
$(NH_4)_2SO_4$	Ammonium Sulfate
NO_3^-	Nitrate
NO_x	Nitrous Oxides
NRC	National Research Council
NREL	National Renewable Energy Laboratory
O_2	Oxygen

Abbreviation	**Definition and Description**
O_3	Ozone
OC	Organic Carbon
OECD	Organization for Economic and Cooperative Development
OLS	Ordinary Least-Squares
OM	Organic Mass
P_Number	Profile Number
P_Type	Profile Type
PA	Photoacoustic Instrument
PAH(s)	Polycyclic Aromatic Hydrocarbon(s)
Pb	Lead
PM	Particulate Matter
$PM_{2.5}$	Particles with aerodynamic diameters < 2.5 micrometers (µm)
PM_{10}	Particles with aerodynamic diameters <10 micrometers (µm)
PP	Ponderosa Pine
PSAP	Particle Soot Absorption Photometer
QA/QC	Quality Assurance/Quality Control
RAINS-Asia	Regional Air Pollution INformation and Simulation-Asia
RCC	Residential Coal Combustion
RR	Robust Regressions
RVP	Reid Vapor Pressure
RWC	Residential Wood Combustion
S	Sulfur
SCC(s)	Source Classification Code(s)
SERDP	Strategic Environmental Research & Development Program
SGIT	U.S. EPA State Greenhouse Gas Inventory Tool
SJV	San Joaquin Valley
SJVAQS/AUSPEX	San Joaquin Valley Air Quality Study/ Atmospheric Utility Signatures, Predictions and Experiments
SMOKE	Sparse Matrix Operator Kernel Emissions
SO_2	Sulfur Dioxide
$SO_4^=$	Sulfate
SOA	Secondary Organic Aerosol
SPEW	Speciated Pollutant Emissions Wizard
TC	Total Carbon
TCEQ	Texas Commission on Environmental Quality
Tg	Teragrams (10^12)
THC	Total Hydrocarbon
TOR	Thermal/Optical Reflectance

Abbreviation	**Definition and Description**
TOT	Thermal/Optical Transmittance
U.S. EPA	U.S. Environmental Protection Agency
UDC	Unified Driving Cycle
UDDS	Urban Dynamometer Driving Schedule
VISTAS	Visibility Improvement – State and Tribal Association of the Southeast
VMT	Vehicle Miles Traveled
VOC(s)	Volatile Organic Compound(s)
WS	Warm Start

9.2 List of Websites

Website	Organization/Database/Model Description	Reference Pages
http://cee.uiuc.edu/research/bondresearch/	Bond et al. (2004) global BC inventory for 1996/Speciated Pollutant Emissions Wizard (SPEW)	2-15 5-2 7-1
http://www.arb.ca.gov/ei/emissiondata.htm	California Air Resources Board (ARB) comprehensive emission inventory (analogous to the NEI)	2-11
http://www.arb.ca.gov/app/emsinv/facinfo/facinfo.php	ARB publically-available web-based Facility Search tool	2-12
http://www.arb.ca.gov/app/emsinv/emssumcat.php	ARB web-based tool for generating an emission inventory for specific data (used for this study to generate a statewide $PM_{2.5}$ emission inventory for 1995 that includes natural sources such as wildfires)	2-15 2-21
http://www.arb.ca.gov/ei/speciate/dnldopt.htm#filelist	ARB Source Profile Library	4-8
http://www.arb.ca.gov/ei/see/mngdburnemissionfactors.xls	ARB emission factors used to estimate emissions from agricultural and other management burns regardless of fuel moisture	3-10
http://www.arb.ca.gov/ei/see/see.htm	ARB Emission Estimation System (EES) Model developed by U.C. Berkley	3-10
http://www.arb.ca.gov/msei/onroad/latest_version.htm	ARB EMFAC2007 mobile source emission model	2-5
http://www.arb.ca.gov/msei/offroad/offroad.htm	ARB OFFROAD model for off-road vehicle emission inventory estimation	2-12
http://www.energy.ca.gov/	California Energy Commission (CEC)	2-14
http://www.epa.gov/AMD/CMAQ/	Community Multiscale Air Quality (CMAQ) chemical model used to estimate ambient concentrations of U.S. EPA criteria pollutants	4-1

Website	Organization/Database/Model Description	Reference Pages
http://www.fs.fed.us/pnw/fera/feps/	Fire Emission Production Simulator (FEPS) for estimation of the fraction of dry and wet vegetation, flaming, and smoldering combustion in a particular burn event	3-12
http://vista.cira.colostate.edu/improve/	Interagency Modeling of PROtected Visual Environments (IMPROVE), National Park Service long-term visibility network at most non-urban National Parks and Wilderness Areas	4-3
http://www.iea.org/	International Energy Agency (IEA)	2-8 2-17
http://www.mmm.ucar.edu/mm5/	National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5)	4-1
http://www.smoke-model.org/index.cfm	University of North Carolina at Chapel Hill Center for Environmental Modeling for Policy Development Sparse Matrix Operator Kernel Emissions (SMOKE) emissions model	4-1
http://www.epa.gov/ttn/chief/ap42/	U.S. EPA Agency AP-42 compendium of emission factors	2-1
http://www.eia.doe.gov/	U.S. Energy Information Administration (EIA), part of the Department of Energy (DOE)	2-14
http://www.epa.gov/ttn/chief/software/fire/index.html	U.S. EPA Factor Information REtrieval (FIRE) Data System to facilitate emission calculations	2-10
http://www.epa.gov/otaq/m6.htm	U.S. EPA most recent on-road mobile source model, MOBILE 6.2	2-10
http://www.epa.gov/otaq/ngm.htm	U.S. EPA MOtor Vehicle Emission Simulator (MOVES), under development to address the inadequacies of MOBILE 6.2	2-10
http://www.epa.gov/ttn/chief/net/	U.S. EPA National Emission inventory (NEI) for criteria pollutants	1-2 7-2
http://www.epa.gov/oms/nonrdmdl.htm	U.S. EPA NONROAD model for non-road vehicle emission estimates	2-11

Website	Organization/Database/Model Description	Reference Pages
http://www.epa.gov/climatechange/emissions/state_guidance.html	U.S. EPA State Greenhouse Gas Inventory Tool (SGIT)	2-13
http://www.epa.gov/ttn/chief/software/speciate/index.html	U.S. EPA SPECIATE version 4.0 PM source profile database	2-10 4-22