

Appendix 2

Black Carbon Emissions Inventory Methods and Comparisons

A2.1 Introduction

This appendix provides specific details on the approach used to generate domestic inventories for stationary, area, and mobile sources, and compares that approach to methods used in compiling international inventories. It explores key methodological similarities and differences between inventories, and also outlines the specific methodologies and data inputs used to construct key global and regional inventories currently available.

In general, existing inventories for BC are based on calculations rather than actual emissions measurements. Direct emissions measurements of BC and other PM constituents are rare, and no known inventory is based on direct BC emissions data. Instead, “BC” inventories are calculated mathematically from PM_{2.5} inventories. These calculations divide the direct carbonaceous particle emissions from the PM_{2.5} inventory into two categories: EC and OC. Thus most “BC” inventories are actually EC inventories. Though sometimes the terms EC and BC are used interchangeably, EC is actually more narrowly defined (see Chapter 2 and Appendix 1). By tracking only EC, current inventories fail to account for the portion of primary OC emissions that is light absorbing (including some BC and also BrC). As discussed in Chapter 4, this means current domestic and international inventories systematically underestimate total LAC; however, the magnitude of this gap has not been adequately quantified to date.

Most inventories use a **bottom-up approach**, first pairing PM_{2.5} emission factors with activity level data for the source category to generate PM_{2.5} emissions estimates, and then applying a speciation factor to estimate the amount of BC (or other constituents) contained in the total mass of PM_{2.5} emissions. The BC emissions for individual source categories are then aggregated to form total BC emissions estimates. The speciation factors for an individual source category relate emissions of specific constituents to total PM_{2.5} mass—for example, the amount of BC to total PM_{2.5}. PM_{2.5} emission factors and the speciation factors for particular constituents

can be based on either fuel consumption data (i.e., estimated emissions of total PM_{2.5} or specific constituents per unit of fuel) or actual measured source emissions from emissions testing (see Appendix 1). Some inventories use a combination of these different approaches, depending on the information available for each source category.

In a few cases, emissions may be back-calculated from remote sensing of primary PM_{2.5} emissions or measured ambient data of the amount of carbonaceous aerosols in the atmosphere. This kind of **top-down approach** is far less common; currently only a few regional inventories in Asia rely on such methods.

Additional information on approaches used to calculate the U.S. emissions inventory and other global/regional inventories is provided in the following text.

A2.2 Development of U.S. National Emissions Inventory for Black and Organic Carbon

EPA’s National Emissions Inventory (NEI) is a bottom-up compilation of estimates of air pollutants discharged on an annual basis by source category (see <http://www.epa.gov/ttn/chief/eiinformation.html>). EPA’s 2002 Consolidated Emissions Reporting Rule (<http://www.epa.gov/ttn/chief/cerr/cerr.pdf>) provides a regulatory basis for the collection of emissions inventory information. Currently, emissions of BC and other PM constituents (OC, nitrates, sulfates, crustal material) are not directly reported as part of the NEI. Rather, BC emissions for most sources are estimated by matching PM_{2.5} emissions from the NEI for those sources to source-specific BC speciation profiles from the “SPECIATE” database (see Appendix 1 for details on this database). The one exception is on-road mobile sources, for which BC emissions are estimated directly through models. The following sections provide more information on the specific methods used to compile the inventory for both stationary and mobile sources. More detail is provided for mobile source inventories due to the

Appendix 2

dominant contribution of these sources to U.S. BC emissions.

A2.2.1 Stationary Sources

Stationary sources in the NEI include both point (fossil fuel combustion, industrial sources) and nonpoint (biomass burning) source categories. The basic method for estimating PM_{2.5} emissions for all of these sources follows the simple conceptual formula described in Equation 1:

$$E = A \times EF (1-ER/100) \quad (\text{Equation 1})$$

Where

- E = PM_{2.5} emissions (for example, in Tons);
- A = activity rate;
- EF = the emission factor, and
- ER = overall emissions reduction efficiency, %

Direct PM_{2.5} emissions are composed of both filterable (solid) and condensable (gaseous) fractions. The condensable fraction condenses rapidly in the ambient air to form tiny liquid droplets. The sum of the filterable and condensable fractions is what is reported in the NEI for all source categories, and these estimates are used in Chapter 4 of this report.

A2.2.2 Emission Factors

AP-42, *Compilation of Air Pollutant Emission Factors (EFs)*, has been published since 1972 as the primary compilation of EPA's EF information. It contains EFs and process information for more than 200 air pollution source categories. More recently, AP-42 has been transitioned into the FIRE 6.25 Data System, which currently represents the most comprehensive collection of emission factors (U.S. EPA, 2010d). It currently contains thousands of records of (mostly) filterable PM_{2.5} EFs updated through calendar year 2004.¹

A source category is a specific industry sector or a group of similar emitting sources. These EFs have been developed and compiled from source test data, material balance studies, and engineering estimates. EFs can be as simple as an average rate per unit process input. In most cases, EFs depend on many variables such as process parameters, effluent temperatures, ambient temperatures, wind speed, and soil moisture. In these cases the formula is applied to estimate emissions for a particular

set of conditions. Under some circumstances in the inventorying of PM_{2.5}, EFs and estimation techniques are applied for analyses other than those for which they were developed. The accuracy and representativeness of the EFs are determined by the reliability of the testing methodology, how uniformly it is applied across sources, or the engineering process information used to derive the EFs.

EFs for some emission categories are more reliable than others. In some cases an EF may not be available for a source category because of insufficient or unacceptable data for generalization across source type. Often it is difficult to determine precisely what the certainty in the EF is. Thus, the application of EFs requires subjectivity and judgment from knowledgeable technical staff for the application of concern. As discussed in a previous chapter, users of EFs in national-, regional-, and urban- scale studies should be cognizant of their potential limitations, and other techniques should be considered to improve the confidence in PM emissions inventories. Several such approaches have been developed and some continue to be explored: continuous emission-monitoring sensors, material balances, specialized source profiling for composition and compositional material balances, source sampling to obtain improved particle-size distributions and location-specific emission rates, near-source ambient characterization, and source apportionment techniques. It is important to note that the reliability of EF estimation decreases when only a few source tests are used as the basis for the factor, or when judgmental decisions are made from analogy between technologies. Differences in EF estimates also can develop if the current operations or processes are significantly different from those upon which the original EFs were derived.

When most people think of PM, they envision solid particles that exist in the exhaust stream. However, PM_{2.5} is composed of both a filterable fraction and a condensable fraction (see earlier discussion). The filterable fraction already exists in solid particle form in the exhaust. The condensable fraction exists in gaseous form in the exhaust stream but condenses rapidly in the ambient air to form tiny liquid droplets. Together, the filterable and condensable fractions are referred to as direct emissions of PM_{2.5}, and the summed number is what is reported in the NEI for all source categories. Most AP-42 EFs do not quantify the condensable fraction of total PM_{2.5} emissions. "Gap filling" techniques are used to estimate condensable PM_{2.5} for many stationary and area source categories. This introduces some uncertainties in the emissions estimates.

¹ <http://cfpub.epa.gov/webfire>.

A2.2.3 Emissions Reduction Factors

The emissions-reduction factor (ER) in Equation 1 accounts for emissions controls employed on a source. For example, these include various effluent exit devices such as bag house filters and electrostatic precipitators for removal of PM. Like other process equipment, emissions controls have variable operating performance depending on their design, maintenance, and nature of the process controlled. Thus, like EFs, values of ERs are overall averages for specific processes and emissions-control designs based on limited testing. Actual values of ERs vary in time and by process in an undocumented manner, adding significant uncertainty to emissions estimates. Note that if no emissions controls are applied, the abatement efficiency equals zero (ER=0) and the emissions calculation is reduced to the product of activity and the emission factor, EF.

A2.2.4 Activity Levels

The last piece of information needed in equation 1 to estimate PM_{2.5} emissions for sources is activity patterns. Activity patterns (AP) describe average temporal operating characteristics of a process, including estimates of the down time for maintenance or process failure. Values of AP for point and non-point sources are each obtained in different ways owing to the differing nature of the sources.

Most point sources or industrial sources operate with local permits, and these require information about process emissions, including temporal characteristics. For sources with CEMs for monitoring opacity (roughly proportional to fine PM loading), such as large utility boilers, real-time data are available to derive activity patterns, and deduce emissions variability over extended time periods. Further, point sources keep and report records of output during operating periods, and maintenance or other down times.

There is a great deal of complexity in acquiring activity data for nonpoint sources, which are diverse in character, individually small, and often intermittent, but collectively significant. Though such sources are difficult to characterize, they are generally important to PM emissions estimation because their aggregated mass emissions can be large and their chemical composition (e.g., BC) may be important for estimating source attribution. One good example of such a category is forest fires, burning of land-clearing debris, and agricultural burning.

Temporal resolution depends on the allocation of emissions aggregated seasonally, weekly, daily or by diurnal variation, depending on use and industry activity patterns. The temporal allocations allow for improved approximation of the actual temporal patterns that can be important not only for precise annual averaging using seasonal or daily allocations, but also for short-term impairment taken over periods of 24 hours or less. "Typical" temporal variations for different sources have been developed from surveys, activity analyses, and expert consensus. These temporal models are approximations that may deviate substantially from actual emissions in a given location. Depending on the requirements for precision in estimations, local testing through observations and activity data may be required, not only for large point or nonpoint sources, but for smaller ones that may be of special interest.

For nonpoint sources, emissions can be estimated coarsely from "top-down" measures of activity at the state or national level, including demographics, land use, and economic activity. The construction industry, for example, is based on the total annual expenditures at the regional level. These estimates are then allocated by county, using a procedure linked with construction costs and estimated area under construction. Because of their potential importance as PM sources, considerable effort has been devoted recently to the characterization of emissions and activity patterns for non-point sources. Another example is estimation of emissions from fires, which depends upon knowledge of the time, location, and areal extent of the burn, fuel loading, types of combustible material and moisture content. Recent efforts by EPA include the use of process modeling and remote sensing data to better estimate fire activity patterns and emissions from fires (Blue Sky Framework, 2010). Finally, residential wood burning is also an important local source of PM and BC. Quantification of emissions from this source category has been approached through acquisition of data on how much fuel is burned in fireplaces and woodstoves using national consumption estimates. Where this source is a large contributor to PM, local surveys of firewood use are used to supplement and improve activity level estimates. For all burning categories, the PM emissions reported via AP-42 contain both condensable and filterable emissions, so that the uncertainties involved with arriving at total PM_{2.5} is less compared to other point and non-point sources.

A2.2.5 Estimating BC and OC Emissions

Next, these PM_{2.5} emissions can be converted to BC and OC by proper application of speciation

factors from the SPECIATE database. (See Appendix 1 for details on SPECIATE.) The equation used is quite simple: $PM_{2.5}$ Emissions (in tons) * fraction of $PM_{2.5}$ that is BC = BC emissions. This can be difficult given that there are thousands of $PM_{2.5}$ source categories but only a limited number of speciation profiles. Therefore, special attention must be given in mapping specific profiles to source categories. These details are explained in Reff et al. (2009). Application of these methods to the inventories results in the 90 source categories for which BC and OC emissions are reported in Chapter 4.

While the process for compiling BC emissions inventories is reasonably straightforward, there are important limitations in this process that introduce uncertainties in final BC emissions estimates. These include:

- The reliability of the $PM_{2.5}$ emission factors used in Equation 1. Some emission factors for point and non-point sources are more reliable than others (NARSTO, 2005).
- The reliability of condensable PM estimates by source category. Some sources include PM condensables as part of their testing protocol (fires, residential wood combustion). Others do not, and a generic emission factor (via AP-42) is applied to estimate the amount of condensable PM each source emits. This introduces a level of uncertainty in determining final BC emissions that is not currently accounted for. The source measurements section of this report gives a clearer indication of what the issues are and how they can be improved.
- The reliability of activity levels used in Equation 1. Some activity levels are generated using process models (Blue Sky Framework, 2010), while some are generated using surrogate information (U.S. EPA, 2005a).
- Finally, many “augmentations” are done in the emissions inventory processing steps. These augmentations include scaling measured PM to $PM_{2.5}$ as well as assigning condensable emissions estimates to point and nonpoint sources that are not available via source testing. Some of the impacts of the uncertainties in doing this have been explored (NARSTO, 2005), but the issue has not been dealt with holistically.

A2.2.6 Mobile Sources

In the U.S. inventory, mobile sources consist of the following general categories of vehicles and engines:

- *On-road gasoline*, such as passenger cars and light-duty trucks
- *On-road diesel*, including light-duty passenger cars, light-duty trucks, and heavy-duty trucks. Unlike in Europe, very few diesel passenger cars are sold in the United States, making heavy-duty diesel trucks the dominant vehicle type in this category.
- *Nonroad diesel*, including construction, agricultural, and other equipment
- *Nonroad gasoline*, including both 2-stroke and 4-stroke cycle engines such as those used in lawn/garden equipment and recreational marine
- *Commercial marine*, classified by engine displacement as categories C1, C2, and C3 (ocean-going)
- *Locomotives*
- *Aircraft*, which are generally turbine aircraft rather than the smaller piston gasoline-powered aircraft

BC emissions from on-road vehicles, both gasoline and diesel, are now calculated directly using EPA’s new MOVES 2010 model. For other mobile source categories, BC emissions are calculated using methods similar to those described above for stationary sources. EPA has released a number of technical reports on MOVES. These give the structure of the model including fleet and activity data such as vehicle miles traveled, the default national vehicle population, and vehicle activity patterns.² They also give information on exhaust emission rates and deterioration by model year for light-duty and heavy-duty vehicles.³ Similar information is available on the EPA NONROAD

² EPA (November 2010) Report EPA-420-R-10-026, MOVES 2010 Highway Vehicle Population and Activity Data, <http://www.epa.gov/otaq/models/moves/420r10026.pdf>.

³ EPA (April 2001) Report 420-R-01-007 EPA’s New Generation Mobile Source Emissions Model: Initial Proposal and issues. MOVES, <http://www.epa.gov/otaq/models/moves/movesback.htm>. EPA (February 2003) Report 420-R-03-005 Investigation for the Physical Emission Rate Estimator to be Used in MOVES, <http://www.epa.gov/otaq/models/moves/movesback.htm>.

model for things like equipment population, emission factors, and engine turn over.⁴

The inventories given below for the United States include all 50 states. They also include all marine activity (both domestic and foreign) within 200 nautical miles of shore.

A2.2.6.1 On-road Gasoline and Diesel

For on-road gasoline and diesel vehicles, EPA's emissions models directly calculate both total PM_{2.5} emissions and BC emissions. Recent improvements in EPA's new MOVES 2010 model (U.S. EPA, 2010e) as compared to the earlier MOBILE6.2 model (U.S. EPA, 2003) include accounting for high emitters, deterioration of PM emissions (i.e., increase in PM mass) with higher mileage, and increased PM emissions at lower temperatures.⁵ This model directly calculates BC emissions (as well as other exhaust PM components such as sulfates and OC), and accounts for the significantly reduced BC fraction emitted from on-road diesels due to application of diesel particulate filters (DPFs) (required for heavy-duty diesel trucks up to 80,000 pounds GVW beginning with the 2007 model year). An important input for the gasoline vehicle PM_{2.5} portion of the MOVES model is a recent study examining PM emissions from about 500 in-use vehicles (Coordinating Research Council, 2008). MOVES accounts for the lower EC/PM fraction (about 10%) for diesels with DPFs. Several studies such as the Health Effects Institute Coordinating Research Council study (Khalek et al., 2009) have evaluated the EC/PM fraction of heavy-duty diesel engines with DPFs

⁴ EPA (December 2005) Report EPA 420-R-05-016 Exhaust Emission Effects of Fuel Sulfur and Oxygen on Gasoline Nonroad Engines, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (July 2010) Report EPA-420R-10-017 Nonroad Engine Population Estimates, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (December 2005) EPA Report 420-R-05-017 Seasonal and Monthly Activity Allocation Fractions for Nonroad Engine Emissions Modeling, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (July 2010) EPA Report 420-R-10-015 Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (December 2005) EPA Report 420-R-05-018 Calculation of Age Distributions in the Nonroad Model: Growth and Scrappage, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (July 2010) EPA Report 420-R-10-018 Exhaust and Crankcase Emission Factors for Nonroad Engine Modeling – Compression Ignition, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

EPA (December 2005) EPA Report 420-R-05-021 Geographic Allocation of Nonroad Engine Population Data to the State and County Level, <http://www.epa.gov/oms/nonrdmdl.htm#model>.

⁵ MOVES also accounts for emissions changes with use of gasoline/ethanol blends, although the effect on PM exhaust emissions from use of gasoline/ethanol blends is extremely small, if not zero (U.S. EPA, 2010e).

finding a fraction of about 10% versus the more typical 70-80%. EPA plans to perform an uncertainty analysis with MOVES, considering the various inputs and what the range of uncertainty might be, and what the overall uncertainty might be.

Gasoline OC and BC emissions increase dramatically at lower ambient temperatures. To calculate this increase for gasoline vehicles, we used calculations done for EPA rulemaking packages for gasoline PM, for which an hourly grid-cell temperature adjustment was done as part of emissions processing at the county level for each of the over 3,200 counties. As a general rule, diesel PM emissions are less sensitive to temperature for a variety of reasons (lower importance of cold start since many diesels trucks do not operate on short trips; easier engine warm up since older diesels do not have catalysts which take a finite time to warm up during which emissions are higher). This means that BC emissions from diesel vehicles are not projected to increase as much at lower temperatures as would be the case with gasoline vehicles.

MOVES can also be used to calculate tire and brake wear PM_{2.5}, with speciation factors applied to calculate BC. Only a small fraction of the PM from tire and brake wear is in the PM_{2.5} range, so estimated BC emissions from these categories are fairly small. However, a large fraction of tire wear PM (about 22%) is BC. In the U.S. inventories reported in Chapters 4 and 8, these detailed calculations at the county level were done for 2005 and projection years (2020, 2030) along with some less detailed calculations (at the national level) for 1990. One important thing to note is that the PM, BC, and OC are relatively high from the on-road gasoline vehicle fleet for 1990 due to the presence of a large number of non-catalyst vehicles still remaining in the fleet.

A2.2.6.2 Nonroad Gasoline and Diesel

For nonroad engines (both gasoline and diesel powered), EPA calculates BC emissions based on PM emissions estimates from the NONROAD model (U.S. EPA, 2008b). Also, the National Mobile Inventory Model (NMIM) uses the current version of the NONROAD model (NONROAD2008) to calculate emissions inventories. The model incorporates emission factors (in g/BHP-hr – that is, grams per brake horsepower-hour), engine output (BHP-hr), and usage data for a wide number of NONROAD sources. For gasoline engines, 2-stroke cycle engines are a separate category from 4-stroke cycle engines. These engines have lubricating oil mixed with the fuel so the exhaust VOC (and PM) will be markedly different from that for the more standard 4-stroke cycle engines. VOC from 2-stroke

cycle engines will contain higher molecular weight compounds from the oil mixed with the gasoline; oil compounds are typically in the C20-C37 range. For these engines, the profile used to derive the emissions estimates in Chapter 4 is that used for non-catalyst equipped gasoline-powered motor vehicles since these nonroad gasoline engines do not have catalysts. This profile (92049) comes from the EPA SPECIATE database and shows 10% of the PM being BC. Admittedly, data specific for nonroad gasoline engines, especially 2-stroke engines with their oil combustion, are needed. EPA plans to add NONROAD into MOVES at some point in the future. Also, at some point possibly beyond that, EPA would perform an uncertainty analysis on the nonroad inventories.

BC emissions are then calculated by using speciation factors denoting the percent of PM emissions represented by BC. A speciation factor for nonroad diesel engines not equipped with DPFs comes from EPA's SPECIATE database (U.S. EPA, 2008a). The profile used to derive the emissions estimates in Chapter 4 (Profile 92035) is actually derived from heavy-duty on-road diesels and has 77% of the PM being BC. Beginning in calendar year 2012, many if not most newly manufactured nonroad diesels for that "model year" will be equipped with DPFs. This technology reduces exhaust PM mass by over 90%, and the small amount of PM remaining has relatively little BC. In effect, DPFs preferentially reduce BC. Roughly 10% of the PM from a diesel with a DPF consists of BC based on a large emissions characterization program on four 2007 model year on-road diesel truck engines equipped with DPFs. The testing was done by Southwest Research Institute for this program conducted by the Coordinating Research Council (Khalek et al., 2009).

A critical factor in compiling BC inventories for nonroad diesels is to correctly apportion the BC emissions between pre-trap-equipped diesel engines and trap-equipped diesels in any given calendar year. The NONROAD model correctly calculates the combined PM mass in a given calendar year accounting for pre-trap and trap-equipped diesels. Though it does not presently calculate BC emissions separately, a later version of the model under development will do so. Meanwhile, when NONROAD is run, one can get a model year emissions output for specific calendar years. One can then probably manually take that model year input and apply the higher BC speciation percent (77%) to the pre-trap equipped engines and the lower percentage (roughly 10%) to the new diesel engines equipped with DPFs. The inventory numbers presented account for this difference. For nonroad gasoline, a speciation profile of 10% of the PM

being BC is used based on tests on older non-catalyst light-duty vehicles. Most nonroad engines do not have catalysts. Since almost no or limited PM speciation has been obtained for the exhaust of these engines, the most appropriate factor to apply is based on older non-catalyst vehicles (of the types produced before introduction of catalysts with the 1975 model year). It is also important to note, however, that 2-stroke cycle engine production will be changed with the advent of new EPA emission standards.

A2.2.6.3 Commercial Marine, Locomotive, and Aircraft

Commercial marine, locomotive, and aircraft emissions are calculated separately in spreadsheet models, with separate BC speciation factors for C1/C2 commercial marine and C3 commercial marine (the larger ocean-going vessels). For the smaller vessels, the profile for nonroad diesel engines is applied even though the higher sulfur content of the fuel will lead to the PM containing higher sulfate emissions than for nonroad diesels. DPFs will be required for these vessels starting in 2014, reducing the BC fraction to about 10% of the PM. However, DPFs will only be used on some engine classes, and implementation dates will vary (depending on factors such as engine size). Thus, there is a need for a model to correctly account for the implementation of these standards. For now, a model year break-out of PM emissions was done for both 2020 and 2030. Separate BC/PM speciation factors were applied to the PM emissions from the diesels with and without DPFs. Currently, the diesel BC speciation factor of 77% BC/PM is used for C1/C2 commercial marine for all years of analysis: 2005 as well as the non-DPF equipped engines in 2020 and 2030. Evidence from recent studies (Lack et al., 2009) suggests that a lower BC speciation factor may be more appropriate for C1/C2 marine.

PM emissions from C3 Marine have substantially different PM speciation profiles than smaller diesel engines used in C1/C2 Marine and on-road and nonroad diesel. C3 marine diesels burn a high molecular weight residual oil that contains very high sulfur levels (up to 45,000 ppm versus the 15 ppm in on-road and nonroad diesel fuel). Past EPA evaluations of C3 marine have used the EPA PM SPECIATE profile of Residual Oil Combustion (U.S. EPA, 2008c), which estimates a 1% BC speciation factor.

For this report, an updated BC speciation profile was estimated from studies available in the literature. Results from relevant studies that measured BC

Table A2-1. Summary of Recent Studies that Measured BC and PM Emission Rates from C3 Marine.
(Source: U.S. EPA)

Study	Vessel	Fuel	Fuel Sulfur Content	BC/PM ^a
Murphy et al. (2009)	Post-Panamax Container	Heavy Fuel Oil	30,000 ppm	0.31%
Agrawal et al. (2008)	Suezmax Marine Tanker	Heavy Fuel Oil	28,500 ppm	0.50%
Petzold et al. (2010) ^b	Medium Speed Diesel Engine	Heavy Fuel Oil	22,100 ppm	2.63%
Lack et al. (2009)	Slow-speed diesel vessels ^c	Variety	Variety ^d	7.33%
Lack et al. (2009)	Medium-speed diesel vessels ^e	Variety	Variety ^f	28.00%

^a Lack et al. (2009) measured BC not EC with Light-Absorption Measurements (photoacoustic aerosol spectrometer with adsorption at 532 nm), other studies measured EC using thermal-optical methods, but are referred to as BC for comparison.

^b Engine test, with engine load 85-110%.

^c PM measurements come from 29 SSD ships; BC emissions come from 52 SSD ships.

^d Mostly high sulfur fuel (>5,000 ppm).

^e PM measurements come from 12 vessels; BC emissions come from 51 vessels.

^f Mostly low sulfur fuel (<5,000 ppm).

Table A2-2. Summary of Speciation Ratios of PM from Relevant Marine Studies. (Source: U.S. EPA)

Reference	BC	EC	OC or OM	BC Measurement	EC/OC Measurement
Agrawal et al. (2008)		0.5%	11%		Thermal optical transmittance (TOT) NIOSH 5040
Murphy et al. (2008)		0.3%	7.4%		
Petzold et al. (2010)	0.85%	2.6%	21%	Multi-Angle Absorption Photometer, MAAP	Thermal-Optical Method, VDI 2465 Part 2
(SSD) Lack et al. (2009)	7.3%		23%	Photoacoustic Aerosol Spectrometer with adsorption at 532 nm	Organic Matter (OM) calculated by subtracting SO ₄ , NO ₃ , and NH ₄ from aerosol mass spectrometer (AMS) measurements
(MSD) Lack et al. (2009)	28%		16%		
(>5,000 ppm) Lack et al. (2009)	7.1%		19%		
(<5,000 ppm) Lack et al. (2009)	51%		35%		

and PM emission rates from marine sources are summarized in Table A2-1.

As noted in Table A2-1, there is substantial variation in the reported BC/PM emission profiles from these studies. Table A2-2 displays the BC, EC, and OC speciation rates from the relevant marine studies. Large variations between BC (light-absorption measurements) and EC (thermal-optical measurements) are observed for C3 Marine emissions. Petzold et al. (2010) noted differences in the EC and BC emissions up to a factor of 3 for a medium speed diesel engine measured in the laboratory. The discrepancies among different BC emission factors for marine sources are additionally noted in the literature (Petzold et al., 2010). Considering the uncertainty of the values, EPA selected a BC/PM speciation factor of 3%

which falls in the middle of the range of reported values. Alternatively, one can also consider which study has vessels that are most representative of the C3 marine population or even a population-weighted average. However, the differences in the measurement techniques and definitions of BC in the cited C3 Marine studies make it difficult to combine the data across studies. EPA recognizes that this is an area of active research and recommends further work be conducted.

In Table A2-2, the results from the Lack et al. (2009) study are subdivided according to vessel type: slow-speed diesel (SSD) and medium speed diesel (MSD). Lack et al. (2009) also grouped the BC emission observations according to fuel sulfur content. Fifty-one ship observations had low sulfur fuel content (<5,000 ppm) and 42 ship observations of vessels

had fuel sulfur content greater than 5,000 ppm. From the available data, BC and OC speciation factors were calculated for each of the subcategories. The ships in the Lack et al. (2009) study with low sulfur content had much lower sulfate speciation factors and higher BC speciation factors than the other studies.

To estimate the BC/PM factor for future years (2020 and 2030), the international fuel sulfur limits were considered (Table A4-2) as well as the speciation rates from the studies evaluated. Lowering the fuel sulfur content is an effective method to reduce the particulate sulfate, which comprises the majority of the PM from marine vessels using heavy fuel oil. Due to the substantial drop in fuel sulfur levels, the BC speciation factor should rise in 2020 and 2030. Due to limited data, the EPA chose a C3 marine BC speciation factor of 6% for 2020 and 2030. For now, EPA is choosing 11% as an OC/PM speciation fraction for 1990 and 2005 with a higher fraction (58.6%) for 2020 and 2030 when fuel sulfur reductions occur, especially in ECA areas.

Various inventories have also been prepared for C3 marine using fuel consumption, emissions, and vessel activity (Paxian et al., 2010).

For locomotives, as for C1/C2 marine, the HDDV on-road profile (77% BC) is presently being used for pre-2014 engines although available data suggest this number might be too high. DPFs will be used in subsequent years, reducing BC to about 10%. For 2020 and 2030, the PM model outputs are obtained by calendar year and for the years when the standards take effect, the 10% number is used.

For purposes of emissions inventory estimates, aircraft operations are often broken into two basic portions. The first portion, landing and take-off (LTO) cycle, is normally defined to include aircraft ground operations (taxi/idle) as well as aircraft operations below 3,000 feet elevation in the local airport terminal area. The second portion is referred to as non-LTO that includes climb (above 3,000 feet) to cruise altitude and descent from cruise to 3,000 feet. Together these portions comprise what is called "full-flight" emissions.

Emissions for the LTO portion are fairly well characterized. Engine emission rates are measured in jet engine test cells during FAA certification testing; it is believed that these measurements reasonably predict engine emissions rates for aircraft in actual LTO operations. Programs for evaluating and controlling LTO emissions have been in place in the United States for about thirty years. Today there are LTO engine emissions standards for hydrocarbons, carbon monoxide, oxides of nitrogen and smoke

number. While work is now underway to develop a sampling and measurement procedure and certification requirement for aircraft jet turbine engine PM emissions, there are not yet specific engine emission standards for PM. To address this shortfall on at least an interim basis, FAA, working with EPA, industry and academic experts developed a methodology to estimate LTO PM emissions. This methodology, known as the "First Order Approximation" (FOA), uses information on smoke number and other engine and fuel parameters to estimate LTO PM emission rates for each engine model (Kinsey and Wayson, 2007). This information is then matched with airframe information on number of engines to get a per LTO emission rate for each aircraft type. Using the airport specific information and the aircraft activity for each airframe/ engine combination, the LTO PM Inventory estimates are made. The total PM emission rate includes all types of compounds contributing to the PM mass. It is estimated that only about 13% of the PM mass is BC; the remainder is composed of sulfates and organics. The average BC PM emission index (EI) is in the range of 0.04-0.05 g/kg fuel burned for the LTO portion.

The estimation of non-LTO BC emissions depends on a very limited set of measurements. Emissions testing in jet engine test cells does not fully characterize PM emission rates at altitude because they are conducted at sea level static conditions and have to be carefully extrapolated to altitude conditions, due to the differences in the atmospheric environment and engine operating conditions outside of the LTO—including cruise altitudes. Although there are research models available to estimate non-LTO BC, there is not yet a consensus approach for estimating non-LTO PM emissions as exists for LTO PM emissions. This is an area of ongoing research within the scientific and technical aviation communities.

However, two important points should be recognized with regard to non-LTO PM BC emissions. First, results from FAA's model entitled "System for Assessing Aviation's Global Emissions" (SAGE) indicate that total fuel burn during non-LTO operations is about ten times that during the LTO.⁶ Since the PM emission inventory is linked to fuel burn, overall PM emissions during the non-LTO portion of the "full flight" would be expected to be larger than those during the LTO portion. Second, this is an area of ongoing research and to-date there are no less than six researchers who have used various methods to estimate the EI for PM BC

⁶ The FAA SAGE website is http://www.faa.gov/about/office_org/headquarters_offices/apl/research/models/sage.

Table A2-3. Estimates of Aircraft BC Emissions. (Source: U.S. EPA)

Reference	Aircraft	Engine(s)	Measurement Condition	BC EI (g/kg fuel)
Kinsey et al. (2011)	DC8 Various air frames APEX 1 to 3	CFM56-2C1 CFM56-7B24 CFM56-3B1/3B2 CFM56-3B1 RB211-535E4B	Non-LTO thrust levels at Sea Level Static (SLS)	0.021, 0.026, 0.032 0.028, 0.025 0.092 0.098 0.275
Petzold et al. (1999a)	ATTAS	Rolls-Royce/SNECMA M45HMk501	Non-LTO thrust levels at SLS In-flight	0.118-0.149 0.11-0.15
Pueschel et al. (1997)	Concorde	Olympus 593	In-flight 16300 m altitude	0.07-0.11
Petzold et al. (1999b)	B737-300	CFM56-3B1	In-flight 7925 m altitude	0.01
Petzold et al. (1999b)	A310-300	CF6-80C2A2	In-flight 10670 m altitude	0.021
Petzold et al. (1999b)	VFW 614	M45H	In-flight 7925 m altitude	0.07-0.11
Lilenfield et al. (1995)	DC8	GE 404	All thrust levels at SLS	0.03-0.4
Anderson et al. (1998)	Multiple	Multiple	In-flight; mass EIs estimated from number EIs based on average particle volume and mass	0.01-0.35
Doppelheuer (2001)	n/a	CF6-50C2	Modeled Cruise Simulation - DLR Method using empirical calculation	0.015

emissions during the non-LTO portion of “full flight” (Lilenfield et al., 1995; Pueschel et al., 1997; Anderson et al., 1998; Petzold et al., 1999a; 1999b; Doppelheuer, 2001; Kinsey et al., 2011). Some researchers have used equivalent non-LTO thrust levels on the ground while the estimates of others were based on in-situ plume measurements of aircraft in flight. It is difficult to make direct comparisons among these values or to use this data to derive a point estimate for the non-LTO BC EI since they were developed on different airframe/engine models of different technology vintages using different measurement approaches. While data from the published researchers ranges from about 0.01-0.35 g/kg fuel burned, the majority of the data lies in the range of about 0.02-0.11 g/kg fuel burned. Each study has its relative strengths and weaknesses and most of the older engines with higher EIs are no longer in service. Table A2-3 summarizes the publicly available literature on this issue.

A2.3 Development of International Emissions Inventories for Black and Organic Carbon

There are a number of methodological differences between the approaches used to compile domestic and international inventories. Specifically, in contrast to EPA’s method of using emission factors paired with activity levels to estimate BC and OC emissions, the most widely used global emissions inventory described in Chapter 4 (Bond et al., 2004)

incorporates other factors to derive estimated BC emissions, including fuel type, combustion source technology type, and emissions controls. There is extensive usage data on emissions from specific vehicles and engines in the United States which is used for input for EPA models. These data exists to a lesser extent outside the United States. Fuel consumption data, which are often used as a substitute in global inventory calculations, are also useful but do not have the detail that vehicle/engine usage data have.

Like the U.S. inventory, global inventories typically rely on Equation 1 (outlined above), for estimating BC and OC emissions. That is, country-specific emission factors are combined with appropriate activity level information to yield an estimate of emissions. For example, on-road cars, trucks, buses, and all on-road mobile sources are generally assessed through travel-based emission factors and vehicle miles traveled (VMT). This approach associates mobile source emissions with traffic patterns, providing spatial and temporal information about the distribution of emissions that can be used in a variety of applications (for example, air quality modeling). However, motor vehicle emission factors are highly variable and uncertain because of different vehicle types, ages, maintenance, and operating conditions (Cadle et al., 2006). Fuel composition data often can be obtained more easily and accurately than activity measures such as VMT. Fuel-based emission factors for fossil fuel and bio-fuel combustion, for example, can be derived easily from diluted in-plume measurements, using

simultaneous CO₂ measurements to determine dilution ratios and to relate other pollutants to the weight of carbon in the consumed fuel (Chow et al., 2010c). Fuel-based emission factors are very common in global and large-scale inventories where detailed information on source activity is very limited.

Global BC and OC inventories are complicated by a lack of specific, detailed information on source types, emission factors, activities, and controls, especially in the developing world. In such cases a simple equation for calculating emissions based solely on emission factors and activity levels cannot be applied rigorously. Therefore, certain proxies have been used to estimate BC and OC emissions.

A2.3.1 Specific Approaches Used in Global Inventories

Most global inventories attempt to estimate BC emissions, even though some of the emission factors used seemingly represent testing on EC. There are important differences in the way various global estimates were generated, resulting in some variation in the total emissions estimates generated in different studies. It is useful to compare the approaches in more detail.

The Bond inventories, which are the most extensively used global inventories, were characterized in Chapter 4. Bond et al. (2004) identified about 50 different combinations of fuel type and usage and subdivided these into processes with different emissions characteristics. This approach is based on combining fuel composition data and assumptions of combustion technologies and emissions controls, and is very similar to earlier work done in the literature (Klimont et al., 2002). Emissions for a fuel/sector combination are calculated as an aggregate of the contributions of all technologies within that sector. The total emissions for each country, in turn, are the sum across all fuel/sector combinations. The reader is referred to published literature for more details on the methods used and the uncertainties inherent in their methodology (Bond et al., 2004; 2007). An overview of the Bond estimation procedure is given in Figure A2-1. Using this method, global BC emissions were estimated at about 8.9 million tons per year, with an uncertainty range of 4.8 -24 million tons/year. The United States accounted for about 6% of global BC emissions in this inventory.

Other authors have compiled inventories based on alternative methods. Penner et al. (1993) looked at developing BC emission in two ways: first, based on fuel consumption estimates, and second based on BC/SO₂ ratios. In examining the relationship between

ambient BC and SO₂ concentrations in urban areas around the world, the authors found strong correlations in source areas and also that various sources had characteristic BC/SO₂ ratios. Site-specific BC/SO₂ ratios were transformed to BC emissions using available SO₂ emissions estimates for each country/world region. The result was a global BC emissions estimate of about 26 million tons per year from urban fuel use. Penner et al. (1993) also calculated global BC emissions on the basis of fuel consumption, assuming constant emission factors for commercial and domestic coal, diesel fuel, wood, and bagasse combustion, yielding a total of 14 million tons BC/yr, with 7.3 million tons/year from fossil fuel combustion and 6.7 million tons/year from wood and bagasse fuel burning. Even though global estimates from the two methods differed by a factor of about 2, larger differences were found for individual countries and regions.

Cooke and Wilson (1996) compiled published estimates for biomass areal density, amounts above ground, the fractions burned, and emission factors for different fuel types (e.g., forests, savanna). Agricultural burning and biomass combustion for heating and cooking were not included. Country-specific fuel consumption rates were compiled for industrial, domestic, and combined sectors for solid, liquid, and gaseous fuels. Country-wide

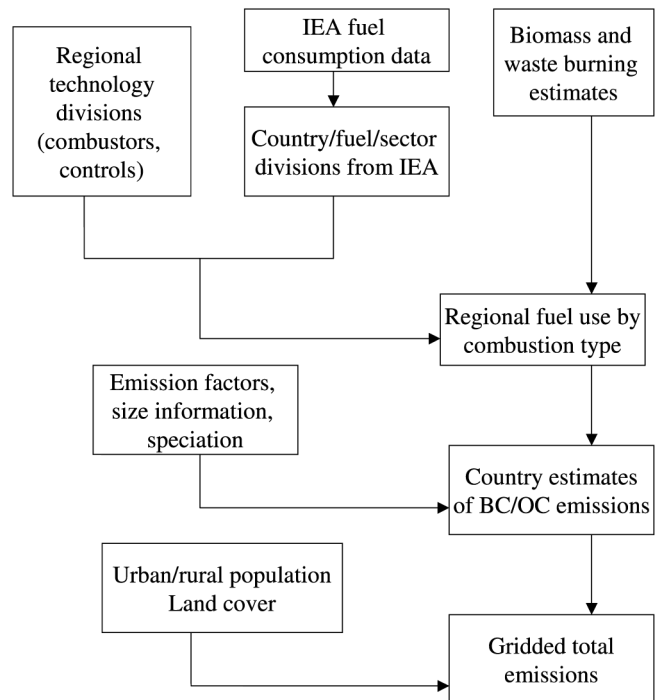


Figure A2-1. Bond et al. Methodology for Developing Emissions Estimates. (Source: Bond et al., 2004)

emissions were distributed to grids according to population density. The Cooke and Wilson global BC inventory of about 15 million tons was comprised of 9 million tons and 6 million tons from fossil fuel and biomass combustion, respectively. The fossil fuel component of 9 million tons was approximately one-third that estimated by Penner using the BC/SO₂ ratio approach (i.e. 26 million tons), but similar to emissions based on Penner's fuel consumption approach (i.e., 7.3 million tons from fossil fuel combustion).

Liousse et al. (1996) reported global BC and OM (organic mass) emissions. OM is divided by 1.3 and converted to measured elements in organic molecules. Their inventory includes categories for biomass (i.e., savanna and forest fires), agricultural waste, wood fuel, and dung combustion as well as domestic coal and diesel fuel combustion. Global fossil fuel combustion (7.3 million tons BC /year) and biomass burning (6.2 million tons EC /year) total 13.5 million tons EC/year, lower than the estimate of 15 million tons BC/year from Cooke and Wilson that excluded agricultural burning and biomass combustion for fuel and energy production. Liousse et al. (1996) also estimated global OC emissions of 69 million tons/year, with 24 million tons OC/year from fossil fuel and 45 million tons/year from biomass burning.

Then, Cooke et al. (1999) refined Cooke and Wilson (1996) by considering the relative ages of vehicles in developed and developing countries and particle size differences for controlled and uncontrolled combustion processes. The estimated global BC inventory from fossil fuel combustion of 7 million tons in Cooke et al. (1999) was consistent with estimates of 9 million tons BC/year by Cooke and Wilson (1996) and 7.3 million tons BC/year by Liousse et al. (1996). The Cooke et al. (1999) estimate of global OC emissions was about 11 million tons, about half that of Liousse et al. (1996) (24 million tons OC/year).

Cofala et al. (2007) have used a global version of the Regional Air Pollution Information and Simulation (RAINS) model to estimate anthropogenic emissions of BC and OC (along with numerous other pollutants). The authors rely on the RAINS methodology (Klimont et al., 2002) for particle emissions, which they modify to capture regional and country-specific characteristics of BC and OC emissions as laid out in other references (Kupiainen and Klimont, 2007) and extend it to developing regions with data from Bond et al. (2004). Their methods result in an estimate of 6 million tons of BC emitted globally in 1995 and about 5.9 million tons of BC emitted in 2000.

A2.3.2 Specific Approaches Used in Regional Inventories

Chapter 4 also discusses the information available from alternative inventories available for specific countries or world regions. Table A2-4 provides a comparison of key differences in data and methods between some of these inventories.

A comparison among the regional inventories listed in Table A2-4 yields some interesting information. It is also helpful to compare the emissions estimates from these inventories with estimates in the appropriate portion(s) of the Bond/Streets global inventory. Specifically:

- Cao et al. (2006) used emission factors from Cooke's 1999 global inventory and Streets' inventory of China BC emissions for the year 2000, along with Andreae and Merlet (2001) emission factors for biofuels. They developed a local inventory based on specific emission factors for crop straw used in cooking stoves by testing five different types of straw in a combustion tower designed to simulate Chinese cooking stoves. Their national BC emissions estimate for 2000 in China is about 1.7 tons, which is somewhat higher than the Bond estimate of 1.6 million tons and the Streets estimate of 1.2 million tons. The authors attributed this to their inclusion of coal combustion in rural industry and rural residential sources, which they noted are often underestimated in more global estimates. They outlined the residential and industrial sectors as being the most important in contributing to Chinese BC emissions.
- Streets et al. (2001) measured Chinese BC emissions for 1995, using mostly emission factors from other literature sources. Their inventory focuses on submicron BC emissions rather than bulk emissions, because submicron emissions are more relevant to radiative transfer calculations. Their study noted also that most inventories assume that the fraction of BC that makes up PM_{2.5} remains constant throughout the combustion process. Streets et al. (2001) states that smoldering combustion, while releasing a higher amount of particulate matter, does not exhibit temperatures high enough to produce the same proportion of BC. They propose a negative correlation between particulate emissions and the fraction of BC emitted. Other observations by this study were that removal efficiency of particles for the industrial sector is lower and less documented than that of the power sector, making emissions from the Chinese industrial sector more uncertain and variable, and that

Table A2-4. Regional Inventories of BC and OC Emissions. (Source: U.S. EPA)

Carbon Emission Inventory Reference	Region, Base Year (Resolution, if available)	Emission Source Categories	Source of Emission Factors	Source(s) of Activity Information ^a
Reddy and Venkataraman (2002b, Fossil Fuel) Reddy and Venkataraman (2002a, Biomass Combustion) Black Carbon and Organic Carbon	India, 1996-1997 (.25 x .25)	4 utilities 5 coal combustion 8 industrial 2 residential/ commercial 8 transportation 4 biomass/biofuels burning	Literature review U.S. EPA AP-42 Customized emission factors to fit Indian technology	Fossil fuel consumption from Central Board of Irrigation and Power, Cement Manufacturers' Association, Centre for Monitoring of India Economy, The Fertilizer Association of India, Ministry of Coal, Ministry of Industry, and Ministry of Petroleum and Natural Gas, Statistics for Iron and Steel Industry in India. Biofuel consumption in rural and urban from Tata Research Institute and National Sample Survey and Forest coverage from the Forest Survey of India.
Streets et al. (2003) Black Carbon Only	Asia, 2000 (1 x 1 to .08 x .08)	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 MOBILE5 model	RAINS-Asia simulation (2000 forecast from the 1995 base year), except for China which was compiled on a provincial basis. For the transportation sector, used World Road Statistics and World Motor Vehicle Data.
Cao et al. (2006) Black Carbon and Organic Carbon	China, 2000 (.2 x .2)	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 and Editorial Board of China Rural Energy Yearbook. Area sources activity from National Bureau of Statistics and various government agencies, mainly at the county level.
Streets et al. (2001) Black Carbon	China, 1995	Covers 37 different source types over five sectors (power, industry, residential, transport, field combustion) and 13 different fuel types, including biofuels	Literature Review	Fuel consumption data by sector and fuel type were developed within the framework of the RAINS-Asia model (Hordijk et al., 1995). Generated by China's Energy Research Institute.
Parashar et al. (2005) Black Carbon and Organic Carbon	India, 1995	Fossil fuel, biofuel, and biomass burning	Literature Review Laboratory tests of biofuels and soft coke	Fossil fuel consumption from TEDDY 2001/2002, biofuel use and biomass burning taken from Reddy and Venkataraman (2002b).
Sahu et al. (2008) Black Carbon	India, 2001 (1 x 1)	Categorized into area sources and LPS and then by fuel type	Literature review	Activity data collected from Central Electricity Authority (CEA), Census of India, Ministry of Coal, Ministry of Road Transport and Highways, Ministry of Agriculture.
Dickerson et al. (2002) Black Carbon	Asia, 1991 and 2001	Same as 37 different source types identified in Streets et al. (2001)	Literature Review MOBILE 5, also used CO/BC ratio to estimate emissions	RAINS-Asia model, Tata Energy Research Institute.

Carbon Emission Inventory Reference	Region, Base Year (Resolution, if available)	Emission Source Categories	Source of Emission Factors	Source(s) of Activity Information ^a
Lamarque et al. (2010) Black Carbon and Organic Carbon	Global, 2000 (.5 x .5)	12 different sectors over 40 different regions	Literature Review (Junker and Liousse, 2008 combination emission factors)	Biomass from RETRO, GICC, and GFEDv2 inventories; ship data from International Maritime Organization (IMO); aircraft data from AERO2K database, EUROCONTROL, Bond et al. (2007), and Junker and Liousse (2008).
Mitra et al. (2002) Black Carbon and Organic Carbon	India, 1996	7 different fuel types	Literature Review (from Cooke and Wilson, 1996)	
Mayol-Bracero et al. (2002) Black Carbon	India, 2000	8 different fuel types across four (five?) sectors	Literature Review (Streets et al., 2001)	RAINS-Asia model.
Ohara et al. (2007) Black Carbon and Organic Carbon	Asia, 2000 (.5 x .5)	Four sectors broken down into fuel type (coal, oil, biofuel, others)	Literature Review U.S. EPA AP-42	LPS activity data from China State Grid Company, RAINS-Asia, Fuel consumption from International Energy Agency (IEA) or UN Energy Statistics Yearbook. Biofuel consumption from RAINS-Asia.
Derwent et al. (2001)	Western Europe, 1995-1998	All sectors	Back calculated using dispersion modeling and ambient data	NA

^a Unless otherwise noted, refer to main Emission Inventory Reference for a list of specific publications and databases from which underlying data were drawn.

domestic emissions in China are responsible for over 80% of Chinese BC emissions. The final estimate of BC emissions was about 1.5 million tons, which is lower than the Bond estimate of 1.6 tons but higher than emissions estimated via other regional Asian studies REAS and TRACE-P (1.3 million tons and 1.0 million tons, respectively).

- Reddy and Venkataraman (2002a; 2002b) estimated BC emissions in India for the year 1996 by developing emission factors using Indian fuel composition and indigenous pollution control technology. Emission factors of coal for the power and industrial sector were derived from those of the EPA. Domestic emission factors were taken from Indian literature sources (Gray, 1986). Transportation factors were taken from an average of PM emission factors from countries with similar transportation statistics. The study noted that most of the BC emissions from India were from the transportation sector (almost 60%). Overall they predicted BC emissions from 1996–1997 to be 0.36 million tons annually. This estimate is lower than almost all other estimates of Indian BC emissions. The authors claimed their lower estimate was due to different emission factors – other emission factors used in more

global inventories were too high due to improper differentiation of fuel composition, combustion type, and PM_{2.5} composition differences.

- Parashar et al. (2005) estimated Indian BC emissions for 1995 and used Bond emission factors for fossil fuel combustion. Biomass combustion emission factors were determined by actually combusting different types of fuels in a U shaped chimney. They found that dung cakes released a particularly high amount of particles due to a smoldering combustion, which releases more particles than other types of burning. Their final emissions estimate for India was 0.92 million tons BC, which is higher than Bond’s estimate of 0.64 million tons of BC. The higher emissions could be due to the higher emission factor they found for dung cakes, which accounted for a higher than proportional amount of domestic emissions.
- Mitra et al. (2002) estimated Indian BC emissions for the year 1996 using Cooke’s 1999 emission factors for “under developed” countries. They only calculated emissions for four fossil fuel categories: coal, diesel, gasoline, kerosene. Their annual emission estimate was approximately

1.1 million tons of BC. This is much higher than Bond's estimate of 0.63 million tons BC in India. The higher emissions could be due to the use of emission factors for under developed countries, in that Bond et al. in their estimates may have used emission factors from more developed countries to represent fossil fuel combustion characteristics in India.

- Sahu et al. (2008) estimated BC emissions from India for the years 1991 and 2001. They used Cooke's 1999 emission factors for "under developed countries" for fossil fuel combustion and Reddy's regionalized 2002 emission factors for biofuel combustion. Their final estimate of BC emission in India was about 1.5 million tons per year, higher than any other inventory despite the fact that they did not inventory small industry. Their high estimates could be due to using under-developed country emission factors for all fossil fuel combustion sectors and also from use of diesel activity information which did not represent current conditions.
- Mayol-Bracero et al. (2002) calculated BC emissions in India using the Chinese emission factors developed by Streets et al. (2001) and national activity data from the GAINS model. Their final estimate of BC emissions in India (2000) was 0.5 million tons, slightly lower than Bond's estimate of about 0.6 million tons.
- Ohara et al. (2007) developed REAS (Regional Emission Inventory for many parts of Asia) for several pollutants including black carbon for the period 1980 – 2003. Emissions were calculated as a product of activity data, emission factors, and removal efficiency of controls. BC emission factors were taken from Streets et al. (2003a), and characterized into developed countries and countries with no known emission controls (this category included India and China). The emission factors for developed countries changed several times over the time period of the inventory. Chinese BC emissions in 2000 were 1.2 million tons and Indian emissions were estimated to be about 0.9 million tons. These numbers compare fairly well to other estimates for those countries. The inventory noted the domestic sector as the main contributor to BC emissions.
- Dickerson et al. (2002) used two different approaches to measuring BC emissions in India and other South Asian countries. They first did a bottom up inventory using emission factors and activity level data. They assumed that South Asia source types of BC were similar to those of China, and they obtained energy use information from the RAINS-Asia model. For residential biofuel combustion, they used the emission factor 1 g/kg, which was taken from measurements in the literature (Muhlbaier-Dasch, 1982) and was similar to that used in the Reddy and Venkataraman study outlined earlier. Their estimates of BC emissions from power plants were lower than Reddy and Venkataraman because of smaller emission factors due to a high level of ash in the particulate emissions. Indian vehicles were assumed to be similar to Chinese vehicles; the authors used emission factors from Streets' 2001 work. The final BC estimate for India was 0.56 million tons. Their estimates differ from Penner et al. (1993), Cooke and Wilson (1996), and Cooke and Wilson (1996) as well as Bond et al. (2004), because of possible inclusion of ash in the emission factors, omission of biofuels, and difference in time periods. For the second method, CO emissions were used as surrogates to estimate BC emissions. They found that that total BC emissions for India using this method were more on the order of 2 million tons. The team concluded that bottom up inventory estimates produce much smaller values of BC emissions than do actual in field observations (or "top down" estimates), which could imply errors in calculating these inventories "bottom up."
- Zhang et al. (2009) focus on the INTEX-B mission, the goals of which were to quantify transport and evolution of Asian pollution to North America and assess its implications for regional air quality and climate. The inventory improved China's emissions estimates by balancing the spread of new and old technology in China's industrial sector and improving energy statistics. For other Asian countries, the mission used IEA energy statistics and emission factors documented in Klimont et al. (2002). The INTEX-B mission also incorporated inventories that were thought to be more accurate representations of individual countries, such as the Indian inventory from Reddy et al. (2002a; 2002b), the Japan inventory from Kannari et al. (2008), and the South Korean inventory from Park et al. (2001). China emissions were 1811 Gg and India emissions were 344 Gg for 2006. INTEX-B also included small industry emissions, but noted that they were uncertain of the numbers. The authors also noted that for Southeast Asia, the activity level data was extrapolated and there were few local emission factors, so the data may not be very accurate. This mission was seen as an improvement on the previous TRACE-P due to the updated methodology and collaboration with local inventory efforts.