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# Speciated $PM_{10}$ Emission Inventory for Delhi, India

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## ABSTRACT

Emission inventories can serve as a basis for air quality management programs. The focus has been mainly on building inventories for criteria pollutants including particulate matter (PM). Control efforts in developing countries are mostly limited to total suspended particles (TSP) and/or $PM_{10}$. Since the adverse effects of $PM_{10}$ depend on its chemical composition, it is important to control emissions of toxic species. The first step is to identify key pollution sources and estimate quantities of various chemical species in emissions. This paper presents a speciated $PM_{10}$ emission inventory for Delhi, the capital and one of the most polluted cities in India. An established $PM_{10}$ inventory for Delhi in conjunction with source profiles was used to estimate emissions of major $PM_{10}$ components including organic and elemental carbon (OC and EC, respectively), sulphates ($SO_4^{2-}$), and nitrates ($NO_3^-$), as well as selected toxic trace metals (i.e., Pb, Ni, V, As, and Hg), some of which are subject to India's National Ambient Air Quality Standards (NAAQS). For the base year of 2007, emission estimates for $PM_{10}$ mass, OC, EC, $SO_4^{2-}$, and $NO_3^-$ are 140, 22, 6.4, 2.8, and 2.1 tonnes/day (TPD; 1 tonne = 1000 kg), respectively. Emissions of Pb, Ni, V, As, and Hg are estimated to be 203, 43, 37, 26, and 9.4 kg/day, respectively. This inventory underestimated Pb and Hg emissions because sources of $PM_{10}$ from unorganized secondary lead smelters are not specifically identified and gas-to-particle conversion of Hg is not accounted for.

***Keywords:*** Emission inventory; Delhi; Speciated $PM_{10}$.

## INTRODUCTION

Emission inventories (EIs) provide a basis for understanding primary pollutant sources and for prioritizing pollution control measures (Mobley *et al.*, 2005; Miller *et al.*, 2006). While compiled over defined urban- to regional-scales to track long-term emission trends (U.S.EPA, 2010), annualized EIs can be apportioned in space and time to support air quality modeling that relates emissions to ambient concentrations (Hogrefe *et al.*, 2003). Such modeling facilitates the selection of emission reduction strategies and evaluation of adverse effects on human health, visibility, climate, ecosystems, and cultural heritage (Watson, 2002; Pope, III and Dockery, 2006; MacCracken, 2008; Mauderly and Chow, 2008; Chow and Watson, 2011; Hu *et al.*, 2011). Most EIs are developed for criteria pollutants such as carbon monoxide (CO), sulphur dioxide ($SO_2$), oxides of nitrogen ($NO_x$), total suspended particles (TSP) and/or $PM_{10}$ and $PM_{2.5}$ (particles with aerodynamic diameters, $d_p$, < 10 and 2.5 micrometers [μm], respectively). Precursors to the formation of ozone ($O_3$) and secondary PM, such as volatile organic compounds (VOCs) and ammonia ($NH_3$), are sometimes included in the EIs. Long-lived greenhouse gases and short-lived climate forcers such as black and brown carbon are also being compiled on regional, continental, and global scales (Bond *et al.*, 2004; Junker and Liousse, 2008; Chow *et al.*, 2010; Lamarque *et al.*, 2010; Chow *et al.*, 2011; Watson *et al.*, 2011; Wang *et al.*, 2012).

Most inventory efforts in India (Gargava and Aggarwal, 1999; Garg *et al.*, 2002; Reddy and Venkataraman, 2002a, b; Gurjar *et al.*, 2004; Dalvi *et al.*, 2006; Mohan *et al.*, 2007; Gurjar *et al.*, 2008; Behera *et al.*, 2011; Lu *et al.*, 2011; Sahu *et al.*, 2011) have focused on primary pollutants related to India's National Ambient Air Quality Standards (NAAQS) (Central Pollution Control Board [CPCB], 2009). The Indian NAAQS include: 1) annual average $PM_{10}$ of 60 μg/m$^3$ and $PM_{2.5}$ of 40 μg/m$^3$; 2) 24-hour average $PM_{10}$ of 100 μg/m$^3$ and $PM_{2.5}$ of 60 μg/m$^3$, 98$^{th}$ percentile for one year, with no exceedance on two consecutive days; 3) annual average PM lead (Pb) of 0.5 μg/m$^3$, nickel (Ni) of 0.02 μg/m$^3$, arsenic (As) of 0.006 μg/m$^3$, and benzo(a)pyrene (BaP) of 0.001 μg/m$^3$; and 4) 24-hour average PM Pb of

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1.0 μg/m$^3$, 98$^{th}$ percentile for one year, with no exceedance on two consecutive days (CPCB, 2009).

Speciated PM and VOC EIs are needed to estimate $O_3$ and secondary aerosol formation from primary emissions, evaluate exposure to toxic pollutants, estimate adverse environmental effects, and compare emission estimates with ambient concentrations. Bhanarkar *et al.* (2005) reported 2001–2002 industrial PM emissions for toxic metals in Greater Mumbai, India, finding that vanadium (V) constituted ~57% of all toxic metals in PM, mostly derived from residual oil combustion. More up-to-date speciated inventories that address additional sources and chemical species are needed for India's major population centers. This study derives a speciated $PM_{10}$ inventory for primary species, including organic and elemental carbon (OC and EC, respectively), sulphates ($SO_4^{2-}$), nitrates ($NO_3^-$), and metals (i.e., Pb, Ni, V, As, and mercury [Hg]) in the Delhi metropolitan area for 2007.

## STUDY AREA

Delhi, the Capital and economic center of India, is one of the world's most polluted megacities (Chow *et al.*, 2004; Molina and Molina, 2004). Despite remediation actions including implementation of the world's largest compressed natural gas (CNG)-fueled public transportation system, air pollution remains a critical issue (Goyal and Sidhartha, 2003; Ravindra *et al.*, 2006; Chelani and Devotta, 2007; Khillare *et al.*, 2008; Saxena and Ghosh, 2010). Measurements from 2001 to 2010 indicate increasing $PM_{10}$ trends with annual averages at nine sites almost four times the NAAQS of 60 μg/m$^3$. Annual average $PM_{2.5}$ concentrations ranged from 72 to 107 μg/m$^3$ at six sites in 2010, far exceeding the 40 μg/m$^3$ NAAQS (CPCB, 2009).

The Delhi emissions domain (i.e., latitudes 28°24' 17" and 28°53'00 N and longitudes 76°50'24" and 77°20'37" E), encompasses an area of approximately 1500 km$^2$. Its population increased from ~13.8 million in 2001 to ~17 million in 2010 (Census of India, 2012); the number of motor vehicles rose from ~3.6 million in 2002, ~5.2 million in 2007, and to ~6.5 million in 2011. The vehicle fleet consists of 63.6% two-wheelers and 30.7% gasoline-fueled passenger vehicles, as well as minor amounts of light commercial vehicles (1.6%), three-wheelers (1.4%), trucks (1.1%), buses (0.8%), and diesel-fueled vehicles (0.5%) (NEERI, 2010). Energy demand increased from ~3100 megawatts (MW) in 2007 to ~5900 MW in 2012 (National Capital Region [NCR] Planning Board. 2001). This growth has the potential to offset many of the emission reduction measures applied to individual sources.

## METHODS

A study was conducted in Delhi during 2007 to: 1) characterize $PM_{10}$ mass and its chemical constituents at 10 monitoring sites, 2) develop micro- and city-wide $PM_{10}$ emission inventories, and 3) conduct dispersion and receptor modeling to estimate the source contribution to $PM_{10}$ and other criteria pollutants (NEERI, 2010). Samples were collected in summer (May–June), post-monsoon (October–November), and winter (December–January) periods on 20 days during each season. $PM_{10}$ samples were analyzed for mass, carbon (i.e., OC and EC), ions (i.e., $SO_4^{2-}$, and $NO_3^-$), and trace metal (i.e., Pb, Ni, V, As, and Hg) concentrations.

Emission inventories were constructed in the NEERI (2010) study for $PM_{10}$ mass and other criteria pollutants in $2 \times 2$ km$^2$ zones of influence (Chow *et al.*, 2002) surrounding each monitoring site. These "micro-inventories" were input to the U.S. EPA Industrial Source Complex-Short Term (ISCST3) dispersion model (U.S. EPA, 1995a, b) to estimate emissions and to compare with measured ambient concentrations. Monitoring sites were located in representative neighborhoods so that area-source activities could be extrapolated to similar neighborhoods throughout the metropolis. These monitoring sites represented various land-use (e.g., industrial, residential, and commercial areas) and activity profiles (e.g., traffic). $PM_{10}$ emission rates were estimated by multiplying emission factors for different source types by their corresponding activities. Table 1 summarizes 30 stationary, area, and vehicular source categories that were included in the 2007 emission inventory.

The methodologies used to estimate emission factors and activity levels for the various sources are described in NEERI (2010). Identification of stationary and area sources, fuel use, and population were collected from surveys of government and non-government departments and agencies and from direct observation, as in the case of open burning. For motor vehicles, traffic volumes were counted for different categories of roads (i.e., arterial, main, and feeder roads). Vehicle kilometers traveled (VKT) were estimated by multiplying traffic volume (number of vehicles) by the effective road length for various road categories. Data on fuel use and vehicle age were assembled through surveys at parking lots and fueling stations (NEERI, 2010). Delhi contains many gasoline-fueled two- and CNG-fueled three-wheeled vehicles that emit carbon in the ultrafine ($d_p < 0.1$ μm) and fine ($d_p < 2.5$ μm) particle size range (Apte *et al.*, 2011). These representative activity data were associated with city land use and roadway plans. Re-suspended dust from paved roads was estimated from silt loading, average weight of vehicles (tonnes/day), road length, and rainfall frequency. Average silt loading has been estimated to be in the range of 0.21 to 7.0 g/m$^2$ depending on the road condition. Re-suspended road dust was estimated for each of the road categories.

A city-wide inventory for stationary, area, and vehicular sources was developed incorporating the 30 fuel usage source categories identified in Table 1, population, and activity levels. Vehicle emissions were extrapolated from the micro-inventories at the 10 monitoring sites by re-scaling road lengths in each road category and estimating emissions per unit length of road for the entire city. Emission factors for stationary and area sources were derived from U.S. AP-42 (U.S. EPA, 2006) and Reddy and Venkataraman (2002a, b). Emission factors for motor vehicles were taken from the Automotive Research Association of India (ARAI; 2007) and CPCB (2011). These emission factors are presented in Appendix 3 of NEERI (2010).

**Table 1.** Source categories in the Delhi $PM_{10}$ emission inventory (NEERI, 2010).

| Source No. | Source ID | Source Description |
|---|---|---|
| **Stationary and Area Sources** | | |
| 1 | PP_Coal | Coal-fired power plant |
| 2 | PP_NG | Natural Gas-fired power plant |
| 3 | Ind_NG | Natural Gas-fueled industrial boiler |
| 4 | Ind_FO | Fuel Oil (Diesel)-fueled industrial boiler |
| 5 | LPG_Dom | Domestic cooking with LPG[a] |
| 6 | Kero_Dom | Domestic cooking with kerosene |
| 7 | Wood_Dom | Domestic cooking with wood |
| 8 | Coal_Dom | Domestic cooking with coal |
| 9 | LPG_Hotel[b] | Commercial cooking with LPG |
| 10 | Kero_Hotel[b] | Commercial cooking with kerosene |
| 11 | Wood_Hotel[b] | Commercial cooking with wood |
| 12 | Coal_Hotel[b] | Commercial cooking with coal |
| 13 | Wood_Bak[b] | Commercial bakeries with wood |
| 14 | Crmt_wood | Crematoria with wood |
| 15 | Waste_Inc | Waste incinerator |
| 16 | SW_burning | Open solid waste (e.g., refuse and biomass) burning |
| 17 | Construction | Construction activities |
| 18 | Genset_K | Generator set using kerosene-fueled engine |
| 19 | Genset_D | Generator set using diesel-fueled engine |
| 20 | PvdRd | Paved road dust |
| **Vehicular Sources** | | |
| 21 | 2W-2S | Two wheeler (2W) with gasoline-fueled two stroke (2S) engine |
| 22 | 2W-4S | Two wheeler with gasoline fueled four stroke (4S) engine |
| 23 | 2W | Two wheeler including both 2W-2S and 2W-4S |
| 24 | 3W_CNG | Compressed natural gas (CNG)-fueled three wheeler |
| 25 | LCV | Diesel-fueled light commercial vehicles |
| 26 | 4W_P | Gasoline-fueled passenger vehicles |
| 27 | 4W_D | Diesel-fueled passenger vehicles |
| 28 | Truck_D | Diesel-fueled trucks |
| 29 | Bus_D | Diesel-fueled bus |
| 30 | Bus_CNG | CNG-fueled bus |

[a] Liquefied petroleum gas.
[b] Hotels, restaurants, and small dining outlets.

Chemically-speciated $PM_{10}$ emission rates were estimated by multiplying $PM_{10}$ mass emission rates from the specific source sub-categories in Table 1 by the corresponding source profiles. Source profiles are the fractional abundances of chemical species with respect to emitted $PM_{10}$ mass (Reff *et al.*, 2009; Chow *et al.*, 2010; 2011; Watson *et al.*, 2012). $PM_{10}$ source profiles specific to India, presented in Table 2, were measured by Sethi and Patil (2008a, b) for stationary and area sources, and by ARAI (2009) for vehicular sources. Emission rates for chemical species were calculated using the following equation:

$$E_{i,j} = PM_j \times F_{i,j}, \quad (1)$$

where $E_{i,j}$ is the emission rate in kg/day of species i from source j; $PM_j$ is the emission rate in kg/day of $PM_{10}$ from source j; and $F_{i,j}$ is the mass fraction of species i from source j.

Table 3 summarizes the chemically-speciated $PM_{10}$ emission inventory. Apart from power plants, industrial boilers (Source Nos. 3 and 4) are classified as small-scale industries (SSI; NEERI, 2010), which account for ~1.6% of the total $PM_{10}$ emissions in Delhi. These industries use mostly fuel oil (diesel) and natural gas. In the absence of specific data on fuel usage, 80 and 20% of SSI combustion was apportioned to fuel oil and natural gas, respectively. For the generator sets (Source Nos. 18 and 19) used during sporadic power outages, emissions were equally distributed between diesel- and kerosene-fueled engines. In December 2007, one coal-fired power plant (Indraprastha Power Station) was permanently shut down. Emissions (~5 tonnes per day [TPD]; 1 tonne = 1000 kg) from this power plant and from a few smaller sources (e.g., locomotives, dung cakes, etc.) were excluded due to non-availability of indigenous source profiles. However, 95% of the $PM_{10}$ emission load was accounted for and used to determine the speciated emission inventory.

To better understand the sectoral emission distributions, the 30 source sub-categories in Table 3 are grouped into 12 primary source categories based on their similarities in source type and/or fuel usage. These include: power plants; small-scale industries; domestic cooking and heating (i.e.,

**Table 2.** Source profiles (percent of $PM_{10}$ mass) and associated uncertainties corresponding to the source categories in Table 1.

| Source No.[a] | Source ID | OC | EC | $SO_4^{2-}$ | $NO_3^-$ | Pb | Ni | V | As | Hg |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | PP_Coal[a] | 8.71 ± 0.44 | 1.88 ± 0.94 | 1.43 ± 0.12 | 6.87 ± 0.51 | 0.100 ± 0.040 | 0.090 ± 0.037 | 0.0523 ± 0.0117 | 0.0257 ± 0.0185 | 0.0070 ± 0.0050 |
| 2 | PP_NG | 26.54 ± 1.33 | 7.48 ± 0.90 | 6.01 ± 0.52 | 39.96 ± 2.97 | 0.114 ± 0.170 | 0.304 ± 0.185 | 0.1273 ± 0.0533 | 0.4732 ± 0.1167 | 0.0369 ± 0.0265 |
| 3 | Ind_NG | 26.54 ± 1.33 | 7.48 ± 0.90 | 6.01 ± 0.52 | 39.96 ± 2.97 | 0.114 ± 0.170 | 0.303 ± 0.185 | 0.1273 ± 0.0533 | 0.4732 ± 0.1167 | 0.0369 ± 0.0265 |
| 4 | Ind_FO | 3.73 ± 0.19 | 16.42 ± 0.82 | 30.06 ± 2.13 | 0.04 ± 0.01 | 0.010 ± 0.007 | 0.299 ± 0.027 | 0.6553 ± 0.0477 | 0.0241 ± 0.0052 | 0.0015 ± 0.0011 |
| 5 | LPG_Dom | 23.21 ± 1.16 | 2.82 ± 0.14 | 7.74 ± 0.63 | 0.25 ± 0.18 | 0.446 ± 0.139 | 0.056 ± 0.121 | 0.0488 ± 0.0350 | 0.3278 ± 0.0814 | 0.0258 ± 0.0185 |
| 6 | Kero_Dom | 96.90 ± 4.85 | 52.68 ± 2.63 | 12.41 ± 0.98 | 0.32 ± 0.23 | 0.237 ± 0.210 | 0.282 ± 0.217 | 0.3148 ± 0.0743 | 0.2039 ± 0.1196 | 0.0444 ± 0.0319 |
| 7 | Wood_Dom | 48.45 ± 2.42 | 8.00 ± 0.40 | 0.83 ± 0.07 | 0.24 ± 0.05 | 0.471 ± 0.062 | 0.022 ± 0.034 | 0.0053 ± 0.0093 | 0.1054 ± 0.0234 | 0.0072 ± 0.0051 |
| 8 | Coal_Dom | 51.72 ± 2.59 | 7.81 ± 0.39 | 5.93 ± 0.44 | 0.29 ± 0.06 | 1.572 ± 0.136 | 0.022 ± 0.034 | 0.0137 ± 0.0099 | 0.0267 ± 0.0192 | 0.0073 ± 0.0052 |
| 9 | LPG_Hotel | 23.21 ± 1.16 | 2.82 ± 0.14 | 7.74 ± 0.63 | 0.25 ± 0.18 | 0.446 ± 0.139 | 0.056 ± 0.121 | 0.0488 ± 0.0350 | 0.3278 ± 0.0814 | 0.0258 ± 0.0185 |
| 10 | Kero_Hotel | 96.90 ± 4.85 | 52.68 ± 2.63 | 12.41 ± 0.98 | 0.32 ± 0.23 | 0.237 ± 0.210 | 0.282 ± 0.217 | 0.3148 ± 0.0743 | 0.2039 ± 0.1196 | 0.0444 ± 0.0319 |
| 11 | Wood_Hotel | 48.45 ± 2.42 | 8.00 ± 0.40 | 0.83 ± 0.07 | 0.24 ± 0.05 | 0.471 ± 0.062 | 0.022 ± 0.034 | 0.0053 ± 0.0093 | 0.1054 ± 0.0234 | 0.0072 ± 0.0051 |
| 12 | Coal_Hotel | 51.72 ± 2.59 | 7.81 ± 0.39 | 5.93 ± 0.44 | 0.29 ± 0.06 | 1.572 ± 0.136 | 0.022 ± 0.034 | 0.0137 ± 0.0099 | 0.0267 ± 0.0192 | 0.0073 ± 0.0052 |
| 13 | Wood_Bak | 48.45 ± 2.42 | 8.00 ± 0.40 | 0.83 ± 0.07 | 0.24 ± 0.05 | 0.471 ± 0.062 | 0.022 ± 0.034 | 0.0053 ± 0.0093 | 0.1054 ± 0.0234 | 0.0072 ± 0.0051 |
| 14 | Crmt_wood | 48.45 ± 2.42 | 8.00 ± 0.40 | 0.83 ± 0.07 | 0.24 ± 0.05 | 0.471 ± 0.062 | 0.022 ± 0.034 | 0.0053 ± 0.0093 | 0.1054 ± 0.0234 | 0.0072 ± 0.0051 |
| 15 | Waste_Inc | 76.04 ± 3.80 | 1.84 ± 0.09 | 0.37 ± 0.04 | 3.70 ± 0.28 | 2.946 ± 0.217 | 0.014 ± 0.013 | 0.0718 ± 0.0079 | 0.0101 ± 0.0073 | 0.0028 ± 0.0020 |
| 16 | SW_burning | 52.06 ± 2.25 | 1.44 ± 0.06 | 0.25 ± 0.02 | 0.01 ± 0.01 | 0.017 ± 0.006 | 0.001 ± 0.005 | 0.0020 ± 0.0014 | 0.0038 ± 0.0027 | 0.0010 ± 0.0007 |
| 17 | Construction | 8.79 ± 0.44 | 1.42 ± 0.07 | 3.21 ± 0.23 | 0.80 ± 0.06 | 0.043 ± 0.043 | 0.007 ± 0.007 | 0.0030 ± 0.0030 | 0.0059 ± 0.0059 | 0.0016 ± 0.0016 |
| 18 | Genset_K | 63.40 ± 3.17 | 0.74 ± 0.04 | 0.20 ± 0.02 | 0.28 ± 0.03 | 0.076 ± 0.017 | 0.008 ± 0.013 | 0.0052 ± 0.0037 | 0.0084 ± 0.0072 | 0.0028 ± 0.0020 |
| 19 | Genset_D | 16.49 ± 0.82 | 32.54 ± 1.63 | 2.65 ± 0.27 | 8.45 ± 0.73 | 0.135 ± 0.148 | 0.097 ± 0.149 | 0.4749 ± 0.0682 | 0.1475 ± 0.0852 | 0.0316 ± 0.0227 |
| 20 | PvdRd | 9.18 ± 0.46 | 2.81 ± 0.14 | 1.32 ± 0.10 | 0.01 ± 0.01 | 0.135 ± 0.009 | 0.013 ± 0.004 | 0.0016 ± 0.0011 | 0.0032 ± 0.0022 | 0.0080 ± 0.0009 |
| 21 | 2W-2S | 57.34 ± 4.64 | 3.10 ± 0.26 | 4.24 ± 0.51 | 0.86 ± 0.15 | 0.037 ± 0.010 | 0.000 ± 0.004 | 0.1919 ± 0.1919 | 0.0000 ± 0.0022 | NA[b] |
| 22 | 2W-4S | 43.22 ± 3.50 | 3.36 ± 0.28 | 2.67 ± 0.39 | 1.15 ± 0.13 | 0.105 ± 0.011 | 0.000 ± 0.005 | 0.8703 ± 0.0029 | 0.0000 ± 0.0025 | NA |
| 23 | 2W | 50.28 ± 4.11 | 3.23 ± 0.27 | 3.45 ± 0.45 | 1.00 ± 0.14 | 0.071 ± 0.011 | 0.000 ± 0.000 | 0.5311 ± 0.0027 | 0.0000 ± 0.0024 | NA |
| 24 | 3W_CNG | 43.73 ± 3.54 | 3.89 ± 0.32 | 2.14 ± 1.03 | 0.09 ± 0.35 | 0.013 ± 0.031 | 0.000 ± 0.013 | 0.0572 ± 0.0079 | 0.0000 ± 0.0069 | NA |
| 25 | LCV | 48.09 ± 3.90 | 23.95 ± 1.99 | 0.93 ± 0.07 | 0.24 ± 0.02 | 0.005 ± 0.001 | 0.001 ± 0.000 | 0.0123 ± 0.0003 | 0.0010 ± 0.0003 | NA |
| 26 | 4W_P | 49.61 ± 4.02 | 12.48 ± 1.04 | 5.26 ± 0.58 | 1.55 ± 0.21 | 0.053 ± 0.020 | 0.020 ± 0.008 | 0.4495 ± 0.0051 | 0.0165 ± 0.0044 | NA |
| 27 | 4W_D | 53.40 ± 4.33 | 18.49 ± 1.53 | 0.82 ± 0.06 | 0.16 ± 0.02 | 0.013 ± 0.001 | 0.001 ± 0.000 | 0.0001 ± 0.0003 | 0.0020 ± 0.0020 | NA |
| 28 | Truck_D | 50.42 ± 4.08 | 26.88 ± 2.23 | 2.91 ± 0.19 | 0.29 ± 0.03 | 0.011 ± 0.002 | 0.001 ± 0.001 | 0.0000 ± 0.0006 | 0.0005 ± 0.0005 | NA |
| 29 | Bus_D | 50.42 ± 4.08 | 26.88 ± 2.23 | 2.91 ± 0.19 | 0.29 ± 0.03 | 0.011 ± 0.002 | 0.001 ± 0.001 | 0.0000 ± 0.0006 | 0.0005 ± 0.0005 | NA |
| 30 | Bus_CNG | 29.57 ± 1.82 | 20.17 ± 1.24 | 8.33 ± 0.47 | 2.99 ± 0.19 | 0.025 ± 0.010 | 0.024 ± 0.004 | 0.0000 ± 0.0024 | 0.0000 ± 0.0021 | NA |

[a] Source Numbers 1 to 20 from Sethi and Patil (2008); Source Numbers 21 to 30 from ARAI (2009) and CPCB (2011).
[b] Information not available.

**Table 3.** Speciated $PM_{10}$ emission rates (kg/day) for Delhi in 2007.

| Source No.[a] | Source_ID | $PM_{10}$ | OC | EC | TC | $SO_4^{2-}$ | $NO_3^-$ | Pb | Ni | V | As | Hg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***I. Stationary and Area Sources[b]*** | | | | | | | | | | | | |
| *Power Plant Sources[b]* | | | | | | | | | | | | |
| 1 | PP_Coal | 25,290 | 2201.5 | 474.7 | 2676.2 | 362.7 | 1737.9 | 25.3 | 22.7 | 13.2 | 6.5 | 1.8 |
| 2 | PP_NG | 6 | 1.6 | 0.4 | 2.0 | 0.4 | 2.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum of Power Plant[c] | | **25,296** | **2203.1** | **475.2** | **2678.3** | **363.1** | **1740.3** | **25.3** | **22.8** | **13.2** | **6.5** | **1.8** |
| *Industrial Boiler Sources* | | | | | | | | | | | | |
| 3 | Ind_NG | 447 | 118.5 | 33.4 | 151.9 | 26.8 | 178.5 | 0.4 | 0.4 | 0.2 | 0.0 | 0.0 |
| 4 | Ind_FO | 1786 | 66.7 | 293.4 | 360.1 | 537.1 | 0.7 | 0.2 | 5.3 | 11.7 | 0.4 | 0.0 |
| Sum of Industrial Boilers[c] | | **2233** | **185.2** | **326.8** | **512.0** | **563.9** | **179.2** | **0.6** | **5.7** | **11.9** | **0.4** | **0.1** |
| *Domestic Cooking Sources[b]* | | | | | | | | | | | | |
| 5 | LPG_Dom | 660 | 153.2 | 18.6 | 171.8 | 51.1 | 1.7 | 2.9 | 0.4 | 0.3 | 2.2 | 0.2 |
| 6 | Kero_Dom | 100 | 96.9 | 52.7 | 149.6 | 12.4 | 0.3 | 0.2 | 0.3 | 0.3 | 0.2 | 0.0 |
| 7 | Wood_Dom | 10,610 | 5140.0 | 848.7 | 5988.7 | 88.0 | 25.7 | 50.0 | 2.4 | 0.6 | 11.2 | 0.8 |
| 8 | Coal_Dom | 230 | 119.0 | 18.0 | 136.9 | 13.6 | 0.7 | 3.6 | 0.1 | 0.0 | 0.1 | 0.0 |
| Sum of Domestic Cooking[c] | | **11,600** | **5509.1** | **937.9** | **6447.0** | **165.1** | **28.4** | **56.8** | **3.1** | **1.2** | **13.6** | **1.0** |
| *Commercial Cooking Sources[b]* | | | | | | | | | | | | |
| 9 | LPG_Hotel | 130 | 30.2 | 3.7 | 33.8 | 10.1 | 0.3 | 0.6 | 0.1 | 0.1 | 0.4 | 0.0 |
| 10 | Kero_Hotel | 1 | 1.4 | 0.7 | 2.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 11 | Wood_Hotel | 20 | 9.7 | 1.6 | 11.3 | 0.2 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 12 | Coal_Hotel | 0 | 0.1 | 0.0 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum of Commercial Cooking[c] | | **152** | **41.4** | **6.0** | **47.4** | **10.4** | **0.4** | **0.7** | **0.1** | **0.1** | **0.5** | **0.0** |
| *Individual Sources[b]* | | | | | | | | | | | | |
| **13** | **Wood_Bak[c]** | **120** | **58.1** | **9.6** | **67.7** | **1.0** | **0.3** | **0.6** | **0.0** | **0.0** | **0.1** | **0.0** |
| **14** | **Crmt_wood[c]** | **1300** | **629.8** | **104.0** | **733.8** | **10.8** | **3.2** | **6.1** | **0.3** | **0.1** | **1.4** | **0.1** |
| **15** | **Waste_Inc[c]** | **17** | **12.9** | **0.3** | **13.2** | **0.1** | **0.6** | **0.5** | **0.0** | **0.0** | **0.0** | **0.0** |
| **16** | **SW_burning[c]** | **1** | **0.7** | **0.0** | **0.7** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** | **0.0** |
| **17** | **Construction[c]** | **12,290** | **1080.7** | **174.9** | **1255.6** | **394.0** | **98.9** | **5.3** | **0.9** | **0.4** | **0.7** | **0.2** |
| *Generator Sources[b]* | | | | | | | | | | | | |
| 18 | Genset_K | 267 | 169.3 | 2.0 | 171.3 | 0.5 | 0.7 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| 19 | Genset_D | 267 | 44.0 | 86.9 | 130.9 | 7.1 | 22.6 | 0.4 | 0.3 | 1.3 | 0.4 | 0.1 |
| Sum of Generators[c] | | **534** | **213.3** | **88.9** | **302.2** | **7.6** | **23.3** | **0.6** | **0.3** | **1.3** | **0.4** | **0.1** |
| *Paved Road Source[b]* | | | | | | | | | | | | |
| **20** | **PvdRd[c]** | **77,275** | **7094.5** | **2173.1** | **9267.6** | **1016.8** | **6.9** | **104.6** | **9.9** | **1.2** | **2.5** | **6.1** |
| ***II. Vehicular Sources[b]*** | | | | | | | | | | | | |
| 21 | 2W-2S | 427 | 244.9 | 13.3 | 258.1 | 18.1 | 3.7 | 0.2 | 0.0 | 0.8 | 0.0 | 0.0 |
| 22 | 2W-4S | 650 | 280.9 | 21.8 | 302.8 | 17.4 | 7.5 | 0.7 | 0.0 | 5.7 | 0.0 | 0.0 |
| 23 | 2W | 1077 | 541.5 | 34.8 | 576.4 | 37.2 | 10.8 | 0.8 | 0.0 | 5.7 | 0.0 | 0.0 |
| 24 | 3W_CNG | 582 | 254.5 | 22.6 | 277.2 | 12.5 | 0.5 | 0.1 | 0.0 | 0.3 | 0.0 | 0.0 |
| 25 | LCV | 2677 | 1287.3 | 641.3 | 1928.6 | 24.9 | 6.4 | 0.1 | 0.0 | 0.3 | 0.0 | 0.0 |
| 26 | 4W_P | 165 | 81.9 | 20.6 | 102.4 | 8.7 | 2.6 | 0.1 | 0.0 | 0.7 | 0.0 | 0.0 |
| 27 | 4W_D | 145 | 77.4 | 26.8 | 104.2 | 1.2 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 28 | Truck_D | 4443 | 2240.1 | 1194.3 | 3434.5 | 129.5 | 13.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 |
| 29 | Bus_D | 601 | 303.0 | 161.6 | 464.6 | 17.5 | 1.8 | 0.1 | 0.0 | 0.0 | 0.0 | 0.0 |
| 30 | Bus_CNG | 10 | 3.0 | 2.0 | 5.0 | 0.8 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sum of Vehicles[c] | | **9700** | **4788.8** | **2104.0** | **6892.8** | **232.3** | **35.6** | **1.7** | **0.1** | **7.1** | **0.1** | **0.0** |
| | Total | 140,518[d] | 21,817.7 | 6400.7 | 28,218.4 | 2765.1 | 2117.0 | 202.6 | 43.2 | 36.6 | 26.2 | 9.4 |

[a] See Table 1 for source category descriptions.
[b] Italicized headers under Stationary and Area Sources indicate source sub-categories.
[c] Bold indicates the 12 primary source categories including sub-category summation and individual source categories.
[d] The difference between this (140 TPD) and the 147 TPD listed in Table E.1 of http://www.cpcb.nic.in/Delhi.pdf is due to the closure of the Indraprastha Power Plant in December 2007 and the exclusion of a few smaller sources (e.g., locomotive, dung cake, etc.).

liquified petroleum gas [LPG], kerosene, wood, and coal); commercial cooking; wood burning; crematoria (wood); waste incineration; open solid waste burning; construction activities (i.e., building and road construction); generators (i.e., diesel- and kerosene-fueled); paved road dust; and motor vehicles (i.e., two- to four-stroke engines for two-

wheelers, gasoline- and diesel-fueled passenger vehicles, commercial vehicles, and diesel- and CNG-fueled buses).

## RESULTS AND DISCUSSION

### *Emissions*

As shown in Table 3, out of 140 TPD of $PM_{10}$ emissions, carbon emissions (OC = 21.8 TPD, EC = 6.4 TPD) accounted for 20% of total $PM_{10}$, followed by primary (emitted directly as particles) $SO_4^{2-}$ (2.8 TPD) and $NO_3^-$ (2.1 TPD). Toxic metals accounted for a small fraction, which was dominated by Pb (203 kg/day), followed by Ni (43 kg/day), V (37 kg/day), As (26 kg/day), and Hg (9.4 kg/day).

Source attributions to daily $PM_{10}$ mass and chemical species among the 12 primary source categories are presented in Table 4. Paved road dust was the principal source of $PM_{10}$ (55%), OC (33%), EC (34%), $SO_4^{2-}$ (37%), Pb (52%) and Hg (65%). Power plants, including both coal- and natural gas-fired, were the largest source of primary $NO_3^-$ (82%), Ni (53%), and V (36%), the second largest contributors to Hg (19%) and As (25%), and the third largest source of Pb (13%). Industrial boilers, mainly burning heavy-duty diesel fuel oil, were the second largest source of $SO_4^{2-}$ (20%) and V (33%), and the third largest source of Ni (13%). Lead was phased out as a gasoline additive starting in 1992 (CPCB, 2010) and vehicles were a minor source of Pb emissions (< 1%). Paved road dust was the major contributor to Hg (65%) and Pb (52%) only because it was the major contributor to $PM_{10}$ (55%). This is also the case for OC, EC, and $SO_4^{2-}$. Table 2 shows that Pb only accounts for 0.135% of $PM_{10}$ in the paved road dust profile; two orders of magnitude lower than the Pb abundance (17.5%) found in secondary Pb smelter emissions (ARAI, 2009). The NEERI (2010) $PM_{10}$ inventory does not specifically identify emissions from unregistered secondary Pb smelting or re-processing of lead-acid batteries, a known source of Pb emissions in Delhi (Gupt, 2012).

Domestic cooking, mainly using wood fuel, was the largest emitter of As (52%) and the second largest emitter of Pb (28%), with abundant Hg (11%) emissions. Vehicle exhaust was also a major emitter of OC (22%), EC (33%), V (20%), and to a lesser extent, $SO_4^{2-}$ (8%) and $PM_{10}$ (7%). Aside from the missing sources in the inventory (Table 1) that inflate the percent species contribution (Table 4), uncertainties in the source sampling and chemical analyses also contribute to the deviations among distributions.

The ratio of ambient concentrations to source emissions (R) may be interpreted as a first-order comparative index to verify how well the inventory accounts for chemical species concentration (Fujita *et al.*, 1992; Brown, 2010). For primary sources, an R greater than unity suggests underestimation of source emissions in the inventory. Table 5 compares the annual average $PM_{10}$ and chemical concentrations at the 10 monitoring sites with daily source emission rates in 2007. India's annual NAAQS levels are also listed for comparison. The network-wide annual average $PM_{10}$ mass and chemical species concentrations exceeded the NAAQS by three- to twelve-fold.

Table 5 shows R = 2.9 for $PM_{10}$ mass, suggesting underestimation of emission rates in the inventory, which might be partially due to the uninventoried wind-blown dust emissions. By contrast, R for OC and EC are 1.0 and 0.6, respectively. High ratios for $SO_4^{2-}$ (9.8) and $NO_3^-$ (8.5) are expected, since these species are mostly secondary aerosol and may be formed during long-range pollution transport. R for trace elements is high, in the range of 2 to 9. In addition to missing sources for Pb (R = 9.2), the inventory is mainly based on fuel use rather than industrial processes, which can cause large uncertainties for trace element emission estimates. This can also explain moderately high ratios for Ni (2.1), V (1.9), and As (2.7). The elevated R for Hg (8.6) is anomalous. Mercury is present mainly as gaseous elemental Hg, while reactive gaseous Hg in coal combustion and other industrial emissions can enter the particle phase through atmospheric oxidation processes (Galbreath *et al.*, 1996; Amos *et al.*, 2012). Gas-to-particle

**Table 4.** Source contributions to daily $PM_{10}$ mass and chemical species in Delhi, India.

| Primary Source Category[a] | Source No.[b] | Percent of Total $PM_{10}$ Mass and Chemical Species Emissions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $PM_{10}$ | OC | EC | $SO_4^{2-}$ | $NO_3^-$ | Pb | Ni | V | As | Hg |
| Power Plants | 1–2 | 18.0 | 10.1 | 7.4 | 13.1 | 82.2 | 12.5 | 52.7 | 36.2 | 24.91 | 18.9 |
| Industrial Boilers | 3–4 | 1.6 | 0.8 | 5.1 | 20.4 | 8.5 | 0.3 | 13.3 | 32.7 | 1.64 | 0.6 |
| Domestic Cooking | 5–8 | 8.3 | 25.3 | 14.7 | 6.0 | 1.3 | 28.0 | 7.1 | 3.4 | 51.89 | 10.6 |
| Commercial Cooking | 9–12 | 0.1 | 0.2 | 0.1 | 0.4 | 0.0 | 0.3 | 0.2 | 0.2 | 1.72 | 0.4 |
| Wood_Bak | 13 | 0.1 | 0.3 | 0.1 | 0.0 | 0.0 | 0.3 | 0.1 | 0.0 | 0.48 | 0.1 |
| Crmt_wood | 14 | 0.9 | 2.9 | 1.6 | 0.4 | 0.1 | 3.0 | 0.7 | 0.2 | 5.22 | 1.0 |
| Waste_Inc | 15 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 | 0.2 | 0.0 | 0.0 | 0.01 | 0.0 |
| SW_burning | 16 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.00 | 0.0 |
| Construction | 17 | 8.7 | 5.0 | 2.7 | 14.2 | 4.7 | 2.6 | 2.1 | 1.0 | 2.75 | 2.1 |
| Generators | 18–19 | 0.4 | 1.0 | 1.4 | 0.3 | 1.1 | 0.3 | 0.7 | 3.5 | 1.51 | 1.0 |
| PvdRd | 20 | 55.0 | 32.5 | 34.0 | 36.8 | 0.3 | 51.6 | 22.9 | 3.3 | 9.57 | 65.4 |
| Vehicles | 21–30 | 6.9 | 21.9 | 32.9 | 8.4 | 1.7 | 0.8 | 0.3 | 19.5 | 0.31 | 0.0 |

[a] See Table 3 for the 12 primary source categories. Emission rates from source sub-category summations and individual source categories were normalized to the total emissions for $PM_{10}$ and chemical speciation to derive percent source contribution.

[b] See Table 1 for Source Number and description.

**Table 5.** Comparison between annual average ambient concentrations for the 10 monitoring sites and daily source emission rates for Delhi in 2007.

| Observable | India Annual Average NAAQS[a] ($\mu g/m^3$) | Annual Average Ambient Concentration[b] ($\mu g/m^3$) | Daily Source Emissions (tonnes/day [TPD]) | Ratio of Ambient Concentration/Source Emissions (R) |
|---|---|---|---|---|
| $PM_{10}$ | 60 | 412 | 140 | 2.9 |
| OC | NA[c] | 22.6 | 21.8 | 1.0 |
| EC | NA | 4.0 | 6.4 | 0.6 |
| $SO_4^{2-}$ | NA | 27.4 | 2.8 | 9.8 |
| $NO_3^-$ | NA | 17.8 | 2.1 | 8.5 |
| Pb | 0.5 | 1.84 | 0.20 | 9.2 |
| Ni | 0.02 | 0.091 | 0.043 | 2.1 |
| V | NA | 0.071 | 0.037 | 1.9 |
| As | 0.006 | 0.071 | 0.026 | 2.7 |
| Hg | NA | 0.081 | 0.0094 | 8.6 |

[a] National Ambient Air Quality Standards.
[b] Averages over three seasons, 20 days per season at the 10 $PM_{10}$ monitoring sites. Seasons are defined as: summer (May–June), post-monsoon (October–November), and winter (December–January).
[c] Information not available.

transformation of Hg is not accounted for in the $PM_{10}$ inventory.

Emission rates for vehicular sources in Table 3 were estimated for vehicle types/fuel types (e.g., diesel-fueled buses, trucks, and vehicles; CNG-fueled three-wheelers and buses; and gasoline-fueled two-wheelers and vehicles). Fig. 1 presents the contributions of diesel-, CNG-, and gasoline-fueled vehicles to $PM_{10}$ mass and chemical species within the vehicular source category. Diesel-fueled vehicles contributed nearly all of the vehicular EC (96%) and most of the $PM_{10}$ mass (81%), OC (82%), primary $SO_4^{2-}$ (75%), and Ni (71%). Heavy-duty diesel vehicles (i.e., mostly trucks, Source No. 28 in Table 3) were the largest emitters among on-road vehicles, contributing 47% of OC, 57% of EC, 56% of primary $SO_4^{2-}$, 37% of primary $NO_3^-$, 30% of Pb, and 35% of Ni emissions. Light commercial diesel vehicles (LCV, Source No. 25) contributed in the range of 10–30% of vehicular emissions.

Fig. 1 shows that gasoline-fueled vehicles contributed nearly all of the V (92%) and the majority of the Pb (54%). Within the vehicular source category, gasoline-fueled two-wheelers (about 65% of total vehicles) contributed ~80% to V and 48% to Pb emissions. None of the vehicular source profiles contain Hg (Table 2), thus, this source category does not contribute to Hg. The large contribution of two-wheeled four-stroke vehicles (2W-4S, Source No. 22) to V (~80%) seems incongruous. $PM_{10}$ V is typically enriched in emissions from residual or heavy-duty fuel oil (Olmez and Gordon, 1985). Yet, Table 2 indicates that the V content in the 2W-4S source profile is 0.87% of $PM_{10}$, the highest in any of the available source profiles for India.

Table 6 presents $PM_{10}$ source attributions for seven emission sources by fuel types (i.e., including vehicular categories but excluding road dust, construction, and non-fuel specific sources [i.e., open burning and waste incineration]) in the city-wide inventory. $PM_{10}$ mass emissions originated mainly from coal (53%) and wood (25%) combustion; OC from wood (43%) and diesel-fuel (29%) combustion; and EC from diesel fuel (56%) and wood (26%) combustion. While wood and coal combustion account for 62 and 31%, respectively, of Pb in the inventory, coal combustion dominates primary $SO_4^{2-}$ (46%), $NO_3^-$ (86%), V (38%), Ni (70%), and Hg (59%) emissions, despite the large apparent under-estimation of Hg emissions in the inventory. $PM_{10}$ As was emitted mainly by wood (55%) and coal (29%) combustion. Similar to the non-inventoried sources discussed above, specific sources of trace metals are not adequately accounted for.

***Comparison with Previous Work***

Large variations in PM emission estimates were found in past studies for Delhi (e.g., WHO-UNEP 1992; Bose, 1996; Garg *et al.*, 2001; Gurjar *et al.*, 2004; 2008; Sahu *et al.*, 2011). TSP emissions were estimated to be 58 TPD in 1990 (Sharma *et al.*, 2002), 317 TPD in 1990 (Bose, 1996), and 386 TPD in 1995 (Gurjar *et al.*, 2004). The two high estimates for TSP (i.e., Bose, 1996 and Gurjar *et al.*, 2004, respectively) are more than twice as large as the current estimate of 140 TPD for 2007 $PM_{10}$. This is reasonable considering that fugitive dust emissions are found in the largest particle size fractions. The vehicular emission factors in NEERI (2010) vary by vehicle age, but they are one to two orders of magnitude lower than those of Gurjar *et al.* (2004): 0.01–0.07 versus 0.5 g/km for motorcycles and 0.002–0.008 versus 0.5 g per kilometer (km) for gasoline-fueled vehicles. Emission factors for diesel-fueled buses are similar: 0.3–2 g/km from NEERI (2010) and 1.15 g/km from Gurjar *et al.* (2004).

The most recent $PM_{2.5}$ and $PM_{10}$ inventories for Delhi by Sahu *et al.* (2011) are compared with the 2007 $PM_{10}$ emission inventory (NEERI, 2010) in Table 7. $PM_{10}$ emission rates by Sahu *et al.* (2011) are higher (645 TPD) than the 140 TPD estimate in the NEERI (2010) inventory. One contributing factor is the size of the study area: 4550 $km^2$ (covering Delhi and surrounding sub-region) in Sahu *et al.* (2011) versus 1500 $km^2$ in NEERI (2010), which was

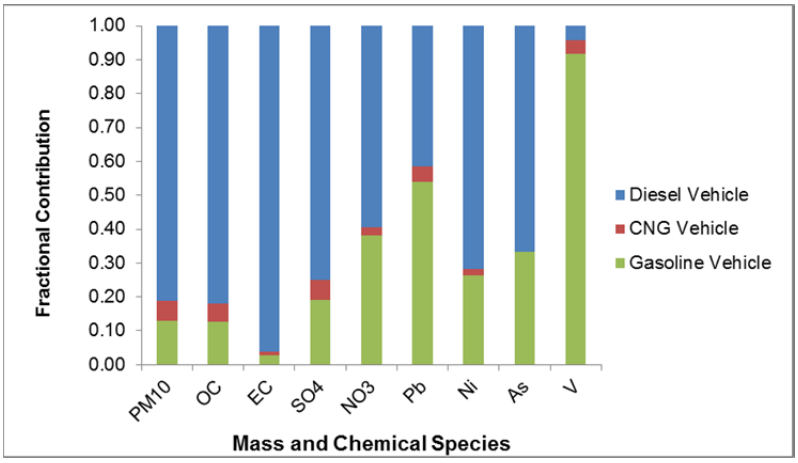


**Fig. 1.** Percent contributions of diesel-, compressed natural gas (CNG)-, and gasoline-fueled vehicles to $PM_{10}$ mass and chemical species within the vehicular source category (NEERI, 2010).

**Table 6.** Source contribution of various fuels to daily $PM_{10}$ mass and chemical species in the 2007 city-wide inventory for Delhi, India.

| Emission Source by Fuel Type[a] | Percent of Total $PM_{10}$ Mass and Chemical Species Emissions | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $PM_{10}$ | OC | EC | $SO_4^{2-}$ | $NO_3^-$ | Pb | Ni | V | As | Hg |
| LPG[b] | 1.65 | 1.35 | 0.59 | 7.5 | 0.10 | 3.8 | 1.36 | 1.09 | 11.2 | 6.7 |
| CNG[c] | 2.2 | 2.8 | 1.56 | 5.0 | 9.0 | 0.58 | 1.31 | 1.62 | 0.12 | 1.10 |
| Gasoline | 2.6 | 4.5 | 1.48 | 5.4 | 0.68 | 1.0 | 0.10 | 20 | 0.12 | 0.00 |
| Diesel | 15.1 | 29 | 56 | 22 | 2.2 | 1.23 | 17.5 | 37 | 3.8 | 3.7 |
| Kerosene | 0.21 | 1.98 | 1.47 | 1.61 | 0.05 | 0.48 | 0.95 | 0.94 | 0.91 | 1.72 |
| Coal | 53 | 17.1 | 13.1 | 46 | 86 | 31 | 70 | 38 | 29 | 59 |
| Wood | 25 | 43 | 26 | 12.2 | 1.45 | 62 | 8.3 | 1.79 | 55 | 28. |

[a] Excluding paved road dust, construction, and non-fuel-specific sources (i.e., waste incineration, open solid waste burning). See Table 3 for different fuel types used in each of the Source Numbers.
[b] Liquefied petroleum gas.
[c] Compressed natural gas.

**Table 7.** Comparison of PM emission rates between 2007 NEERI[a] (NEERI, 2010) and 2010 Sahu et al. (2011) emission inventories.

| | Inventory Year | | | | | |
|---|---|---|---|---|---|---|
| Base Year | 2010 | | 2010 | | 2007 | |
| Source Category[b] | Sahu *et al.* (2011) $PM_{2.5}$ | | Sahu *et al.* (2011) $PM_{10}$ | | NEERI (2010) $PM_{10}$ | |
| | Tonnes/day | Percent of Total Emissions | Tonnes/day | Percent of Total Emissions | Tonnes/day | Percent of Total Emissions |
| Power Plant | 7.9 | 1.4% | 30 | 4.6% | 25 | 18% |
| Industrial Boilers | 45 | 8.2% | 74 | 11.5% | 2.2 | 1.2% |
| Residential | 51 | 0.9% | 99 | 15.3% | 11.6 | 8.3% |
| Paved Road Dust | 360 | 66% | 360 | 56% | 77 | 55% |
| Vehicle | 83 | 15.2% | 82 | 12.7% | 9.7 | 6.9% |
| Total Emissions | 546 | | 645 | | 140 | |

[a] National Environmental Engineering Research Institute.
[b] For NEERI (2010) see Table 3 for details on Power Plants (Source Numbers 1 and 2), Industrial Boilers (Source Numbers 3 and 4), Paved Road Dust (Source Number 20), and Vehicle (Source Numbers 21–30) emission rates. Residential includes domestic cooking and heating sources (Source Numbers 5–8).

focused more on the city center. Nonetheless, Sahu *et al.* (2011) estimate $PM_{10}$ emissions over 8 times higher for vehicular and residential sources and over 30 times higher for industrial sources.

***Speciated Emission Inventory Uncertainties***

It is clear that PM emission inventories vary widely from study to study. Annual emission estimates depend on the representativeness of specified emission factors and activity

levels. There are no standards for estimating activity levels, and consistency must be established among independent studies and comparisons need to be made between measured ambient concentrations and those estimated from models in the inventories. Speciated PM emissions also depend on the representativeness of the chemical source profiles. Even in the most advanced air quality and source apportionment studies, source profiles are often non-representative or inaccurate (Watson *et al.*, 2008). This is evident for vehicular sources, emissions from which can represent a mixture from thousands if not millions of different vehicles. In the 2007 study, local source profiles were developed based on a limited number of tests (e.g., four post-2000 vintage diesel-fueled heavy-duty commercial vehicles [ARAI, 2009] and two coal-fired power plants [Sethi and Patil, 2008a]). Source profiles should be continuously improved upon with more vehicle tests under different driving conditions covering a broad range of fuels and engine types and ages (e.g., Wang *et al.*, 2012).

Although several area and vehicular source emission factors were specifically measured in India, with some in Delhi, the 2007 inventories (NEERI, 2010) rely heavily on U.S. AP-42 emission factors (U.S.EPA, 2006). Most of these emission factors result from laboratory testing of only a few individual emitters, whereas more real-world emission factors require measurements for the actual hardware, fuels, and operating conditions specific to the study region (Watson *et al.*, 2012). Domestic cooking activities in Delhi constitute another major uncertainty, as LPG is the dominant fuel near the city center, while greater amounts of wood and kerosene are used in the lower-income areas at the periphery of the city. Fugitive dust emissions are based on silt loadings, and this activity indicator is not considered accurate in North America for $PM_{10}$ or $PM_{2.5}$ size fractions (Watson *et al.*, 2000). As noted, uncertainties of emission inventories and source characterization should be evaluated. A weight-of-evidence approach (U.S. EPA, 2007) should be used to reconcile differences between source modeling and ambient measurements in future studies.

## CONCLUSIONS

Paved road dust, construction activities, power plants, domestic cooking and vehicles are the main sources of $PM_{10}$ in Delhi. Ground-level emissions of toxic species are the most significant sources in terms of exposure and impacts on human health. For the selected toxic metals, paved road dust and domestic cooking are the principal ground-level sources of $PM_{10}$ Pb, Ni, and Hg while vehicle exhaust is the main source of V. Residential wood combustion for cooking and heating is the dominant source of As.

Paved road dust dominates $PM_{10}$ emissions (55%) and is the main source of OC (33%) and EC (34%). Dust suppression should be an important component of air quality remediation efforts in Delhi. Vehicles are the next most important source of EC (33%). While conversion to cleaner fuels like CNG and movement towards a newer fleet will lower vehicle emissions, an efficient public transport system that minimizes the use of personal vehicles, especially two-wheelers, is the key to improving air quality in Delhi. This would also reduce traffic volume and, in turn, decrease re-suspension of road dust.

Efforts should be made to use natural gas for domestic cooking and to eliminate other cooking fuels (e.g., coal, kerosene, and wood). Estimated speciated $PM_{10}$ emissions need to be further refined by determining more representative source profiles for $PM_{10}$ from specific sources that emit toxic chemical species. It is also necessary to continue ambient measurements of $PM_{2.5}$, $PM_{10}$, and their major chemical components in order to establish a long-term database for evaluating the effectiveness of pollution control measures.

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