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Health impacts of particulate pollution in a megacity—Delhi, India

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ABSTRACT

In Delhi and its satellite cities, vehicle exhaust, industries, waste burning, and construction activities account for the bulk of the particulate (PM) pollution, which between 2008 and 2011, averaged $123 \pm 87\ \mu g/m^3$ for $PM_{2.5}$ and $208 \pm 137\ \mu g/m^3$ for PM_{10}, both exceeding the national annual ambient standards of 40 $\mu g/m^3$ and 60 $\mu g/m^3$, respectively.Amulti-sectoral emissions inventory for 2010 was modeled using the ATMoS dispersion model and local meteorology to estimate health impacts in terms of premature mortality and morbidity effects. For the observed PM levels in the city, the health impacts analysis estimates 7,350–16,200 premature deaths and 6.0 million asthma attacks per year. For six residential and industrial zones, we also modeled the sector contributions to ambient $PM_{2.5}$ ranging 16–34% for vehicle exhaust, 20–27% for diffused sources, 14–21% for industries, 3–16% diesel generator sets, and 4–17% brick kilns. Finally, we present some thoughts on technological, institutional, and behavioral interventions that might help the Government of Delhi to develop an action plan encompassing multiple sources and include interventions to reduce health impacts in the future years.

1. Introduction

The scientific evidence about the health effects of air pollution is compelling (HEI, 2004; Dominici et al., 2006; Jerrett et al., 2009; HEI, 2010a; Atkinson et al., 2011; Pope et al., 2011). The longer and more intense the exposure of people to air pollutants like particulate matter (PM), nitrogen oxides

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(NO_x), carbon dioxide (CO_2), and Ozone, the greater the impacts on their health, ranging from minor eye irritations, respiratory symptoms to decreased lung and heart function, hospitalization, and even premature death. Studies in India and in other countries, have consistently demonstrated higher rates of respiratory and cardiovascular disease in populations exposed to PM, NO_x, and Ozone pollution (Chhabra et al., 2001; Pande et al., 2002; Gupta et al., 2007; Siddique et al., 2010; Balakrishnan et al., 2011). The higher pollution levels have increased health risks as reflected by an increase in respiratory and cardiovascular ailments. The Directorate of Economics and Statistics (New Delhi, India) recorded between 2006 and 2009, an increase from 11.4% to 20.4% in certified deaths due to diseases in the cardiovascular systems, and an increase from 3.8% to 4.6% in certified deaths due to diseases in the respiratory systems; both of which have direct linkages to air pollution (DoES, 2010). Cropper et al. (1997) estimated based on the monitoring data, an excess of 1385 deaths and 51,400 life years lost per year for every 100 $\mu g/m^3$ of increase in total suspended PM concentrations for the 1990s. Apte et al., (2011) highlighted the risks of exposure to air pollutants on the roads of Delhi, which can be on average 1.5 times the ambient particulate matter levels.

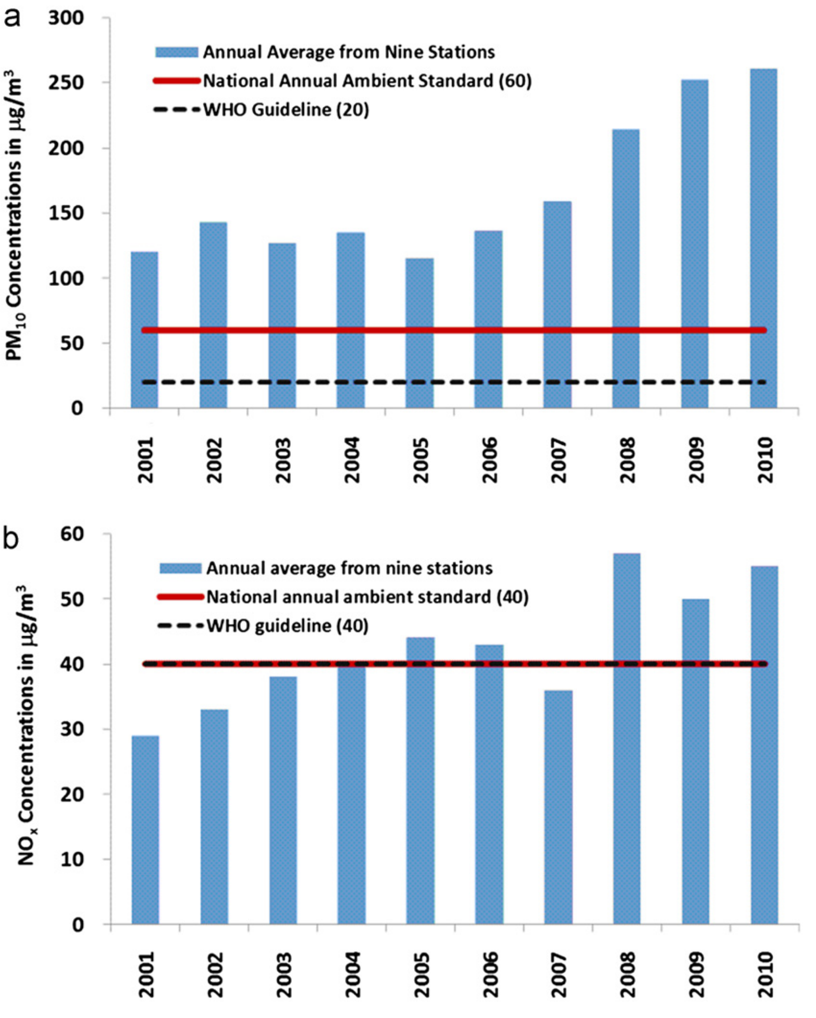

Fig. 1. Chronology of annual average ambient concentrations of PM_{10} from nine monitoring stations in Delhi.

WorldHealth Organization (WHO) studied publicly available air quality data from 1,100 cities and listed Delhi among the top 20 cities with the worst air pollution (WHO, 2011).

As India's capital, Delhi has grown across all sectors—industry, transport, and housing, all of which have contributed to an increase in city air pollution (Narain and Bell, 2006;Goswami and Baruah, 2008; Firdaus and Ahmad, 2011; Guttikunda and Gurjar, 2012; Sahu et al., 2011; Guttikunda, 2012). During a Parliamentary session in March, 2012, the Minister of State for Environment and Forests (Government of India) presented the annual averages from 2001 to 2010 for particulate matter (PM_{10} –with aerodynamic diameter $< 10\ \mu m$) measured at nine stations in Delhi (Rajya-Sabha, 2012) (Fig. 1). Since 2001, the annual average has risen more than 2.5 times. In 2010, PM_{10} averaged 260 $\mu g/m^3$, which is 4 times more than the national annual standard of 60 $\mu g/m^3$and 13 times more than the guideline stipulated by WHO (20 $\mu g/m^3$). For all the stations (Fig. 2), for the period of 2008 and 2011, measured $PM_{2.5}$ (with aerodynamic diameter $< 2.5\ \mu m$) concentrations averaged $123 \pm 87\ \mu g/m^3$ and PM_{10} concentrations averaged $208 \pm 137\ \mu g/m^3$. The variation is one standard deviation of daily average concentrations over the period. The national annual standard for $PM_{2.5}$ is 40 $\mu g/m^3$.

Pollution levels are worse in the winter months with concentrations at least double the annual averages, due to increased emissions from heating and unfavorable meteorological conditions for dispersion (Guttikunda and Gurjar, 2012). In December 2011, the daily average $PM_{2.5}$ was $267 \pm 105\ \mu g/m^3$ and PM_{10} was $368 \pm 116\ \mu g/m^3$ at four stations in Delhi.

Multiple sources contribute to the air pollution problem in Delhi, which requires a multi-prong approach to define and analyze policy measures. MoEF (1997) was the last official review of strategies for the air pollution control in Delhi and a second generation action plan is being considered in CSE (2012). The Minister also highlighted measures undertaken by the Government for regulating air pollution in the Delhi city: (a) the largest ever compressed natural gas (CNG) switch for public transport buses, three wheelers, and taxis (b) introduction of new CNG buses before the 2010 Commonwealth Games (c) introduction of the metro system covering 180 km over five lines and (d) introduction of Bharat-IV stage (equivalent of Euro-IV) fuel for Delhi and 16 other cities in India (Rajya-Sabha, 2012). While these initiatives helped improve air quality in the initial stages of the programs, their marginal benefits have fallen short over the years. The benefits of leapfrogging to alternative fuels is outdone by the increasing number of passenger vehicles on road (SIAM, 2012), lack of enough public transport buses (Pai, 2012), lack of maintenance programs for the trucks, buses, and roads (Badami, 2005), growing demand for electricity leading to diesel generator sets, booming construction activities, and industrial growth (SoE-Delhi, 2010).

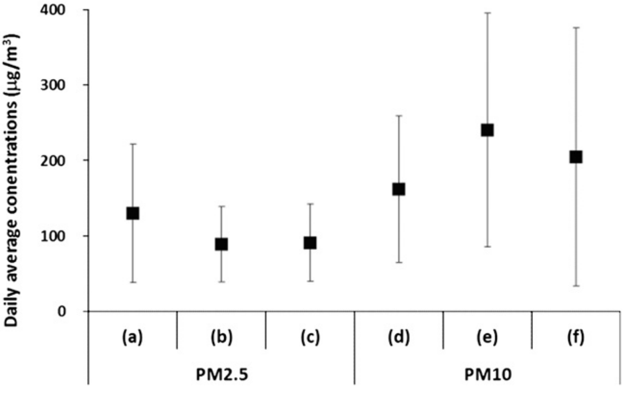

Fig. 2. Range of daily average particulate matter concentrations at monitoring stations near (a) Income Tax Office (traffic junction) (b) Mandir Marg (residential) (c) RK Puram (residential) (d) Netaji Subhash Institute of Technology (educational campus) (e) Institute Of Human Behavior And Allied Sciences (traffic junction) (f) Shadipur (industrial). Station locations are presented in Fig. 3.

In this paper, we present health impacts of particulate pollution modeled using a bottom-up emissions inventoryand dispersion modeling for year 2010 and a discussion on multi-sectoral options for particulate pollution management for reducing premature mortality and morbidity in the future years.

2. Methodology and inputs

2.1. Study domain

The city of Delhi and its satellite cities cover an area of 2,500 km^2. The study domain, presented in Fig. 3 covers Delhi and its satellite cities—Gurgaon, Noida, Greater Noida, Faridabad, and Ghaziabad, between 76.85°E and 77.65°E longitude and 28.2°N and 29.0°N latitude. Also in Fig. 3 are the two ring roads, main highways, brick kilns, power plants, and some points of interest.

2.2. Health impacts

The methodology utilized to estimate the health impacts in terms of mortality and morbidity was previously applied for similar studies—Ostro (2004) for global disease burden; Bell et al. (2006) for Santiago, Mexico city, and Sao Paulo; GAINS (2010) for Asia and Europe regional studies; Cropper et al. (2011) forpower plants pollution in India; World-Bank (2011) for Dhaka, Bangladesh; Guttikunda and Jawahar (2012) for six cities in India.

We estimate the health impacts, using the following equation

$$\delta E = \beta * \delta C * \delta P$$

where,

δE = number of estimated health effects (various end points for mortality and morbidity)
β = the concentration–response function, which is defined as the change in number cases per unit change in concentrations per capita

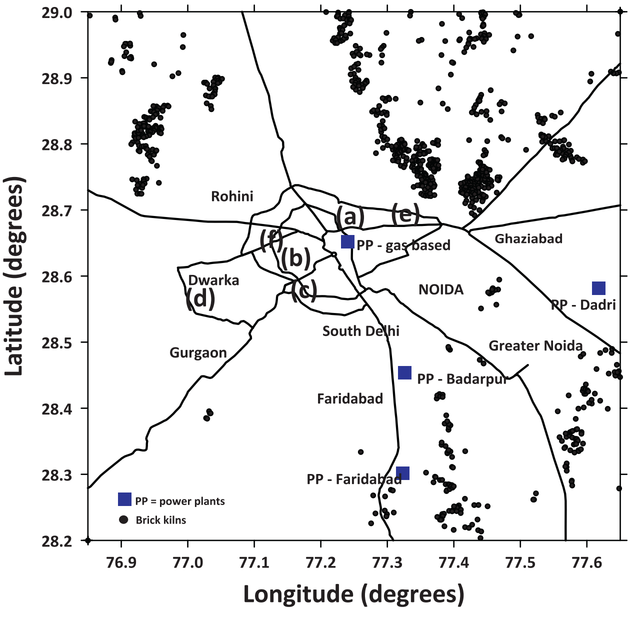

Fig. 3. Study domain over the national capital region of Delhi, along with location of ring roads, main highways, brick kiln clusters, major power plant.

δC=the change in concentrations, although, the World Health Organization claims that there is no threshold over which the health impacts are measured, in this paper, we considered the change in concentrations modeled above a threshold value 20 μg/m^3
δP=the population exposed to the incremental concentration δC, defined as the vulnerable population in each grid, of age less than 65 years.

2.2.1. *Concentration–response functions*

HEI (2004,2010), and Atkinson et al. (2011) summarizes the current scientific literature and epidemiological studies related to health impacts of outdoor air pollution. Wong et al. (2008) present results from epidemiological studies in Asia, including India, conducted under the public health and air pollution in Asia (PAPA) program.

In case of mortality, Atkinson et al. (2011) presents a meta-analysis of 115 epidemiological studies conducted around the world and the range of concentration–response function for PM_{10} pollution. An average increase in the mortality per 10 μg/m^3 change in ambient PM concentrations of all low and high estimates is 0.34% and 0.75% respectively. A combined analysis for the 4 cities in Asia, under the Public Health and Air Pollution in Asia (PAPA) program estimated an average of 0.55% increase in mortality per 10 μg/m^3 change in ambient PM_{10} concentrations (Wong et al., 2008), which is also an average of all the studies presented in Atkinson et al. (2011). We estimated the range of premature mortality using the low and high mortality rates.

A total death incidence rate of 241 per 1,000 people was utilized and adjusted for those due to lower and upper respiratory illnesses (including bronchitis and asthma) and cardio vascular diseases. Among the reported number of deaths, these account for 12.5% of the annual death rate in India (DoES, 2010).

We also estimate morbidity in terms of asthma cases, chronic bronchitis, hospital admissions, and work days lost. CRFs for mortality and morbidity are summarized in Table 1.The following assumptions are applied that (a) the concentration–response to changing air pollution among Delhi residents is similar to those of residents where the epidemiological studies were performed (b) the population baseline health status in Delhi is similar to those observed at the national level (CBHI, 2010) and (c) the public health status of people in the future years remain the same as in year 2010.

2.2.2. *Particulate concentrations*

We utilized the Atmospheric Transport Modeling System (ATMoS) dispersion model—a meso-scale forward trajectory Lagrangian Puff-transport model to estimate ambient PM concentrations (Caloriand Carmichael,1999). This model was utilized for similar pollution dispersion studies in India (Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013).

The spatial resolution of the model is 0.01° resolution for an area of 80 km × 80 km covering Delhi and its satellite cities. The vertical resolution is maintained in three layers—surface, mixing layer, and upper layer, reaching up to 6 km. The multiple layers allow the model to differentiate the

Table 1
Concentration–response functions (in effects per capita per μg/m^3 change in PM concentrations) for premature mortality and morbidity.

Health impact	Effects/capita (μg/m^3)
Premature mortality (low)	0.000010
Premature mortality (high)	0.000022
Adult chronic bronchitis	0.00004
Child acute bronchitis	0.000544
Respiratory hospital admission	0.000012
Cardiac hospital admission	0.000005
Emergency room visit	0.000235
Asthma attacks	0.0029
Restricted activity days	0.03828
Respiratory symptom days	0.183

contributions of near-ground diffused area sources, like transport and domestic combustion emissions and elevated sources like industrial, brick kilns, and power plant stacks. The model also includes first order chemical reactions for SO_2 and NO_x emissions to estimate the secondary contributions in the form of sulfates and nitrates, added to the total $PM_{2.5}$ concentrations. The model has flexible temporal resolution and can run for periods ranging from one month to a year.

As an input to the dispersion model, the emissions inventory for Delhi and its satellite cities was developed. A detailed review of the data resources and methodologies applied for building the inventory, improvements compared to the previous studies, gridding procedures to achieve a 1 km × 1 km spatial resolution and temporal allocation of emissions at 1-h resolution suitable for atmospheric dispersion modeling are presented in Guttikunda and Calori (2013). A summary of the total emissions for year 2010 is presented in Table 2, along with sector contributions. This is an update from the inventory presented in CPCB (2010) and Sahu et al. (2011) with further details on emissions from diesel generator sets and brick manufacturing industry.

The meteorological data for the city (3 dimensional wind, temperature, and pressure, as well as surface heat flux and precipitation fields) is derived from the National Center for Environmental Prediction global reanalysis (NCEP, 2012), interpolated on the model grid. The mixing height plays a critical role in dispersion of the emissions. A summary of the mixing heights is presented in Fig. 4. During the daytime, the mixing heights are as high as 2,500 m in the summer months compared to 800 m in the winter months.Mathematically, the concentration is defined as mass over volume. Assuming that the emissions are equally mixed in an urban environment, for the same emissions, a lower mixing height means higher ambient concentrations. In Delhi, a substantial difference in the meteorological conditions and relatively higher emissions from heating leads to aggravated pollution levels in the winter months.

Table 2
An activity based emissions inventory (tons/year) by sector for Delhi, India.

	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	VOC
Transport	10,850 (17%)	14,550 (13%)	700 (2%)	198,850 (53%)	256,200 (18%)	132,150 (51%)
Domestic	7,500 (12%)	8,950 (8%)	2,050 (6%)	2,900 (1%)	204,700 (14%)	17,250 (7%)
Diesel gen sets	3,750 (6%)	4,950 (4%)	1,250 (3%)	94,000 (25%)	98,450 (7%)	36,550 (14%)
Brick kilns	9,250 (15%)	12,400 (11%)	4,000 (11%)	6,750 (2%)	171,850 (12%)	24,200 (9%)
Industries	9,000 (14%)	12,650 (11%)	8,500 (23%)	41,500 (11%)	219,600 (15%)	13,250 (5%)
Construction	3,250 (5%)	10,750 (9%)	100 (1%)	2,850 (1%)	3,600 (1%)	50 (1%)
Waste burning	5,300 (8%)	7,550 (7%)	350 (1%)	2,000 (1%)	27,800 (2%)	2,250 (1%)
Road dust	3,850 (6%)	25,450 (22%)				
Power plant	10,150 (16%)	16,850 (15%)	20,250 (55%)	27,200 (7%)	442,150 (31%)	34,900 (13%)
Total	62,700	113,900	36,950	375,900	1,424,250	260,450

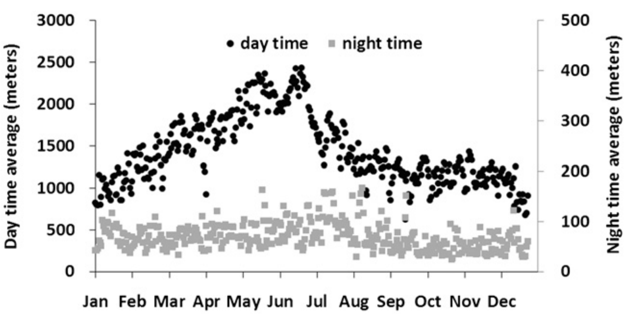

Fig. 4. Harmonic mean mixing layer height in Delhi, India.

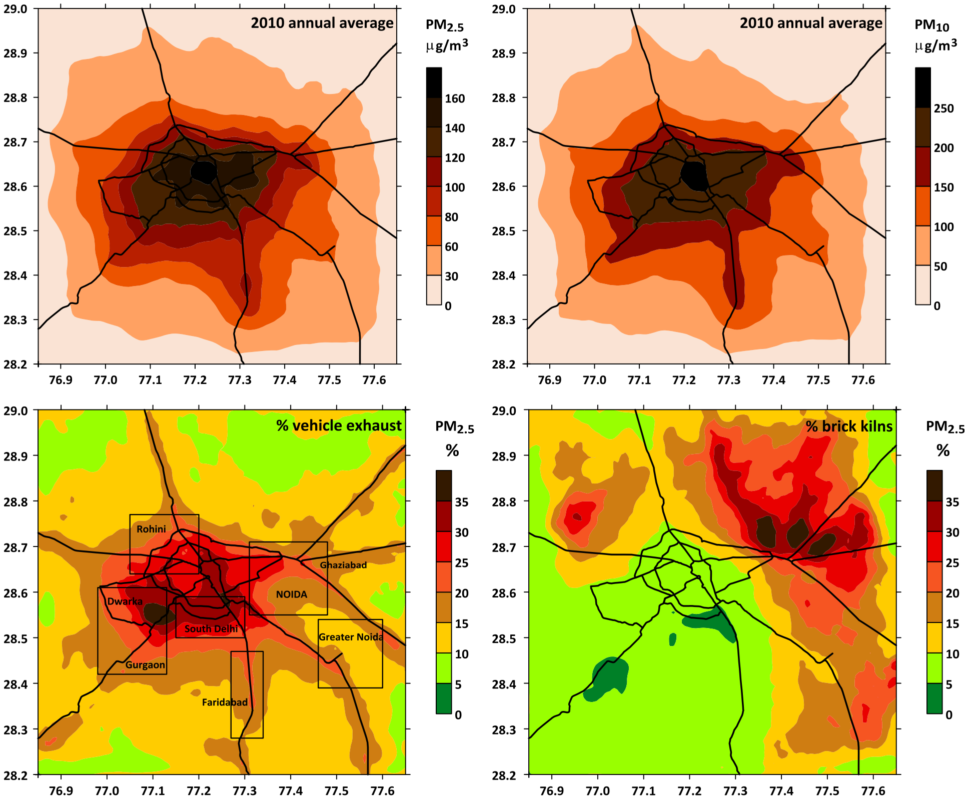

Fig. 5. Modeled annual average $PM_{2.5}$ and PM_{10} concentrations and percent contributions of vehicle exhaust and brick kiln emissions to modeled annual average $PM_{2.5}$ concentrations for year 2010 in Delhi, India .

The modeled annual average total PM_{10} and $PM_{2.5}$ concentrations for year 2010 are presented in Fig. 5. The validation of the modeled particulate concentrations with the data from monitoring stations across the city, are presented in Guttikunda and Calori (2013).

2.2.3. Gridded population data

The 1 km $\times$ 1 km grid level population is estimated using GRUMP (2010). Delhi and its satellite cities (Gurgaon, Noida, Ghaziabad, and Faridabad) cover an area of 2,500 km^2 and the region has grown rapidly over the past 20 years; in 1990, the total population stood at 8.4 million and in 2011 at 21.6 million (Census-India, 2012). For the population exposed (δP) to the incremental concentrations (δC), 55% of the grid population is considered vulnerable to chronic exposure to outdoor air pollution (HEI, 2010b).

3. Health impacts

The health impacts are calculated for the base year 2010, by overlaying the gridding population with the modeled $PM_{2.5}$ concentrations. Total premature mortality using the low and high average mortality rates in Delhi is estimated to range from 7,350 to 16,200 respectively. The mortality and morbidity results are summarized in Table 3. For the health impacts calculation we utilized only the total PM concentrations, which includes both primary PM contributions and secondary PM contributions from SO_2 in the sulfates and NO_x in the form of nitrates. This was necessary to avoid any double counting of effects, by adding the impacts of SO_2 and NO_x separately. We considered a

Table 3
Estimated health impacts per year in 2010.

Premature mortality	7,350–16,200
Adult chronic bronchitis	53,500
Child acute bronchitis	391,500
Respiratory hospital admission	24,700
Cardiac hospital admission	6,700
Emergency room visit	483,200
Asthma attacks	6.0 (million)
Restricted activity days	51.2 (million)
Respiratory symptom days	244.6 (million)

threshold value of 10 $\mu g/m^3$ for the impact analysis. However, WHO claims that there is no threshold over which the health impacts are measured.

Our estimates are comparable to the levels presented for other cities and regions. For example, World-Bank (2006a) estimated 15,000 premature deaths per year due to air pollution from transportation and brick kiln emissions in Dhaka, Bangladesh. Colbeck et al. (2009) reviewed air pollution in urban centers of Pakistan, estimating 21,000 premature deaths per year. Yim and Barrett (2012) concluded that fossil fuel combustion causes 13,000 premature deaths per year in the United Kingdom, while anadditional 6,000 deaths are caused by long-range transport of combustion emissions from the European Union. Guttikunda and Jawahar (2012) estimated an annual premature mortality due to PM_{10} pollution of 15,200 for six Indian cities—Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot, with a combined population of 32.5 million in 2010. The Health Effects Institute, estimated an annual mortality of 3,000 in Delhi due to on-road exposure, based on proximity of inhabitants along the major and arterial roads in the city (HEI, 2010b).

We present the estimated mortality as a range because of the uncertainties involved in the emissions and modeling exercises. Overall, the emissions inventory estimation and dispersion modeling has an uncertainty of $\pm$20–30%. Since, the inventory is based on bottom-up activity data in the city and secondary information on emission factors, mostly from the studies conducted in India, Asia, and global databases, it is difficult to accurately measure the uncertainty in our estimates. In the transport sector, the largest margin is in vehicle km traveled and vehicle age distribution with an uncertainty of $\pm$20% for passenger, public, and freight transport vehicles. The silt loading, responsible for road dust resuspension, has an uncertainty of $\pm$25%, owing to continuing domestic construction and road maintenance works. In the brick manufacturing sector, the production rates which we assumed constant per kiln, has an uncertainty of $\pm$20%. The data on fuel for cooking and heating in the domestic sector is based on national Census surveys with an uncertainty of $\pm$25%. Though lower in total emissions, open waste burning along the roads and at the landfills has the largest uncertainty of $\pm$50%. The fuel consumption data for the in-situ generator sets is obtained for random surveys to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of $\pm$30%. The fuel consumption data with the least uncertainty is from the power plants. The uncertainty in estimating and using the concentration–response functions is explained in Atkinson et al. (2011).

4. Implications

4.1. Sector contributions

CPCB (2010), based on receptor modeling approach,estimated the sector contributions to PM pollution in Delhi, which ranged from 9–21% for vehicle exhaust; 15–29% for road dust resuspension; 3–10% for domestic sources; 11–25% for garbage burning; 7–10% for industrial fumes; 22–24% for construction activities; and 7–13% for diesel generator sets. These results represent average estimates for filter samples from select monitoring sites in 2006. Collectively, due to representative nature of the sampling sites in the experiment, these results can be interpreted as city averages.

However, besides the receptor modeling studies, knowledge about the spatial spread of emissions and concentrations is crucial to assess sectoral contributions and their implication on health impacts.

Besides the total PM concentrations, we applied the ATMoS dispersion model at the sectoral level, where emissions from each sector are modeled independently and aggregated to obtain the percent contributions. In Fig. 5, we also present the percent contribution of emissions from vehicle exhaust and brick kilns. For the six designated zones, the average $PM_{2.5}$ concentrations and the average percent contribution from eight sectors (vehicle exhaust, road dust resuspension, industries, brick kilns, diffused, diesel generator sets, construction activities, and power plants) are presented in Table 4.

For the vehicle exhaust emissions, heavy duty and light duty trucks are the main culprit ($>50\%$ of the total presented in Table 2). Most of these, except for some light duty vehicles, operate on diesel. In the early 2000s, most of the light duty vehicles were retrofitted to operate on CNG, along with the public transport and 3-wheelers. For the $PM_{2.5}$ fraction, the contribution of road dust resuspension is the least. Most of the road and construction dust resuspension is accounted in the coarser fractions of PM_{10}.

The North-West, North-East parts, and the Greater Noida region are closest to the brick kiln clusters and experience high percentage of pollution from them. The black dots in Fig. 3 show the location of $\sim$1,000 kilns. These have a production capacity of 25,000 bricks per day, using a mix of coal and biomass for brick heating (Guttikunda, 2012). While the brick kiln clusters are limited to these pockets, due to their stack height and intensity of emissions, the effects are felt beyond their locations. For example, South Delhi (area covering the southern ring roads), with a population density of $\sim$10,000 people per km^2, is 30 km away from any of the clusters and yet experiences 5–10% of fine $PM_{2.5}$ pollution originating from them.

4.2. Opportunities for pollution management

In the face of rapidly growing economy and resulting increase in the vehicle ownership of individuals, measures introduced to reduce emissions from vehicle exhaust have lost their effectiveness over time. In order to achieve this reduction on a sustained basis, measures to increase share of non-motorized modes as well as public transportation need to be implemented. While short-trips are more likely to be catered to by walking and cycling, public transportation is most suitable for longer trips. The successful implementation of dedicated bus corridors in many cities around the world has paved way for planners to provide safe, efficient and reliable road-based public transportation. Cities like Bogota (Colombia) and Curitiba (Brazil) serve as model examples with bus modal share of 62% and 45% respectively, made possible due to dedicated bus lanes (LTA-Academy, 2011). While there are commuters in Indian cities who are captive users of public transportation because of their low-income (Tiwari, 2002), the challenge, however, lies in attracting commuters who have an alternative of a personal motorized vehicle. Among them, those likely to shift will be two-wheeler and second hand car owners, who are less sensitive to bus fare but highly sensitive to the service quality (CoST, 2002). The high income bus commuters are also less

Table 4
Average $\pm$ one standard deviation of $PM_{2.5}$ concentrations modeled and average percent contribution of the sectors in six designated zones in Delhi in 2010.

Zone	$PM_{2.5}$ ($\mu g/m^3$)	Average percent contribution of the sectors (%)							
		VEH	DST	DIFF	DGS	CON	IND	BK	PP
South Delhi	122 ± 10	30	6	20	16	4	14	5	5
Gurgaon+Dwarka	90 ± 20	24	5	22	16	8	18	4	3
North-West Rohini	93 ± 26	25	5	27	12	3	18	8	2
Noida+Ghaziabad	93 ± 23	22	5	21	9	6	16	16	5
Greater Noida	42 ± 10	18	6	24	3	8	16	17	8
Faridabad	77 ± 11	16	5	22	17	8	21	5	6

VEH=vehicle exhaust; DST=dust resuspension; DIFF=diffused sources, including cooking, heating, and open waste burning; DGS=diesel generator sets; CON=construction activities; IND=industrial activities; BK=brick kilns; PP=power plants.

likely to make more than two transfers and walk longer distance to and from the bus stops (Advani, 2007). For these commuters, the factors persuading to shift will be reduction in travel time from origin to destination, waiting time at bus stops, higher level of comfort, less crowded buses, and easier and safer access to bus stops, which are achievable using proper pricing and bus rapid transit systems. For achieving this, availability of cheap parking facilities (and in some cases free) is a deterrent. However, the trips by public transport could become more attractive if the location of parking places is so planned that they are as far as public transportation stops (Knoflacher, 2007).

For direct vehicle exhaust emissions, the largest margin of benefit is in the maintenance of the cars, buses, and trucks and maintenance of roads (World-Bank, 2004). Often the public transport buses are decommissioned or under repair due to poor regular maintenance, which leads to lesser number of buses to serve the passengers. Reynolds et al. (2011) tested emission rates for 3-wheelers in Delhi and identified fleet with a high fraction of poorly tuned or malfunctioning engines. In India, there is "pollution under check" (PUC) program, under which all private vehicles are required to undergo emission tests and receive an inspection certificate. The inspection certificate currently refers to a more formally structured and rigorous vehicle emissions inspection program, with stipulated norms by age group. All vehicles are required to possess this certification which shows compliance with the emission norms, but the PUC program does not supervise or guarantee vehicle maintenance. Fostering a system of regular and proper preventive vehicle maintenance among public and private vehicles, especially the gross polluters and vehicles older than 5 years, is an essential element in controlling the deterioration of the emission control equipment and thus reducing the emissions per vehicle km traveled.

Heavy duty truck emissions from diesel combustion account for 50% of the total transport emissions in the city (Table 2). A third ring road circling the Delhi Metropolitan Area is under construction and is expected to be operational before 2020, to reduce at least 50% of the through truck traffic in the city limits. Currently, heavy duty trucks are allowed to operate in the city limits only between 9:00 PM and 6:00 AM, which effectively reduces the day time exposure rates. The light duty trucks carry most of the distribution operations during the day time. A reduction in the movement of heavy duty trucks in the city limits will result in not only cutting the vehicle exhaust emissions, but also some dust resuspension on the roads.

Most of the electricity needs for Delhi are met by the six power plants (totaling 2700 MW) with a mixed share of 25% natural gas (for those closer to the city) and 75% by coal. However, in the satellite cities of Gurgaon, Noida, Faridabad, and Ghaziabad, this is supplemented using in-situ diesel generator sets. For example, big hotels, hospitals, institutions, cinema halls, malls, markets, and mobile phone towers are known to consume 5,000–30,000 l of diesel per month to counter the regular power cuts. The use of diesel generator sets is prevalent in most parts of the country. For example, the telecom industry has set up over 400,000 mobile phone towers in India, which require round-the-clock electricity. However, nearly 70% of those are situated in areas with inadequate power, which necessitates the use of diesel generators. The potential for large entities like mobile phone towers, hotels, hospitals, and institutions to shift from diesel based power generation to alternative renewable power is substantial (Green-Peace, 2011). Discounting the initial investments necessary for such a shift, the benefits for local air pollution will be immediate.

Between 1998 and 2003, following the Supreme Court orders, the coal and fuel oil based industries, including brick kilns, were relocated to the then city outskirts. This helped improve the air quality in Delhi in the early 2000s (Fig. 1) (Narain and Bell, 2006). Due to expansion of Delhi and its satellite cities resulting in a booming construction industry, the brick kilns are again contributing to the air pollution problem. Maithel et al. (2012) and World-Bank (2011) reported emission rates at four kiln types—traditional bull trench, emerging vertical shaft, zigzag, and Hoffman techniques. These studies also estimated at least 40% improvement in energy efficiency and emissions compared to the current bull trench kilns in practice. Given the nature of an unorganized form of this industry, we believe that the uncertainties in estimating the fuel consumption patterns, production cycles, and emission rates is unavoidable; yet it is important to raise the necessary scientific awareness on a booming sector. Any technology shift in burning of these clay bricks has to take into consideration the infrastructure needs, labor availability, and production cycle. Currently, most of the labor force is migrants, who work at the kilns in non-monsoonal months and in the agricultural sector during the monsoons.

The urban clusters of small-scale manufacturers, such as leather tanneries, textiles, smelters, and metalworking shops account for a large portion of the 6,000 industries in Delhi. These industries are mostly located in the North-West, North-East, Faridabad, and Gurgaon regions and use coal, coke, fuel oil, gas, and diesel. The Bureau of Energy Efficiency of the Ministry of Power designed the energy efficiency improvement program under the Perform, Achieve, and Trade (PAT) energy trading scheme aimed at large energy-intensive industries and facilities in nine sectors–cement, thermal power plants, fertilizers, aluminum, iron and steel, chlor-alkali, pulp and paper, textiles and railways(BEE, 2010). Any improvement in the energy consumption rates through proper implementation of the program will have a direct impact on the emissions and pollution.

There are three active landfills in Delhi with a combined processing capacity of 5,000 t per day. However, the total garbage generation is estimated at 9,000 t per day (SoE-Delhi, 2010). A portion of the garbage is regularly burnt in the residential areas, collection sites, roadside sites, and in some cases, at the landfill sites. There is considerable knowledge of best practices to improve the waste collection and management in India (World-Bank, 2006b). The basic problem has been in adapting these practices to specific local conditions. In Delhi, waste management is labor intensive and promises basic employment opportunities, which means we need a consolidated effort between the communities and management, to reduce the garbage burning emissions.

5. Summary

Air quality in Delhi, especially particulate pollution, has worsened from 2001 to 2010 and the sources of air pollution ranged from vehicle exhaust, industrial fumes, diesel generator sets, brick kilns, and waste burning. No single source or sector alone can reduce the current levels of PM_{10} and $PM_{2.5}$ concentrations below the regulatory standards of 60 $\mu g/m^3$ and 40 $\mu g/m^3$ respectively. For the current levels of PM pollution in the city, the health impacts analysis estimates 7,350–16,200 premature deaths and 6.0 million asthma attacks per year. The Government of Delhi needs to develop an action plan encompassing multiple sources and include technological, institutional, and behavioral interventions.

Not discussed in this paper are the potential combined benefits for health and climate, by controlling the climate precursors like CO_2 and black carbon from the same sources. Since anthropogenic climate change is largely driven by fossil fuel combustion, analysis of these emissions will provide further insight into the particulate pollution control strategies, with dual benefit in reducing health costs and limiting climate forcing impacts.

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