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Application of SIM-air modeling tools to assess air quality in Indian cities

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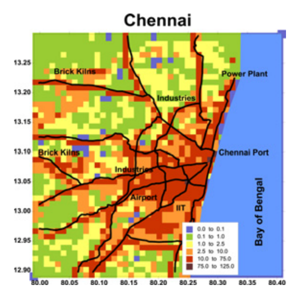
HIGHLIGHTS

► An overview of the SIM-air modeling system to assess urban air quality.
► A multi-pollutant emissions inventory for six cities in India.
► An analysis of sectoral contributions and health impacts of particulate pollution.
► A review of pollution control strategies and their implications.

GRAPHICAL ABSTRACT



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ABSTRACT

A prerequisite to an air quality management plan for a city is some idea of the main sources of pollution and their contributions for a city. This paper presents the results of an application of the SIM-air modeling tool in six Indian cities – Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot. Using existing and publicly available data, we put together a baseline of multi-pollutant emissions for each of the cities and then calculate concentrations, health impacts, and model alternative scenarios for 2020. The measured annual PM_{10} (particulate matter with aerodynamic diameter less than 10 micron meter) concentrations in μg m^{-3} averaged 94.7 ± 45.4 in Pune, 73.1 ± 33.7 in Chennai, 118.8 ± 44.3 in Indore, 94.0 ± 20.4 in Ahmedabad, 89.4 ± 12.1 in Surat, and 105.0 ± 25.6 in Rajkot, all exceeding the annual standard of 60 μg m^{-3}. The PM_{10} inventory in tons/year for the year 2010 of 38,400 in Pune, 50,200 in Chennai, 18,600 in Indore, 31,900 in Ahmedabad, 20,000 in Surat, and 14,000 in Rajkot, is further spatially segregated into 1 km grids and includes all known sources such as transport, road dust, residential, power plants, industries (including the brick kilns), waste burning, and diesel generator sets. We use the ATMoS chemical transport model to validate the emissions inventory and estimate an annual premature mortality due to particulate pollution of 15,200 for the year 2010 for the six cities. Of the estimated 21,400 premature deaths in the six cities in 2020, we estimate that implementation of the six interventions in the transport and brick kiln sectors, can potentially save 5870 lives (27%) annually and result in an annual reduction of 16.8 million tons of carbon dioxide emissions in the six cities.

1. Introduction

Urban air pollution is a complex issue, fueled by multiple sources ranging from – vehicle exhaust, on-road resuspended dust due to vehicles, industrial flumes, construction dust, garbage burning, domestic cooking and heating, and some seasonal sources such as agricultural field residue burning, dust

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storms and sea salt (for coastal areas) (Shah et al., 1997; Fenger, 1999; Molina and Molina, 2004; Schwela et al., 2006; Speizer et al., 2008; Parrish and Zhu, 2009; Johnson et al., 2011). Accelerating growth in the transport sector, a booming construction industry, and a growing industrial economy are increasingly responsible for worsening air quality in Indian cities (CPCB, 2010). While city and national authorities are introducing steps to control ambient pollution, a lack of coherent policy as well as unplanned growth across sectors is exacerbating pollution levels in most Indian cities.

Studies that measure health impacts of pollution are effective in raising concern about air quality in India and serve as a call to action (Chhabra et al., 2001; Pande et al., 2002; HEI, 2004, 2010b; Wong et al., 2008; Balakrishnan et al., 2011). However, these are not specific in terms of identifying sources and their relative contributions to ambient pollution levels, much less the impact of various control strategies for a given city. For Indian states and cities, there are a few integrated models that collate information at the regional level (Shah et al., 2000; Balakrishnan et al., 2007; GAINS, 2010) and there are receptor modeling studies which identified source contributions (Balachandran et al., 2000; Chowdhury et al., 2007; Srivastava and Jain, 2007a,b; Srivastava et al., 2009; CPCB, 2010).

Often, studies cite lack of relevant and/or reliable data, lack of modeling and assessment capabilities, which hinder an accurate assessment of urban air quality and its management (Shah et al., 1997; Schwela et al., 2006; Johnson et al., 2011). In this paper, we present an overview of the SIM-air modeling tool and its application in six Indian cities – Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot, to establish an information base of multi-pollutant emissions, dispersion modeling for ambient particulate concentrations, an analysis of interventions, and a review of information gaps, especially those necessary to support an effective urban air quality management plan.

2. City background

We have defined the study domains for the six cities such that they are large enough to cover the main district area, the nearest satellite cities, and locations with sources that could influence the air quality in the populated district areas. Table 1 presents a summary of the city domains, sizes, population, monitoring stations, range of ambient PM_{10} levels, vehicle fleet, power plants, and brick kilns in the vicinity of the city district. PM_{10} refers to the particulate matter (PM) with an aerodynamic diameter less than 10 micron meter. We present the geographical location of the cities in Fig. 1 and the city maps with features such as, main roads, highways, points of interest, brick kiln clusters, industrial estates, power plants (for three cities – Chennai, Ahmedabad, and Surat) and an approximate main district boundary are presented in Supplementary Figures S1–6. The large patches in the city maps of Chennai and Surat indicate the Bay of Bengal and the Arabian Sea respectively; and the smaller in-land patches in Pune, Chennai, Indore, and Rajkot indicate lakes and dams.

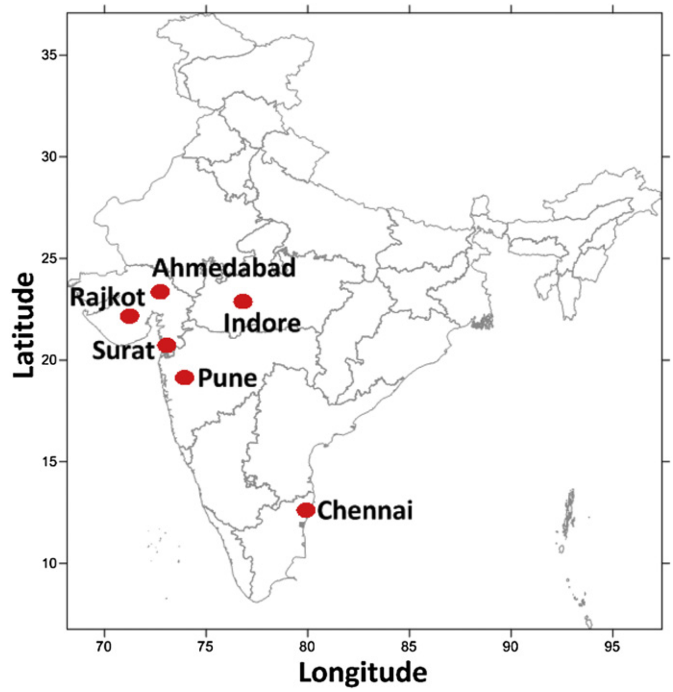

Fig. 1. Geographical layout of the six Indian cities in the study.

Table 1
Summary of the geographical layout, monitoring data and emission sources for year 2010 for the six Indian cities.

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
Study domain size (km × km)	32 × 32	44 × 44	32 × 32	44 × 44	44 × 44	24 × 24
Longitude (degrees)	73°48′E	80°16′E	75°32′E	72°35′E	72°50′E	70°47′E
Latitude (degrees)	18°28′N	13°52′N	22°25′N	23°02′N	21°10′N	22°18′N
Land–Sea breeze	NO	YES	NO	NO	YES	NO
Elevation (m)	560	7	550	53	13	134
Domain population (million)	6.5	8.5	3.3	7.8	5.0	1.4
City area (square km)	450	1200	134	700	105	310
Number of monitoring stations	5	6	3	6	3	2
Annual average PM_{10} ($\mu g\ m^{-3}$)	60–160	60–120	60–170	80–100	75–100	80–120
$PM_{2.5}$ measurements	Limited	Limited	NO	Limited	NO	NO
Vehicle fleet (millions)	2.3 (2008)	3.8 (2010)	1.2 (2010)	1.4 (2010)	1.3 (2007)	1.1 (2010)
Cars and Jeeps	323,400	565,350	127,300	213,500	132,750	126,700
2 Wheelers	1,708,100	2,986,600	907,000	1,038,000	1,063,000	878,000
3 Wheelers	66,500	55,400	14,000	65,500	65,400	8860
Buses + Stage carriers	15,100	15,600	35,200	5400	1900	79
HDV + LDV + Others	151,730	123,920	93,200	75,860	69,840	46,900
Power plants	NO	YES (2)	NO	YES (2)	YES	NO
Power plants (main fuel)	–	Coal	–	Coal	Gas	–
Brick kilns (number)	400	600	120	320	200	–
Brick kilns (type)	Clamp	Bull trench	Clamp	Clamp	Clamp	–

2.1. Pune (State: Maharashtra)

Pune city, formerly known as a university town, has over the years grown substantially and has a well-established manufacturing, glass, sugar, and forging industries and more recently the information technology and auto industry units. The Hinjewadi Information Technology Park (located west of the Pimpri Chinchwad satellite city) is a project started by Maharashtra Industrial Development Corporation. Similarly, under the special economic zone scheme Magarpatta city to the east has over 5000 households and 20,000 inhabitants. The black polygons to the northeast of the city map represent stone quarries, a source of construction material. These quarries cover an area more than 11 square km. The fugitive dust emissions from the quarrying process, use of diesel for power generation in the commercial and industrial sectors, and vehicle exhaust of heavy duty trucks moving in and out of the quarries, brick kiln clusters, and manufacturing industries are major sources of emissions, in addition to more traditional sources such as passenger cars, brick kilns, and waste burning.

2.2. Chennai (State: Tamilnadu)

With its proximity to the Bay of Bengal and thus access to markets in East Asia, Chennai is an important and busy port city. Apart from trade and shipping, the automobile industry, software services, medical care, and manufacturing, form the foundation of the economic base for Chennai. Manufacturers like Ford, Hyundai, Mitsubishi, Ashok Leyland, Massey Ferguson, Eicher, and other engineering and manufacturing units, have taken advantage of the proximity to the port, as well as skilled labor in the region, to establish manufacturing centers in Chennai, thus accounting for 30 percent of India's auto industry – Chennai has been dubbed the "Detroit of India" (CDP-JNNURM, 2012). The chemical, petrochemical and mineral industries have also set up base on the outskirts of Chennai. The Ennore port, the first major corporate port, which was originally built to handle oil, has now grown to handle various commodities. The major cargo includes coal (most of the supply is for the two power plants with dedicated feeder lines running from the ports), and iron ore. The current capacity of 15 million tons of cargo is expected to reach 30 million by 2012 and triple to 90 million tons by 2020; which is linked to road and rail transport, from and to the port, to most parts of South India.

2.3. Indore (State: Madhya Pradesh)

Indore city is the commercial center of Madhya Pradesh, 200 km from the capital of Bhopal. The city is well connected to other parts of the state through a network of national and state highways, because of which, it is fast emerging as an important transport and logistics hub in the country. The major highways passing through the city are national highway No. 3 (Agra to Bombay); national highway No. 59 (Indore to Ahmedabad); national highway No. 59A (Indore to Betul); state highway No. 27 (Indore to Burhanpur); and state highway No. 34 (Indore to Jhansi). The main economic activities in Indore are manufacturing and service industries (soybean processing, automobile, software, and pharmaceutical). Major industrial areas are in Pithampur special economic zone and the Sanwer industrial belt.

2.4. Ahmedabad (State: Gujarat)

Ahmedabad city is the 7th largest city in India and was the capital of Gujarat state in 1960–70s (thereafter the capital was shifted to Gandhi Nagar, 30 km north). The city is well connected to major cities like Mumbai, Pune, Vadodara, and Surat with seven major roadways, one expressway, and five rail networks. The Sabarmati River divides the city into the eastern and western regions. The eastern bank houses the old city and industries. As the population grew, the city expanded to the west, with newer construction, educational institutions, residential areas, shopping malls, and business districts clustered around arterial roads. The city was once known for its textile industry, with as many as 66 mills employing a workforce of over 100,000. The chemical and petrochemical industries have grown rapidly within its municipal limits of Naroda, Odhav, Vatwa, and Behrampura. These total about 5000 and employ more than 300,000 inhabitants.

2.5. Surat (State: Gujarat)

Surat city, lies between Ahmedabad and Mumbai on the river Tapi and like the city of Chennai, includes a busy port. The Hazira industrial estate, closer to the port, hosts a number of petrochemical and steel refining units and several well known corporations such as ONGC, Reliance, ESSAR, and Shell. The Gujarat Industrial Development Corporation has set up industrial estates in Pandesara, Khatodara, Udhana, Katargam, Sachin and Bhestan areas. Economically, Surat is known for its textile manufacturing (accounts for 40% of manmade fabric production and 33% of manmade fiber production), trade, diamond cutting and polishing industries (accounts for 75% of the country's total rough diamond cutting and polishing and 43% of diamond exports), and intricate textile works. A large number of small and medium sized industrial units (more than 42,000 units) account for about 15% of the small scale industrial units in Gujarat state (CDP-JNNURM, 2012).

2.6. Rajkot (State: Gujarat)

Rajkot city is the smallest of the six cities that are part of this study. It has a dry and arid climate, yet several agricultural goods are grown in the region. It has a large processing sector, especially for oils. There are 5 large and more than 25 small edible oil extraction mills for ground nut, sesame, castor, and cottonseed. Other industries such as foundries, machinery, engineering, and automobile components, gold and silver jewelry, are clustered around two main industrial estates of Aji and Bhaktinagar. Rajkot city hosts approximately 8000 agricultural and automotive industrial units.

3. SIM-air model

Every city has unique air quality challenges that require customized approaches to monitor and model pollution. Critical pollutants, sources, meteorology, geography, population distribution, history, institutions, and information base vary for every city. The cost of establishing a complex and detailed air quality model is time consuming and computationally challenging. A potential solution is thus to develop tools that are simple, yet customizable and provide a framework to organize and update critical data on air quality. As awareness grows and policy makers are convinced of the need for science-based analysis in an environment of poor information; they can use more resources to develop more complex tools as well as improve institutional capacity.

The SIM-air, "Simple Interactive Models for better AIR quality", family of tools have been developed to use the available information to support integrated urban air quality management. The modules are designed to estimate emissions and to simulate the interactions between emissions, pollution dispersion, impacts, and management options. These tools and supporting documentation are distributed for free. All the databases, calculations, and interfaces are maintained in spreadsheets for easy access. For the analysis of emissions inventory and health impacts, a database of emission factors and concentration-response functions are included in the tools, which can be adjusted with specific data from cities.

4. Analysis methods and inputs

4.1. Monitoring data

The Central Pollution Control Board (New Delhi, India) has a network of 400 stations in 130 cities across India, operated by the respective State boards that measure ambient levels of criteria pollutants such as PM_{10}, sulfur dioxide (SO_2), and nitrogen oxides (NO_x). A majority of these stations are operated manually using high volume samplers for PM_{10} and the data is collected 2–3 times per week. The range of monthly average PM_{10} concentrations measured in Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot is presented in Table 2. All six cities exceed the annual ambient standard of 60 μg m^{-3}. Of the six cities, only Pune, Chennai, and Ahmedabad measure $PM_{2.5}$ concentrations and even that data availability is limited. The annual ambient standard for $PM_{2.5}$ is 40 μg m^{-3}.

4.2. Emission inventories

We compiled an emissions inventory for the year 2010 based on fuel consumption data for transport, industrial, and domestic sectors. We used activity based emission factors to estimate the emissions inventory for PM, SO_2, NO_x, carbon monoxide (CO) and carbon dioxide (CO_2) (Schipper et al., 2000). The same method has been used for building similar regional and urban inventories published in Timilsina and Shrestha (2009) for Asia; Zhang et al. (2008) for Hangzhou, China; Kan et al. (2004) for Shanghai, China; Tung et al. (2011) for Hanoi, Vietnam; EEA (2002, 2010) for EU nations; Ramachandra and Shwetmala (2009) for States of India; Reddy and Venkataraman (2002), Garg et al. (2006), Singh et al. (2008) and Baidya and Borken-Kleefeld (2009) for India; Gurjar et al. (2004) and Mohan et al. (2007) for Delhi city in India, and recently, CPCB (2010) for Delhi, Mumbai, Pune, Bangalore, Kanpur, and Chennai cities in India for the base year 2006–07. For the activity based methodology we used

A = total activity, defined as travel kilometers for vehicle exhaust emissions or total energy consumed for the industries, power plants, and domestic sectors. Table 1 lists a summary of the activity data for the registered vehicles in the six cities, number of kilns, and power plants. For Pune and Chennai, vehicle registration data is obtained from the respective police departments; for Ahmedabad from their ministry of road transport; for Indore from the local pollution control department; and for the cities of Rajkot and Surat, data is collated from their respective CDP-JNNURM (2012) reports. The fuel consumption and stack information for the power plants in Chennai, Ahmedabad, and Surat was obtained from the Central Electricity Authority (New Delhi, India) and for the domestic sector from the Census-India (2001, 2011). The locations of the brick kilns, around the six cities were digitized using the visual images from Google Earth and physically verifying and surveying the location of some clusters.
F = emission factor, defined as the emitted mass per vehicle-km traveled (for transport) or emitted mass per unit of fuel burnt (for industries, power plant, domestic, or waste sectors). We utilized applicable emission factors for transport, industrial, and power sectors (Reddy and Venkataraman, 2002; Gurjar et al., 2004; SEI, 2006; USEPA, 2006; ARAI, 2007; DIESEL, 2008; EEA, 2009; CPCB, 2010; GAINS, 2010). For the domestic sector, we obtain activity based emissions factors for various fuels from Zhang et al. (1999), Bhattacharya et al. (2000), and GAINS (2010). The emission factors for brick kilns are obtained from GAINS (2010) and Maithel et al. (2012).

The average emission factors are included in the SIM-air program and available as an open-source information database. We acknowledge the uncertainties involved in the use of available emission factors instead of us calculating and/or measuring the emission factors for every activity, which is an expensive and time consuming process. As more information becomes available in terms of emission factors, we can refine the model inputs.

4.3. Spatial allocation of emissions

We maintain the emissions inventory on a GIS based platform to spatially segregate emissions for further use in atmospheric modeling. We subdivided the domains presented in Supplementary Figures S1–6 to 1 km × 1 km grids and used spatial proxies and methodology summarized in Fig. 2 to allocate the emissions for each sector to the grids.

For the population density maps, we used data from GRUMP (2010) at 30″ spatial resolution. We used GIS data interfaced with Google Earth, to map roads (including information on bus stops, bus depots, traffic signals, and landmarks), industries, brick kilns, hotels, hospitals, markets, malls, cinemas, apartment complexes, large institutions, and farm houses. For the transport

Table 2
Monitored monthly average PM_{10} concentrations in the six Indian cities for 2009–10.

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
January	156.9 ± 16.8	86.3 ± 44.8	151.5 ± 28.0	80.3 ± 12.1	92.1 ± 12.8	83.6 ± 20.0
February	143.5 ± 21.9	96.6 ± 38.1	151.9 ± 25.0	87.1 ± 9.7	93.5 ± 13.1	85.3 ± 18.1
March	116.8 ± 19.1	73.2 ± 23.4	149.5 ± 17.2	90.5 ± 10.7	97.7 ± 14.4	95.5 ± 25.6
April	94.9 ± 26.4	64.7 ± 17.3	129.3 ± 27.2	96.9 ± 22.2	93.4 ± 13.8	99.9 ± 12.1
May	71.9 ± 21.8	62.4 ± 21.4	120.3 ± 16.5	102.5 ± 21.7	97.1 ± 12.7	116.4 ± 32.1
June	48.4 ± 18.4	69.4 ± 37.6	66.2 ± 38.4	100.0 ± 18.8	97.9 ± 12.5	126.4 ± 42.3
July	43.6 ± 6.8	62.8 ± 26.1	67.6 ± 12.3	95.9 ± 18.2	79.1 ± 11.8	109.3 ± 42.7
August	41.2 ± 11.5	57.9 ± 12.6	75.2 ± 20.0	98.2 ± 22.1	82.9 ± 11.9	98.9 ± 24.6
September	49.1 ± 7.4	58.1 ± 17.0	83.9 ± 9.4	96.1 ± 14.3	85.3 ± 12.3	99.1 ± 27.5
October	85.3 ± 9.7	87.3 ± 13.4	146.6 ± 44.1	99.6 ± 16.4	98. ± 13.2	117.9 ± 32.5
November	86.4 ± 13.4	84.9 ± 67.8	103.5 ± 24.4	90.1 ± 21.0	86.8 ± 6.1	113.3 ± 31.8
December	139.6 ± 23.8	124.1 ± 18.7	180.5 ± 46.0	88.6 ± 26.1	80.8 ± 6.1	115. ± 32.9
Annual average	94.7 ± 45.4	73.1 ± 33.7	118.8 ± 44.3	94.0 ± 20.4	89.4 ± 12.1	105.0 ± 25.6
Annual standard	60.0	60.0	60.0	60.0	60.0	60.0

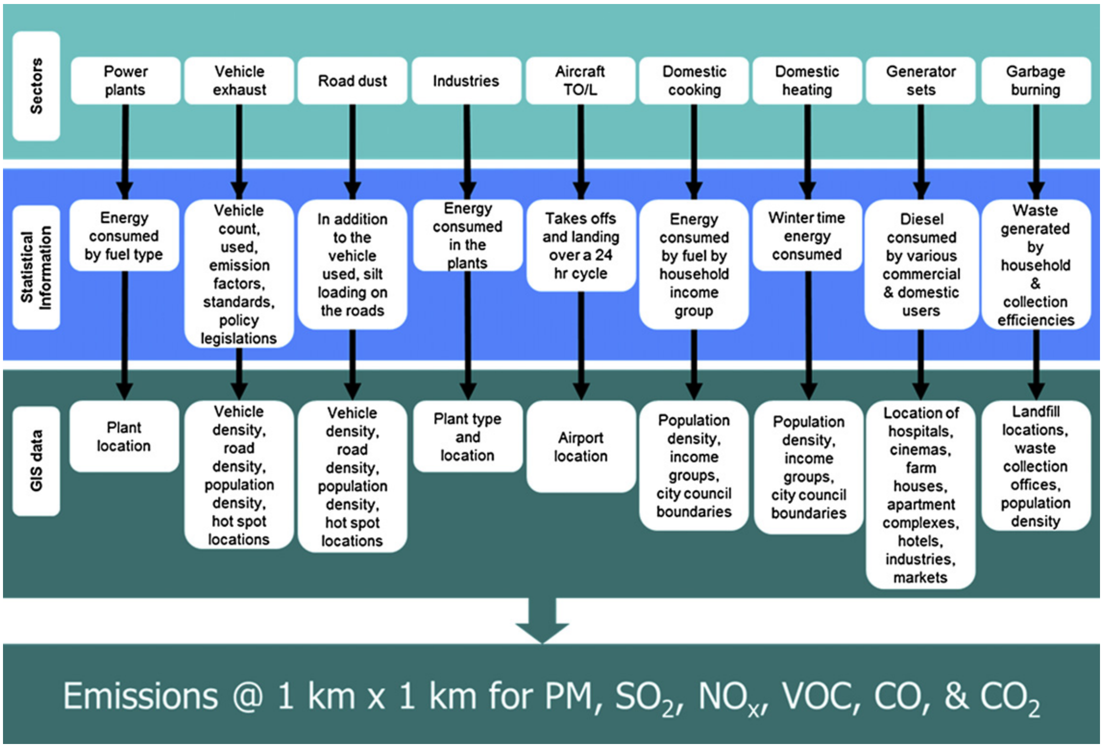

Fig. 2. Schematics utilized for spatial segregation of the total emissions to 1 km grids.

sector, we used grid based population density and vehicle density surveys conducted by Ministry of Road Transport and Highways (New Delhi) to distribute emissions on feeder, arterial and main roads.

Emissions from power plants, industries, and brick kilns were directly assigned to their respective locations. The scattered garbage burning emissions were distributed using population density information and location of the landfills.

4.4. Dispersion modeling

We used the Atmospheric Transport Modeling System (ATMoS) – a meso-scale three-layer forward trajectory Lagrangian Puff-transport dispersion model to estimate PM concentrations (Calori and Carmichael, 1999). This model was previously utilized in similar pollution management studies in Asia at a regional scale (Arndt et al., 1998; Streets et al., 2000; Guttikunda et al., 2001; Holloway et al., 2002; Carmichael et al., 2008) and urban scale (Guttikunda et al., 2003; Kan et al., 2004; Guttikunda and Gurjar, 2012). The ATMoS model is a modified version of the USA National Oceanic Atmospheric Administration, Branch Atmospheric Trajectory (BAT) model (Heffter, 1983). The layers include a surface layer, boundary layer (designated as the mixing layer height) and a top reservoir layer. The multiple layers allow the model to differentiate the 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 and spatial resolution and can run for periods ranging from one month to a year and from regional to urban scales.

The meteorological data for the dispersion modeling is derived from datasets distributed by the National Center for Environmental Prediction program (NCEP, 2012). A summary of wind speeds, wind direction, precipitation rates, and mixing heights is presented in the Supplementary Figures S7–9.

4.5. Health impacts

We estimate health impacts of baseline and future scenarios, using the methodology

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

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. This is established based on epidemiological studies conducted over a period of time, analyzing the trends in hospital records and air pollution monitoring. In case of mortality, this is set at 0.15% per 20 μg m^{-3} increase in the PM_{10} concentrations (HEI, 2010b; Wong et al., 2008) and using a death incidence rate of 241 per 1000 people for India (extracted from the database of World Health Organization, Guttikunda, 2008); 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, approximately 55% of the inhabitants (HEI, 2010a). The grid level population is estimated using GRUMP (2010) and Census-India (2011).

5. Results and discussion

5.1. Urban emission totals and sector contributions

A summary of the total emissions resulting for year 2010 for the six cities is presented in Table 3. We compiled an emissions

Table 3
Summary of the emissions inventory for PM_{10}, $PM_{2.5}$, SO_2, NO_x, CO, and CO_2 for the six Indian cities for year 2010.

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
PM_{10} (tons)	38,400	50,200	18,600	31,900	20,000	14,000
$PM_{2.5}$ (tons)	18,000	24,600	10,400	19,300	12,000	7800
SO_2 (tons)	4100	18,100	2800	15,100	3400	2200
NO_x (tons)	129,000	262,900	147,300	186,300	146,500	91,800
CO (tons)	472,400	1,000,200	276,500	207,000	372,000	237,000
CO_2 (million tons)	15.2	31.6	9.4	22.4	11.8	7.4

inventory for PM_{10}, $PM_{2.5}$, NO_x, SO_2, CO, and CO_2 for different sectors – vehicle exhaust, road dust, domestic solid fuel combustion (in the low income and high income groups), food kiosks, generator usage in multiple venues (such as hospitals, hotels, markets, and apartment complexes), industrial emissions including those from brick kilns and rock quarries, construction activities in the city, and waste burning along the roadside and at the landfills. The sector contributions to total PM_{10} emissions are presented in Fig. 3. Some interesting features from the emissions inventory:

- Among the fuel burning sources of PM, transport is the dominant source, in particular diesel based trucks
- Re-suspension of dust due to constant vehicular movement on the roads with percentages ranging from 24 to 46 percent for PM_{10} emissions inventory. The rate of re-suspension of road dust is higher for the trucks than the cars and the motorcycles (Kupiainen, 2007)
- All the cities, except for Rajkot are surrounded by brick kilns and their emissions contribute 6–15 percent of the emissions
- Among other sources, the use of diesel based generator sets at telecom towers, hotels, hospitals, institutions, apartment complexes, and markets; is a major contributor to PM and CO_2 emissions
- One source with the largest uncertainty is the waste burning. Due to lack of enough waste management programs, parts of the domestic waste is burnt along the roads and at the landfills, and is responsible for PM and other carcinogenic emissions.

Of the six cities, published emissions inventory exists for Pune and Chennai. CPCB (2010) estimated 32.3 tons PM_{10} per day, 41.4 tons per day of NOx, and 7.1 tons per day of SO2 for Pune city; and 11.02 tons PM_{10} per day, 12.1 tons per day of NOx, and 1.3 tons per day of SO2 for Chennai city. In CPCB (2010), low lying sources like road dust and vehicle exhaust were identified as major sources. Interestingly, among other sources, liquefied petroleum gas (LPG) was identified as a key contributor to $PM_{2.5}$ in residential areas, which no other studies have reported in the past (Pant and Harrison, 2012). The PM_{10} totals are lower than those presented in Table 3, due to methodological differences. The CPCB (2010) study

- reported the results for the base year of 2006–07 and represents only the sources in the main city district
- does not include the areas surrounding the main district where the industrial activity is generally higher than the in-district activities
- was conducted by primarily surveying and estimating emissions for an area of 2 km × 2 km around the monitoring site selected for the source apportionment and then extrapolated to the city district area.
- does not account for the brick kiln emissions, which are 20 km away from the city district boundaries of Pune and Chennai.

Thus in the final inventory as calculated by the CPCB, the modeled concentrations did not account for the long-range transport of emissions.

In our study, the domains selected are typically larger than the main district areas, surrounding satellite locations with significant industrial loads to account for the non-transport sector. For example, we have included, the satellite city of Pimpri Chinchwad for the Pune domain; the city of Gandhi Nagar for the Ahmedabad domain; and all the neighboring industrial estates with brick kiln clusters (at least 20–30 km away from main district area) for the Chennai domain.

5.2. Spatial distribution of emissions

All the emissions are spatially segregated into grids at 1 km resolution following the procedure presented in Fig. 2. The gridded vehicle exhaust PM_{10} emissions (in tons/year/square km) are presented in Fig. 4. The power plant, industrial, and brick kiln emissions are allocated directly to the location of the plants and are not shown in these figures. In case of vehicle exhaust, the highest density of emissions was observed along the major roads, due to

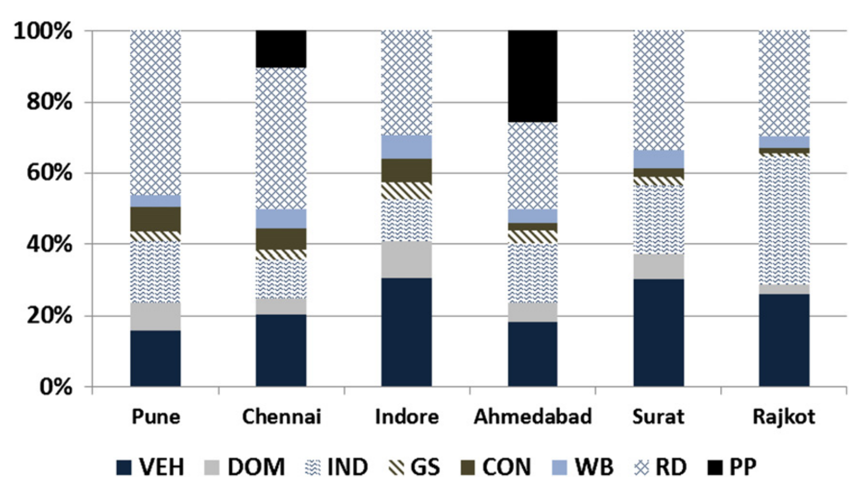

Fig. 3. Sectoral contributions to annual PM_{10} emissions in 2010 in the six Indian cities (VEH = vehicle exhaust; DOM = domestic cooking and heating; IND = industries, including brick kilns; GS = diesel generator sets; CON = construction activities; WB = waste burning; RD = road dust; and PP = power plants).

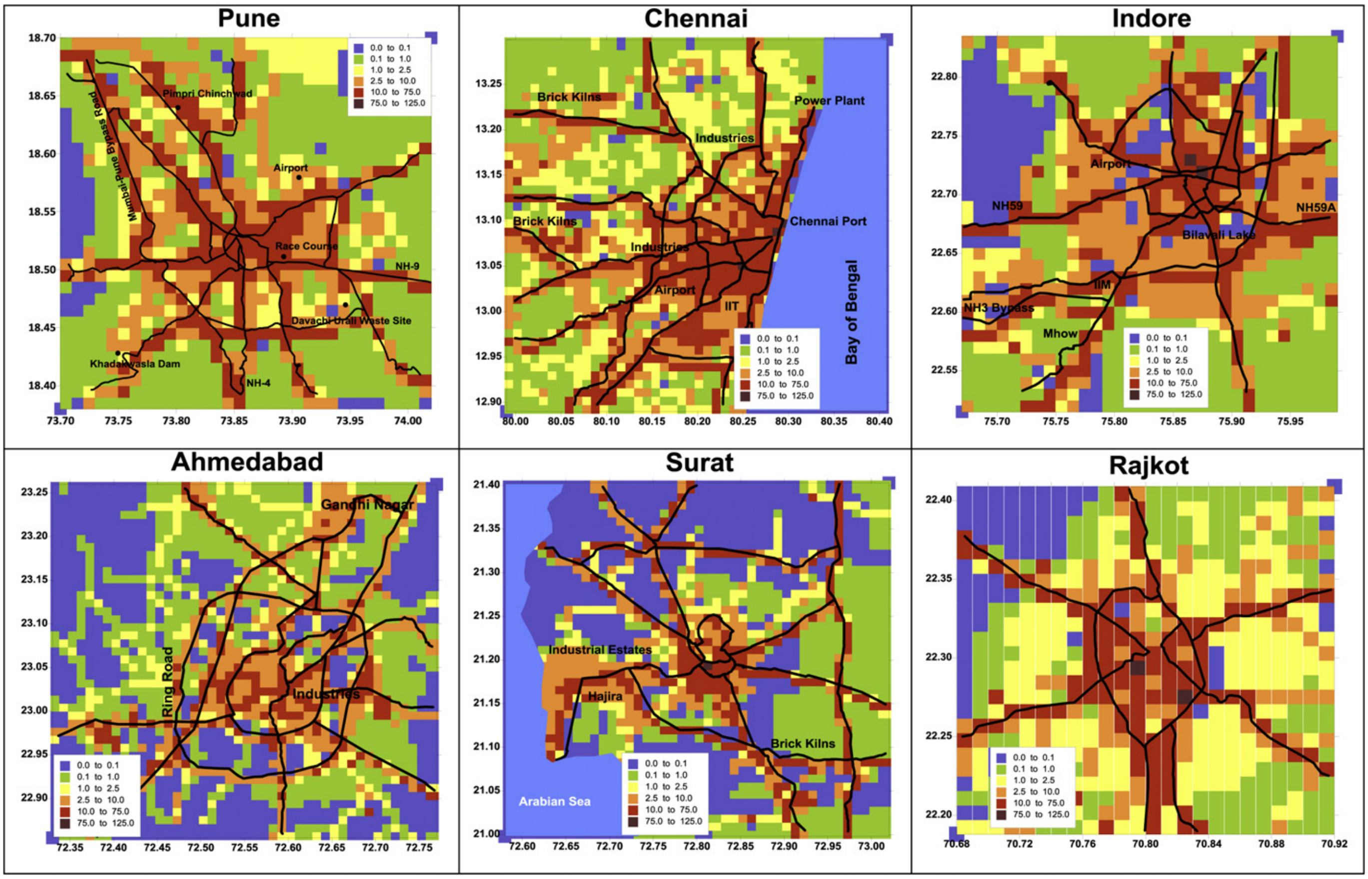

Fig. 4. Gridded vehicle exhaust PM_{10} emissions (units: tons/square km/year).

large heavy duty truck emissions, and the emissions inside the main district areas is linked to the density of the feeder roads in each grid. A combination of vehicle, road, industrial, and population density is used to assign weights for congestion emissions. For convenience, only vehicle exhaust of PM_{10} emissions is presented this paper. The gridded fields were also developed for $PM_{2.5}$, SO_2, NO_x, and CO, and for all sectors. Upon request, the gridded 2010 emissions fields for the cities are available as text files.

5.3. Modeled PM concentrations

We present the modeled annual average concentrations for PM_{10} in Fig. 5. We ran the dispersion model by sector and then aggregated to the total $PM_{2.5}$ and PM_{10} bins. These totals include primary PM and contributions from chemical transformation of SO_2 and NO_x emissions in the form of sulfates and nitrates (Guttikunda et al., 2001; Holloway et al., 2002). The effects of long-range transport from the regions outside the city modeling domain were estimated using the results from GAINS (2010) – formerly RAINS (Regional Air pollution Information and Simulation) model. The average background concentrations for the cities ranged from 5 to 10 $\mu g\ m^{-3}$ for annual average PM_{10}.

The land–sea breeze plays a vital role for two cities (Supplementary Figure S7). Chennai and Surat, both coastal, have large emissions from the industrial sector and yet experience the lowest concentrations (Table 2) relative to their geographical and population sizes (Table 1). These strong winds blowing away from the city, for the most part of the year, result in dispersing a significant amount of the pollution from the industries and the power plants located along the coast. The precipitation fields (Supplementary Figure S8) account for the wet deposition and entrainment of suspended particles; and thus reducing the ambient pollution levels naturally. The wet surface conditions also suppress re-suspension of road-dust, which is accounted in the dispersion model.

The mixing height plays a critical role in dispersion of the emissions. Typically, the winter months are more polluted than the summer months (Table 2) for two reasons – precipitation is higher during the summer monsoon and the mixing layer height is lower during 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. The summer time mixing heights are estimated as high as 2500 m during the daytime compared to the lows of less than 100 m in the winter months (Supplementary Figure S9).

The range of measured annual average PM_{10} concentrations and the range of modeled data for the central district area are presented in Table 4. For the measured data, it is the average and standard deviations for all the stations in each city and for the modeled data is the average of all grid cells covering the main district areas. The modeling results capture the quantitative ranges measured in each city. The differences in the ranges can be attributed to monitoring locations and sources around them, variations in spatial disaggregation of the emissions and concentrations to grids. For example, the limited number of stations in Indore, Surat, and Rajkot, are located closer to the industrial estates, which tend to measure higher concentrations for most part of the year. This is reflected in the large variation in the averages.

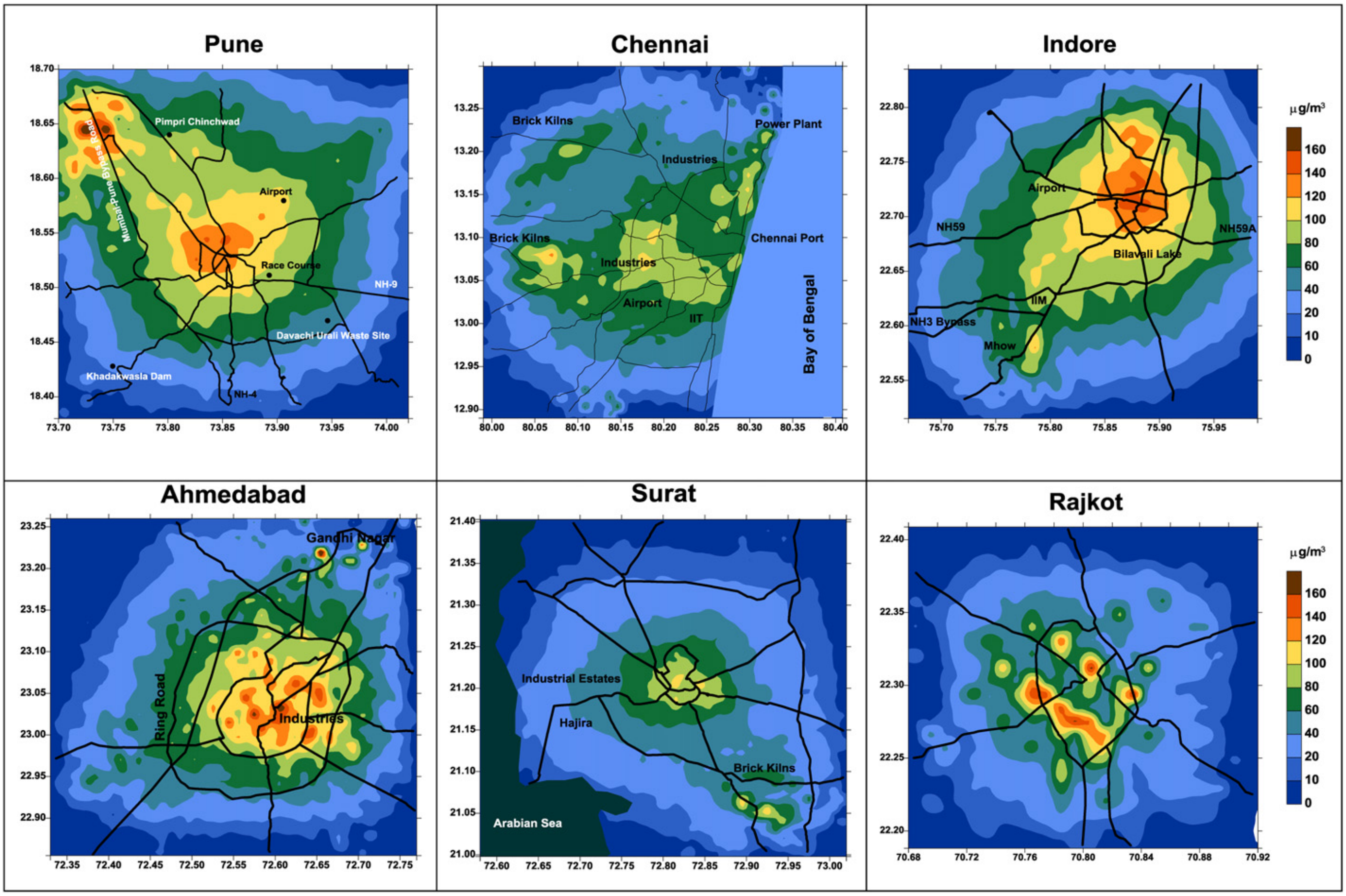

Fig. 5. Model estimated annual average PM_{10} concentrations ($\mu g\ m^{-3}$).

Most of the PM_{10} pollution is from the low lying sources, which tend to affect the immediate vicinity of the sources. This is particularly true for the sources like vehicle exhaust, road dust, garbage burning, and emissions from the diesel generator sets. In Chennai, unlike other cities, the brick kilns are designed with stacks of at least 50 m, which allow for the emissions to travel farther than the low lying sources. The four power plants (two in Chennai and two Ahmedabad) also contribute to the local pollution, but the contributions are lower compared to the transport and industrial activities, because their stacks are above 200 m which disperses most emissions to vicinities outside the cities.

5.4. Health impacts

In 2010, we estimated premature deaths of 3600 in Pune, 3950 in Chennai, 1800 in Indore, 4950 in Ahmedabad, 1250 in Surat, and 300 in Rajkot per year (a total of 15,200 per year), due to exposure to air pollution above the World Health Organization guidelines (Table 4). These levels are significant and comparable to the levels estimated elsewhere. For example, World-Bank (2006) 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 an additional 6000 deaths are caused by long-range transport of combustion emissions from the European Union.

We also include in Table 4, premature deaths per capita. This value is the lowest for the Rajkot, due to the small city size (24 km × 24 km) and a small population (1.8 million). Pune, Indore, and Ahmedabad, with similar values ranging from 0.54 to 0.63, are all in-land with similar mix of pollution sources. Chennai and Surat, have lower values (0.45 and 0.25 respectively), in spite of higher emissions from a large industrial estate, large population, and significant vehicle activity due to ports, due to land–sea breeze effects (Supplementary Figure S7). Surat has a lower value, due to significant landuse separation between the industrial estate and

Table 4
Comparison between the range of measured PM_{10} concentrations at multiple stations and the range modeled concentrations for the central district; and estimated health impacts for the year 2010 in the six Indian cities.

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
2009–10 Measured ($\mu g\ m^{-3}$)	94.7 ± 45.4	73.1 ± 33.7	118.8 ± 44.3	94.0 ± 20.4	89.4 ± 12.1	105.0 ± 25.6
2010 Modeled ($\mu g\ m^{-3}$)	90.8 ± 21.4	75.3 ± 13.4	98.0 ± 22.7	96.6 ± 24.7	70.2 ± 18.0	69.6 ± 37.4
2010 Premature deaths	3600	3950	1800	4950	1250	300
Deaths per 1000 inhabitants	0.55	0.46	0.54	0.63	0.25	0.21

Table 5
Estimated health impacts and benefits of select interventions in 2020 for the six Indian cities.

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
2020 PM_{10} emissions (baseline – tons/yr)	38,000	55,100	21,000	31,800	23,200	18,500
Estimated premature deaths	4300	6000	2500	7850	2050	670
PM_{10} emissions reduced under six interventions in 2020 (tons/yr)	13,900	17,400	6200	8800	8200	7900
% compared to 2020 baseline	37%	31%	30%	27%	35%	42%
Premature deaths saved	1700	1270	630	1390	590	290
CO_2 emissions reduced under six interventions (million tons/yr)	3.0	5.7	1.8	2.5	2.4	1.4

the residential zones; while in Chennai, the industrial zones are in the midst of the city (Supplementary Figures S2 and S5).

5.5. Scenario analysis for 2020

We extended the emissions, dispersion, and health impacts calculations to the year 2020, taking into account economic growth. In case of the transport sector, we extrapolated the passenger vehicles to 8%, motorcycles to 10%, and the remaining private sector vehicles like short buses and commercial vehicles to 1% (SIAM, 2012). We estimated that the industrial sector will grow at 10% and have taken population growth rate estimated from Census-India (2011). We also assume that emission standards will improve in the coming decade, including on-road conditions for vehicle movement, which will reduce deterioration rates and thus emission loads. Hence, while the total vehicle population is expected to increase, we expect that emissions will plateau. In 2020, the six cities account for an estimated 21,400 premature deaths per year due to exposure to air pollution. The estimated emission totals and the health impacts by city for 2020 baseline are presented in Table 5.

These estimates are subject to available data and are calculated to compare benefits of interventions to control air pollution in these cities. The kind of questions that can be answered following this analysis are (1) what interventions can reduce the health impacts associated with the pollution exposure (2) do the estimated health benefits warrant an immediate response to pollution control?

We present a summary of emission reductions and estimated health benefits in premature mortality for a combination of six interventions in Table 5. The six interventions are (a) promotion of non-motorized transport increasing its modal share by 20%, thus decreasing shares from cars and motorcycles, (b) increasing the modal share of public transport by 20%, thus decreasing shares from cars and motorcycles, (c) alternative fuels for buses and 3-wheelers, (d) reduction of silt loading on roads by 50%, (e) change in the brick manufacturing technology, improving the efficiencies by 50% and (f) plying trucks on a by-pass to reduce their emission loads on ambient concentrations. Of the estimated 21,400 premature deaths under the 2020 baseline, implementation of the six scenarios can potentially save 5870 lives (27%) annually and reduce 16.8 million tons of CO_2 emissions in the six cities. By intervention, the number of lives saved are as follows (a) 900, (b) 80, (c) 140, (d) 2790, (e) 1140 and (f) 820 respectively.

Note that for ease of calculations, the scenarios were treated as mutually independent activities, which may not be the case at the time of implementation. For example, the interventions designed to promote public transportation, are expected to invariably affect the non-motorized transport, especially the trips less than 2–3 km and thus effecting the emissions and pollution patterns.

In case of direct vehicle exhaust emissions, the largest margin of benefits for health and carbon emissions is in the maintenance of the truck fleet, maintenance of roads, reducing idling of traffic within the city limits. For the cities like Chennai and Surat with busy port activity, providing mass transport options for freight management and improving rail links thus reducing the in-city emissions due to truck movement could reduce pollution loads. Of the six transport and non-transport interventions analyzed in this study, one with consistent reductions in PM and CO_2 emissions is promotion of non-motorized transport.

While vehicle exhaust are a major source of air pollution in the cities, we should not neglect an additional indirect impact – re-suspension of dust due to constant vehicular movement, most often from heavy duty trucks carrying raw material and finished products from the construction sites and industries. The intervention to reduce road dust, targets only PM pollution and has no direct effect for CO_2 emissions. We highlight this intervention as a low-hanging fruit, as it has significant and immediate benefits for air quality in cities.

In all six cities, industries are within city limits in areas of high population density. Emissions from smelters, foundries and other industrial activity affect a large and dense population. Similarly, power plants within the city limits (in Chennai, Ahmedabad and Surat) need to have good emission control technologies. An improvement in energy efficiency for brick kilns, within and on the outskirts of cities, will reduce PM and CO_2 emissions. For this study, it was assumed that kiln clusters will eventually move to vertical shaft kiln technology or similar systems that provide higher benefits compared to the currently in-use clamp and bull trench kiln technology. Maithel et al. (2012) concluded that a shift from the current bull-trench style kilns to zigzag or vertical shaft technologies can yield 40–50 percent improvements in heat efficiency and total emissions.

As cities grow, the demand for electricity is being met by diesel generators especially by utilities (a few to tens of MW each) such as telecom towers, hospitals, hotels, markets, malls, apartments, and institutions. These distributed generator sets are very polluting and are an inefficient method of generating electricity.

An intervention not included in the analysis is waste management. Garbage burning along the roads, at collection centers and at the landfills is a growing contributor to ambient pollution and toxic carcinogens. A waste management policy that includes waste segregation, composting, recycling, and using incinerators could control emissions.

6. Conclusion

In this paper, we presented the benefits of six interventions for controlling air pollution, improving public health and reducing CO_2 emission. The interventions for 2020 were designed in a co-benefits framework which reflects on how air pollution and climate change strategies can be usefully brought together (Garg et al., 2006; GAPF, 2008; Shindell et al., 2012). The difficulties arise, in part, because policies with co-benefits have varying levels of impacts and therefore require coordination between stakeholders operating at different levels. For instance, climate negotiators are likely to be more interested in mitigating GHGs through international agreements and cap-and-trade schemes, while city officials are more inclined to reduce air pollution through local regulations and end-of-the-pipe controls. This kind of research could help clarify synergies and trade-offs between climate and air pollution goals and support the development of instruments that interact on multiple levels.

The SIM-air modeling tool has been used to make the best use of the available data. As the quality of the data improves, the emission inventory, spatial weights for gridding, and model can be improved accordingly. The emissions inventory and meteorological datasets presented in this paper are available upon request as MS Excel spreadsheets and GIS shapefiles.

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Appendix A. Supplementary material

Supplementary material associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.atmosenv.2012.08.074.

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