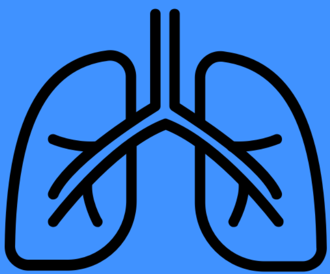
URBAN AIR POLLUTION & CO-BENEFITS ANALYSIS FOR INDIAN CITIES



+ C →

Pune
Chennai
Indore
Ahmedabad
Surat
Rajkot

URBAN emissions .info

Sarath Guttikunda

SIM-air working paper series # 39-2012

(UEinfo) was founded in 2007 with the vision to be a repository of information, research, and analysis related to air pollution. There is a need to scale-up research applications to the secondary and the tertiary cities which are following in the footsteps of the expanding mega-cities. Advances in information technology, open-data resources, and networking, offers a tremendous opportunity to establish such tools, to help city managers, regulators, academia, and citizen groups to develop a coordinated approach for integrated air quality management for a city.

UEinfo has four objectives: (1) sharing knowledge on air pollution (2) science-based air quality analysis (3) advocacy and awareness raising on air quality management and (4) building partnerships among local, national, and international airheads.

This report was conceptualized, drafted, and designed by the members of UEinfo.

All the working papers and more are accessible @ www.urbanemissions.info/publications

Send your questions and comments to simair@urbanemissions.info

Urban Air Pollution and Co-Benefits Analysis for Indian Cities

Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot

Synthesis Report

Sarath Guttikunda and Puja Jawahar
UrbanEmissions.info, New Delhi, India

Air pollution is a complex issue, fuelled by multiple sources ranging from – vehicle exhaust, resuspended dust on the roads due to vehicle movements, industrial flumes, construction debris, garbage burning, domestic cooking and heating, and some seasonal sources such as agricultural field residue burning, dust storms and sea salt (for coastal areas). While state and national authorities are taking necessary action and introducing interventions in varying capacities to curb these emissions and reduce ambient pollution levels, a lack of coherent policy as well as unplanned growth across sectors (construction, transport, industry) is hindering these efforts.

Figure 01: Location of the six cities

Accelerating growth in the transport sector, a booming construction industry, and a growing industrial sector are responsible for worsening air pollution in Indian cities. While estimates of health impacts are effective in raising overall concern about air quality, they do not specifically answer the question of where the pollution is coming from and how much each of these sources contributes towards air pollution. Further uncontrolled growth will lead to more pollution and require large recurring investments to control pollution. This study under ***the SIM-air program*** was initiated with support from the Climate Works Foundation (USA) and the Shakti Sustainable Energy Foundation (India) to better understand the sources of air pollution in six cities in India, to support an integrated dialogue between local pollution management and climate policy in a co-benefits framework. The six cities selected for this study are - Pune (Maharashtra); Chennai (Tamil Nadu); Indore (Madhya Pradesh); and Ahmedabad, Rajkot, and Surat (Gujarat).

The main objectives of this study, using local air pollution as the primary indicator in a co-benefits framework are

- To establish a baseline emissions inventory for the criteria pollutants PM, SO_2, and NO_x, and the greenhouse gas (CO_2) from the known sources of air pollution in these six cities
- To analyze pollution due to these emissions and associated health impacts, based on dispersion modeling for the selected city domain
- To analyze select interventions (from emissions and pollution perspective) for health benefits and GHG emission reductions
- To identify information gaps while building the emission inventories, which could further understanding of air pollution sources in these cities

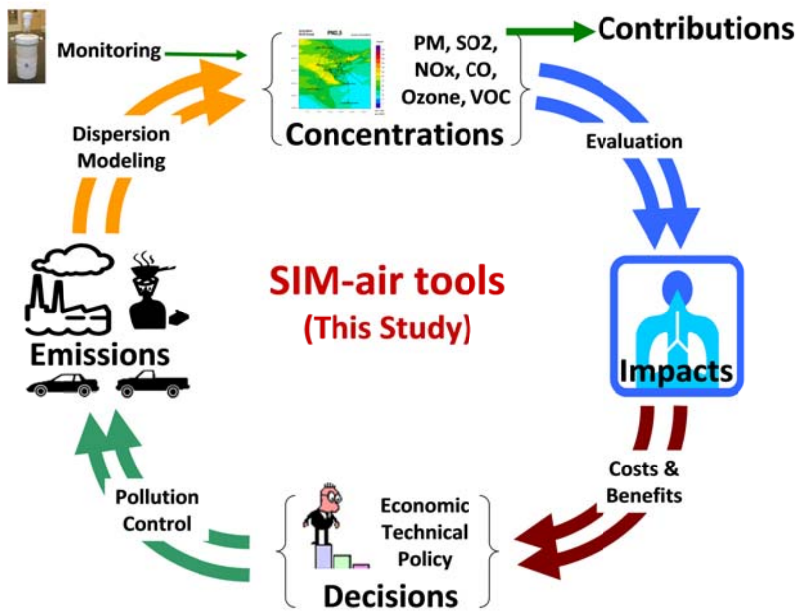
A summary of the study results is presented in **Table 01**.

Table 01: Summary of Air Pollution Analysis in Six Indian Cities

	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
Study domain size (km x km)	32 x 32	44 x 44	32 x 32	44 x 44	44 x 44	24 x 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 (meters)	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	1,200	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	NO	NO	NO
Vehicle Fleet (millions)	2.3 (2008)	3.8 (2010)	1.2 (2010)	1.4 (2010)	1.3 (2007)	1.1 (2010)
(numbers rounded) 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	8,860
Buses + Stage Carriers	15,100	15,600	35,200	5,400	1,900	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
Brick Kilns (number)	400	600	120	320	200	-
2010 PM_{10} emissions (tons/yr)	38,400	50,200	18,600	31,900	20,000	14,000
2010 $PM_{2.5}$ emissions (tons/yr)	18,000	24,600	10,400	19,300	12,000	7,800
2010 CO_2 emissions (mil tons/yr)	15.2	31.6	9.4	22.4	11.8	7.4
Estimated Premature Deaths	3,600	3,950	1,800	4,950	1,250	300
Mortality per ton of PM_{10}	0.1	0.07	0.1	0.14	0.06	0.02
Mortality costs (million USD)	151	165	75	207	52	13
Morbidity costs (million USD)	246	269	122	336	85	21
2020 PM_{10} emissions (tons/yr)	38,000	55,100	21,000	31,800	23,200	18,500
Estimated Premature Deaths	4,300	6,000	2,500	7,850	2,050	670
PM_{10} emissions reduced under six interventions (tons/yr)	13,900	17,400	6,200	8,800	8,200	7,900
% compared to 2020 baseline	37%	31%	30%	27%	35%	42%
Premature deaths saved	1,700	1,270	630	1,390	590	290
% compared to 2020 baseline	39%	21%	25%	18%	29%	42%
Mortality savings (million USD)	71	53	26	57	24	12
Morbidity savings (million USD)	114	87	44	94	40	20
CO_2 emissions reduced under six interventions (million tons/yr)	3.0	5.7	1.8	2.5	2.4	1.4

Integrated air quality management (AQM) is a challenge in developing countries because of the lack of information on sources of air pollution and insufficient ambient monitoring data in the public domain. While we understand these technical constraints, the objective of this study is *to establish an information base* and a methodology for the cities to follow in building emissions inventories, conduct an analysis of interventions utilizing available information, and identify information gaps for further studies, especially those necessary to support and implement an effective air quality management plan for a city.

Figure 02: SIM-air program schematics



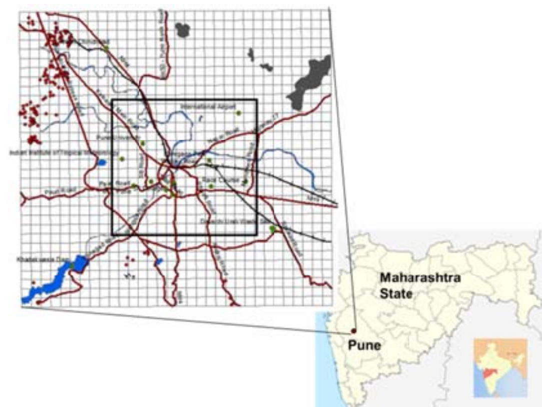
In this study, the integrated AQM in the six cities was conducted using the Simple Interactive Models for better air quality (SIM-air) program. The SIM-air program (**Figure 02**) is a family of open-source analytical tools to establish baseline emissions inventory, to conduct dispersion modeling, to assess the health impacts of air pollution, and to evaluate benefits of interventions to control pollution. The tools are designed in plug-n-play modules to estimate and supported by publicly available software (such as MS Excel) and Geographic Information Systems (GIS) data. Previous urban applications of these tools include Hyderabad and Delhi (India); Bangkok (Thailand); Lagos (Nigeria); Antananarivo (Madagascar); Shanghai and Shijiazhuang (China); Hanoi (Vietnam); Dhaka (Bangladesh); and Ulaanbaatar (Mongolia).

The evaluation of co-benefits in terms of mortality and morbidity (due to exposure to pollution levels) and concurrent reductions in greenhouse gas emissions for the select interventions (to support climate policy at global and national level) were evaluated for the baseline and control scenarios. The health impacts of air pollution are calculated using methodologies and dose response functions established through epidemiological studies.

Cities at a Glance

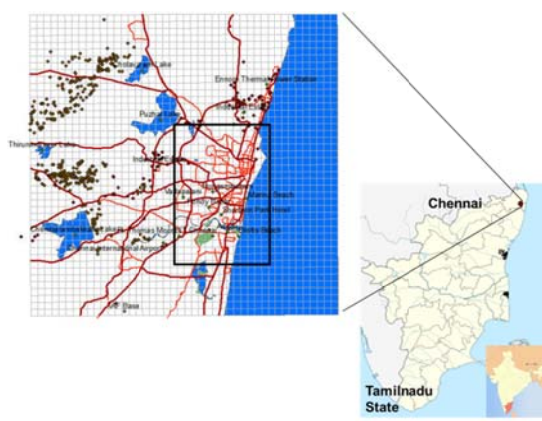
The study domains for each of the cities are selected to be large enough to cover the main district area, the nearest satellite cities, and cluster locations with sources that could influence the air quality in the main district areas. Each of the city maps, represent the main roads running through the city, including highways, points of interest, brick kiln clusters (red dots), industrial estates, power plants (for three cities – Chennai, Ahmedabad, and Surat) and the main city district boundaries. The big blue patches in the city maps of Chennai and Surat indicate the Bay of Bengal and the Arabian Sea; and the smaller in-land blue patches in Pune, Chennai, Indore, and Rajkot indicate lakes and dams.

Figure 03: Pune modeling domain



Pune is known for several universities and educational institutions. It also has a well-established manufacturing, glass, sugar, and forging industries since the 1950-60s. Recently, the information technology (IT) and the auto industry have grown substantially. The Hinjawadi IT Park (officially called the Rajeev Gandhi IT Park) (located west of the Pimpri Chinchwad city is a project started by Maharashtra Industrial Development Corporation. Similar IT parks constructed under the special economic zone (SEZ) schemes include the Magarpatta city to the east with ~5,000 households residing in the area. The black polygons in the city map of Pune represent the quarries, a primary source of construction material for the city covering an area of 11 square km, a significant emissions source of fugitive dust emissions from the manufacturing processes, use of diesel in the in-situ power generator sets, and the vehicle exhaust from the trucks moving in and out of the quarries; and the red dots indicate the brick kilns.

Figure 04: Chennai modeling domain



Chennai is the most commercial of the six cities. With its proximity to the Bay of Bengal and access to the markets in East Asia, the city has emerged as an important port. Apart from trade and shipping, the automobile industry, software services, medical care, and manufacturing form the foundation of the economic base for Chennai. In particular, the auto industry for domestic use and export purposes has established itself around Chennai – thus giving it the label of "Detroit of India". Manufacturers like Ford, Hyundai, HM-Mitsubishi, Ashok Leyland, TAFE, etc., have taken advantage of the proximity to the port, engineering and manufacturing industry as well as the skilled labor to establish themselves to the extent that the city accounts for ~30 percent of India's auto industry. For example, Nissan indicated that exports are expected to reach 110,000 units in 2011. Similarly, the chemical, petrochemical and mineral industries have also established themselves in the outskirts of Chennai.

The Ennore Port, the first corporate major port, which was originally started for handling only oil, had now grown into one handling 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), oil, 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.

Indore 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 national highways passing through the city are National Highway No. 3 (NH3 - Agra Bombay); National Highway No. 59 (NH 59 - Indore Ahmedabad); National Highway No. 59A (Indore - Betul); State Highway No. 27 (Indore to Burhanpur); and State Highway No. 34 (Indore to Jhansi). The main economic activities in Indore are manufacturing & service industries (soybean processing, automobile, software, and pharmaceutical). Major industrial areas surrounding the city include the Pithampur special economic zone and the Sanwer industrial belt.

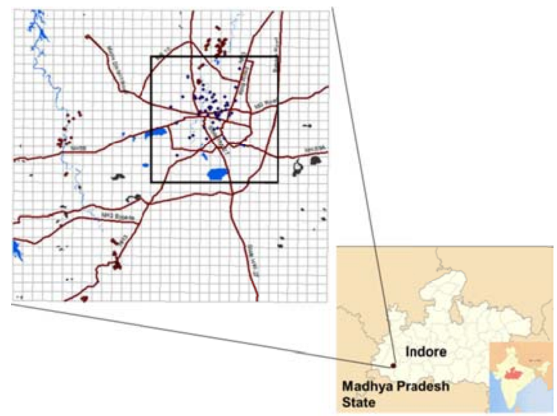


Figure 05: Indore modeling domain

Ahmedabad city is the 7th largest city in India and was the capital of Gujarat in 1960-70s (thereafter the capital was shifted to Gandhi Nagar, 30 km away) and 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 of the river 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. A rapid growth of chemical and petrochemical industries in South Gujarat districts was observed within its municipal limits of Naroda, Odhav, Vatwa, and Behrampura, accounting a total of ~5,000 industries and employing ~300,000 workers. The city accounts for ~19 percent of main urban workers in the state and 60 percent in Ahmedabad District.

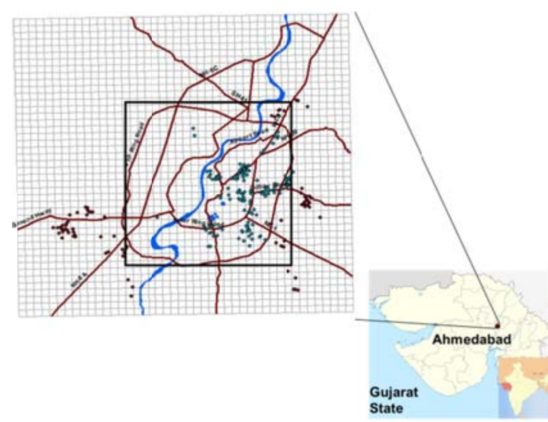
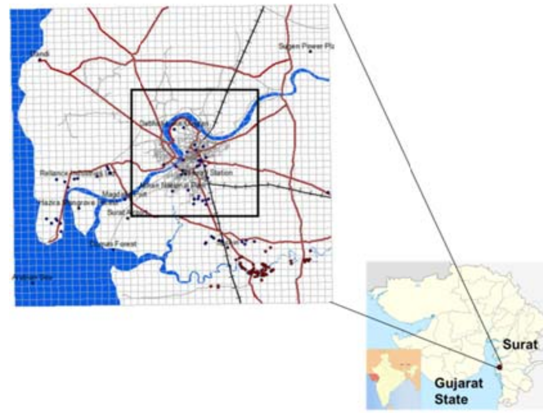


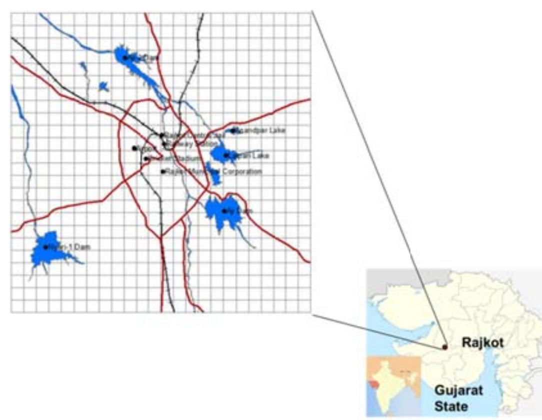
Figure 06: Ahmedabad modeling domain

Figure 07: Surat modeling domain



Surat, lies between Ahmedabad and Mumbai on the river Tapi and like the city of Chennai, includes an active port to the west. The Hazira industrial estate, closer to the port, hosts a number of petrochemical and steel refining units. The Gujarat Industrial Development Corporation (GIDC) has set up industrial estates in Pandesara, Khatodara, Udhana, Katargam, Sachin and Bhestan areas. Much of the industrial activity in Surat supports the major industries in the port of Hazira. 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), intricate zari works, chemical industries and the gas based industries at Hazira established by leading industry houses such as ONGC, Reliance, ESSAR, and Shell. There are a large number of small and medium sized industrial units (42,509 units) that account for about 15 percent of the small scale industrial units within the state of Gujarat. Much of the industrial development is located within the limits of Surat city and over 50 percent of the workforce in Surat is engaged in manufacturing related activity.

Figure 08: Rajkot modeling domain



Rajkot is a relatively small city with a population of 1 million. It has a dry and arid climate, yet several agricultural goods such as cotton, groundnut and other oil seeds are grown in the region. It has a large processing sector, especially for oils. About 5 large edible oil mills operate in the city, in addition to more than 25 small oil mills that extract edible oils like ground nut, sesame and cottonseed oils. Other small and medium industries include foundries, machinery, engineering and automobile components, castor oil processing, gold and silver jewellery, most of which are clustered around the two main industrial estates of Aji and Bhaktinagar. Of the estimated 8,000 industrial units in Rajkot, 3,150 units produce ~300,000 oil engines and parts thereof. These engines are mainly used in agriculture and for the export market. There are ~400 foundries and forging units in the city. For the automobile sector, the units in Rajkot manufacture colors, ball bearings, etc.

The vehicle fleet characteristics are presented as a summary in **Table 01** and detailed break-up of the fleet in **Table 02**. The vehicle fleet information utilized in this study comes from multiple sources and compiled for multiple years (with the base year mentioned next to the total vehicle fleet size in **Table 01**).

In case of Pune and Chennai, information comes 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 JNNURM reports and extrapolated to the base year of 2010. Since this information is sourced from multiple locations, there is lack of consistency in the categories between the cities. This shouldn't imply that any of the categories are missing form the list, but more likely to have been clubbed together in broader titles. For example, in case Indore, there is no listing for the heavy duty vehicles, which is unlikely for a city as industrial and commercial as Indore, with a budding freight handling hub in the vicinity. Upon enquiry, it was noted that all the trucks are listed under the light duty vehicles – primarily due to lack of segregated information available with the local pollution control board.

Table 02: Baseline vehicle inventory for the six cities

Vehicle	Pune (2008)	Chennai (2010)	Indore (2010)	Ahmedabad (2009)	Surat (2007)	Rajkot (2010)
Motorcycle	1,074,891	1,805,213	907,062	887,210	1,062,949	878,133
Scooter	402,523	417,899		-		
Moped	230,698	763,481		150,829		
Car	268,957	553,286	122,943	199,732	121,862	88,706
Jeep	53,401	11,197	4,392	13,773	10,890	38,017
Station Wagon	1,015	871		-		
Taxi/ Cab	19,221	45,807	4,348	2,845	2,298	3,825
3 Wheeler	66,522	55,366	13,963	65,518	65,385	8,860
Stage Carrier	5,845	6,268	34,691	1,759	1,113	
Contract Carrier	6,864	499	502	716	443	57
Mini Bus	-	170		2,238		
School Bus	545	3712		304		22
Private Service Vehicle	1,835	4,955		367	313	
Ambulance	1,321	1,545		485	407	
Heavy Duty Truck	39,128	61,661		10,589	16,189	22,032
Tanker	3,938	5,417		1,114	691	
Light Duty Truck	65,171	30,106	65,328	27,776	27,472	24,851
Tractor	24,889	15,009	16,147	18,995	14,410	
Trailor	13,005	-	9,239	10,222	9,427	
Others	4,277	10,186	2,490	6,679	1,247	
Total	**2,284,046**	**3,792,648**	**1,181,105**	**1,401,151**	**1,335,096**	**1,064,503**

This is an important information gap, which could induce some uncertainty into the emissions calculations. For the emissions inventory calculations, the categories are clubbed into cars, multi-utility vehicles (including jeeps, ambulances, police vans), motor cycles, 3 wheelers, city buses, short haul buses (including school buses), light duty commercial vehicles and heavy duty commercial vehicles (including trailors, tractors). The total fleet size is the highest for Chennai at ~3.8 million registered vehicles in the city.

For comparative purposes in **Table 01**, the truck fleet numbers are clubbed for light duty and heavy duty vehicles, including tractors, ambulances, police vehicles, tankers, and trailers; and the bus fleet numbers include the regular public transport vehicles, stage carriers, private service vehicles, school buses, and mini buses. For all the cities, the 2-wheeler population dominates, while ranging from 0.8 million for Rajkot to 3.0 million in Chennai. The 2-wheeler fleet includes mopeds, scooters, and motorcycles, with a mix of 2-stroke and 4-stroke engines. The 4-stroke engines are considered more fuel efficient and the manufacturing groups are promoting these models; with little in the way of phasing out the 2-stroke vehicles. On average, ~30-40 % of the in-use 2-wheeler fleet is estimated to have 2-stroke engines.

Chennai being a port city, the freight movement to and from the two major ports is supported with the mix of road and rail transport and the heavy duty vehicle fraction (~50%) of the total truck fleet is the highest here. For other cities, the fractions are under 25% and largely supported by light duty vehicles. For most cities in India, the heavy duty vehicles are restricted from entering city limits during the daytime. This policy was introduced primarily to cut down diesel emissions and related health impacts due to chronic exposure during the daytime. An unintended consequence of this policy is an increase in the use of the light duty vehicles during the daytime to move the cargo in, out, and around the cities.

Of the six cities, Chennai, Ahmedabad, and Surat are the only cities with power plants within the study domain. In Chennai, electricity demand is supported by two thermal power plants – the North Chennai power station (630 MW) and the Ennore power station (450 MW), both of which are located to the north of the Chennai district. In Ahmedabad, it is supported by two thermal power stations – one in the vicinity of the city along the Sabarmati River, also called Sabarmati power station and a bigger power station of ~800 MW in Gandhi Nagar. The 400 MW Sabarmati Thermal Power Station in Ahmedabad is one of the oldest operating power stations in the country. Total power generation capacity installed in Chennai and Ahmedabad is ~1,200 MW, all of which is supported by coal. In case of Surat, majority of the power generation is supported by co-generation in the steel and petroleum refineries in the Hajira area, with an installed capacity of ~400-500MW.

Figure 08: An aerial view of a brick kiln cluster outside Chennai (Google Earth)

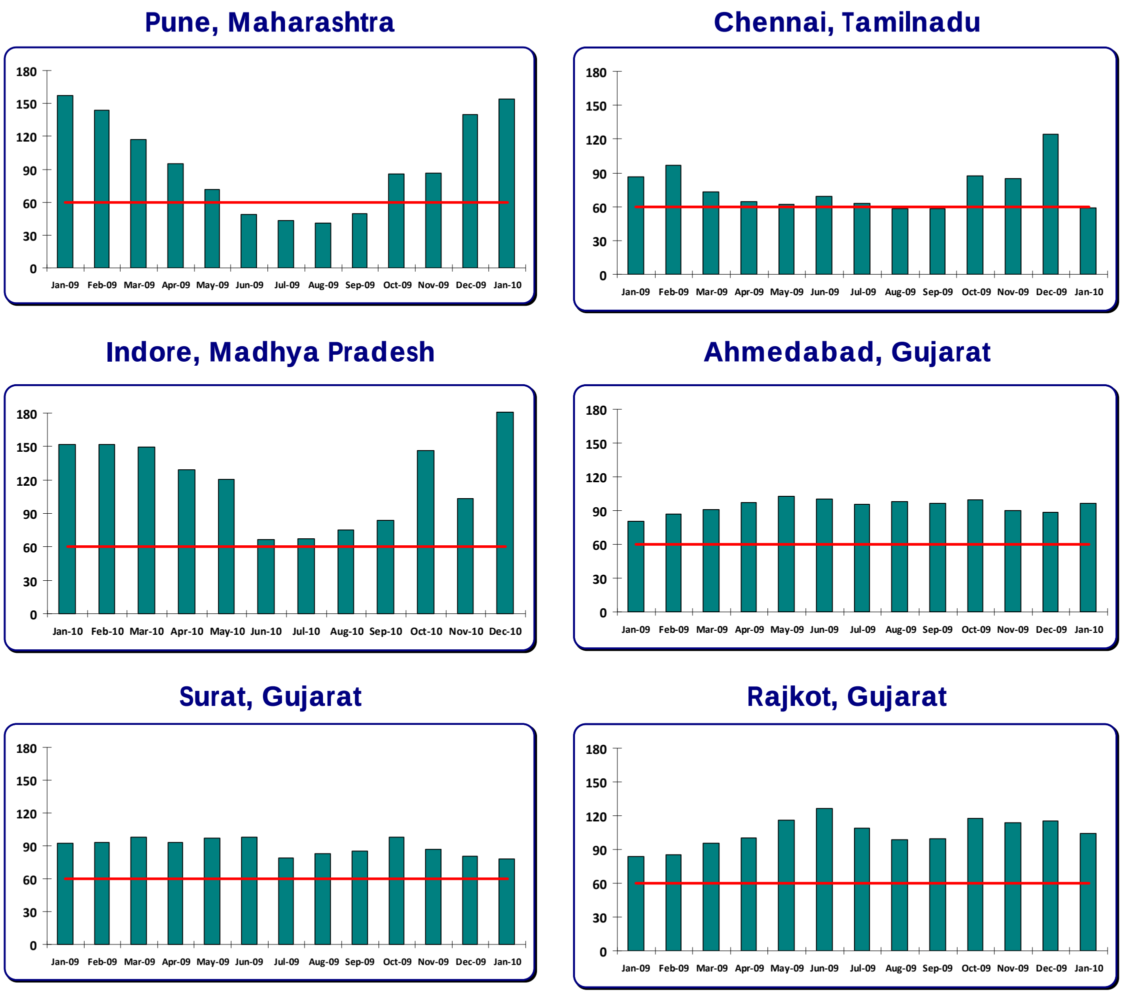
The number of brick kilns surrounding the vicinity of the six cities is substantial with numbers ranging from 120 for Surat to 600 for Chennai (**Table 01**). The type of kilns also varies significantly between the cities – from clamp style kilns to bull-trench kilns. The former is an inefficient method of baking bricks, which is predominant in Pune, Indore, Ahmedabad, and Surat and the later is comparatively an efficient method to bake bricks with higher production capacity. An example of a kiln cluster from Chennai is presented in **Figure 08**. The bull trench kilns are a common sight in this area and also commonly found around the cities of Delhi, Varanasi, Patna, Kanpur, and other cities along the Indo-Gangetic plans. Of the six cities Rajkot is the only city with no known brick kiln manufacturing units.

Besides the brick kilns, the stone quarries are a common in these cities (for example, ~11 square km of area (black polygons to the northeast of the Pune city in **Figure 03**) at Moshi near Pune-Nashik highway, where on a daily basis ~500 truckloads of stone, black boulder, and murum are extracted and transported to various parts of the district and the state. The health risks associated with constant exposure to the dust particles in these areas is under study. In this study, the quarry locations are mapped to account for the re-suspension of dust due to crushing and handling of rock and emissions from the truck movement and in-situ diesel generator usage.

Particulate Pollution Monitoring in the Cities

The Central Pollution Control Board operates a network of approximately 400+ stations in 130 cities across India, measuring ambient levels of criteria pollutants such as SO_2, NO_x, and PM_{10}. A majority of the stations are manually operated, which results in a discontinuity of data from these stations. The range of average PM_{10} concentrations measured in Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot is presented in **Table 01** and a summary of the monthly average concentrations from all stations in each city is presented in **Figure 09**. All six cities exceed the annual ambient standard of 60 $\mu g/m^3$.

Figure 09: Monitored monthly average PM_{10} concentrations



Of the six cities, Pune, Chennai, and Ahmedabad are the only cities conducting $PM_{2.5}$ monitoring, however the data availability is limited. For $PM_{2.5}$, the daily ambient standard is 60 $\mu g/m^3$ and an annual ambient standard is 40 $\mu g/m^3$.

The SIM-air analysis schematics are presented in **Figure 02**, which involved the following steps (a) Data collection – most of the information utilized to establish the baseline emissions inventory for 2010 is obtained from literature review, correspondence with local groups working on similar issues or specialized topics (like transport and health), and using publicly available resources from national and international agencies. No additional surveys were conducted as part of this study. (b) Analysis – the emissions inventory was developed using data collected from various departments, which is then spatially distributed over the study domain at 1km x 1km resolution using GIS based information on roads, population, commercial activities, and followed by dispersion modeling to convert the emissions into ambient concentrations, utilizing the local meteorological conditions. (c) Health impacts - the grid cells with concentrations exceeding the threshold values, along with population data per grid cell, were then utilized to evaluate the health impacts.

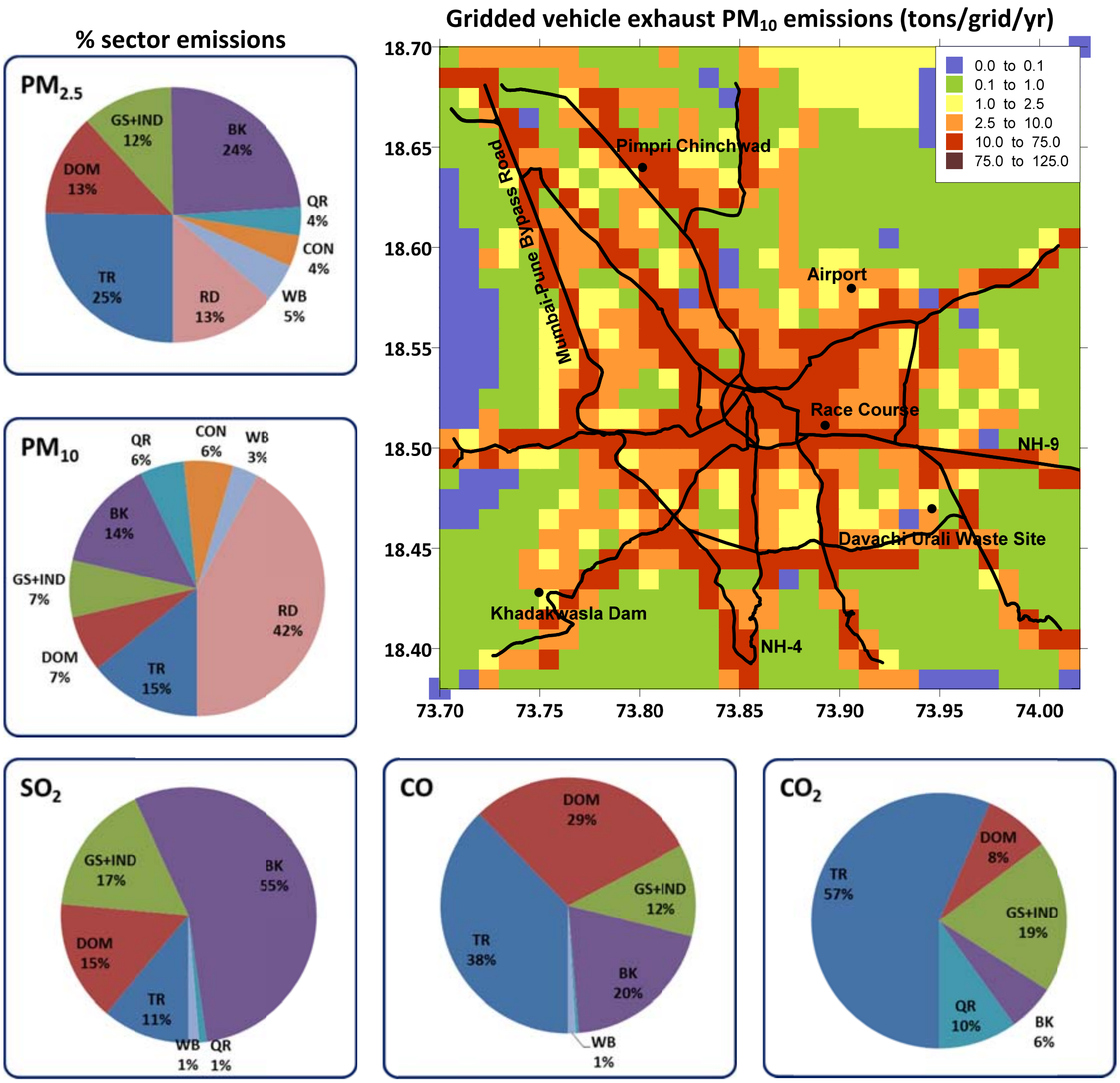
Multi-Pollutant Gridded Emissions Inventories

The emissions inventory was developed for all the criteria pollutants including PM_{10}, $PM_{2.5}$, NO_x, SO_2, CO, VOCs and CO_2. The sectors included in the analysis are – 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. Some interesting features from the emissions inventory -

- Among the fuel burning sources of PM, the transport sector is the dominant source, especially the diesel based trucks
- Overall, the re-suspension of dust due to constant vehicular movement on the roads is a growing problem in the cities. The road dust dominates the coarse fraction of PM (with particle diameter between 2.5 and 10 micron meter) and thus its dominance in the PM10 emissions inventory with percentages ranging from 22 to 44
- All the cities, except for Rajkot are surrounded by brick kilns and their emissions contribute 6 to 15 percent of the emissions and similar fractions to the ambient pollution (presented in the later sections)
- Among the size fractions, $PM_{2.5}$ is considered more harmful than PM_{10}. With $PM_{2.5}$ as the controlling pollutant, the direct vehicle exhaust is the largest contributor and with PM_{10} as the controlling pollutant, the road dust is the largest contributor.
- Among the silent contributors to PM and CO2 emissions, we have the domestic cooking and heating emissions, especially the low-income groups, outside the city district areas, where use of coal, biomass, and biofuels is at large; followed by the use of generator sets within the city limits in the sectors of hotels, hospitals, institutions, apartment complexes, and markets.
- One source with the largest uncertainty in the emissions inventory is the waste burning. Due to lack of enough waste management programs, parts of the domestic waste is burnt and accounting for PM and other carcinogenic emissions.

An emissions inventory for the city of Pune was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~38,400 tons of PM_{10}, ~18,000 tons of $PM_{2.5}$, ~4,100 tons of SO_2, ~129,000 of NO_x, ~472,400 tons of CO, and ~15.2 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 10: Multi-pollutant emissions inventory for Pune city



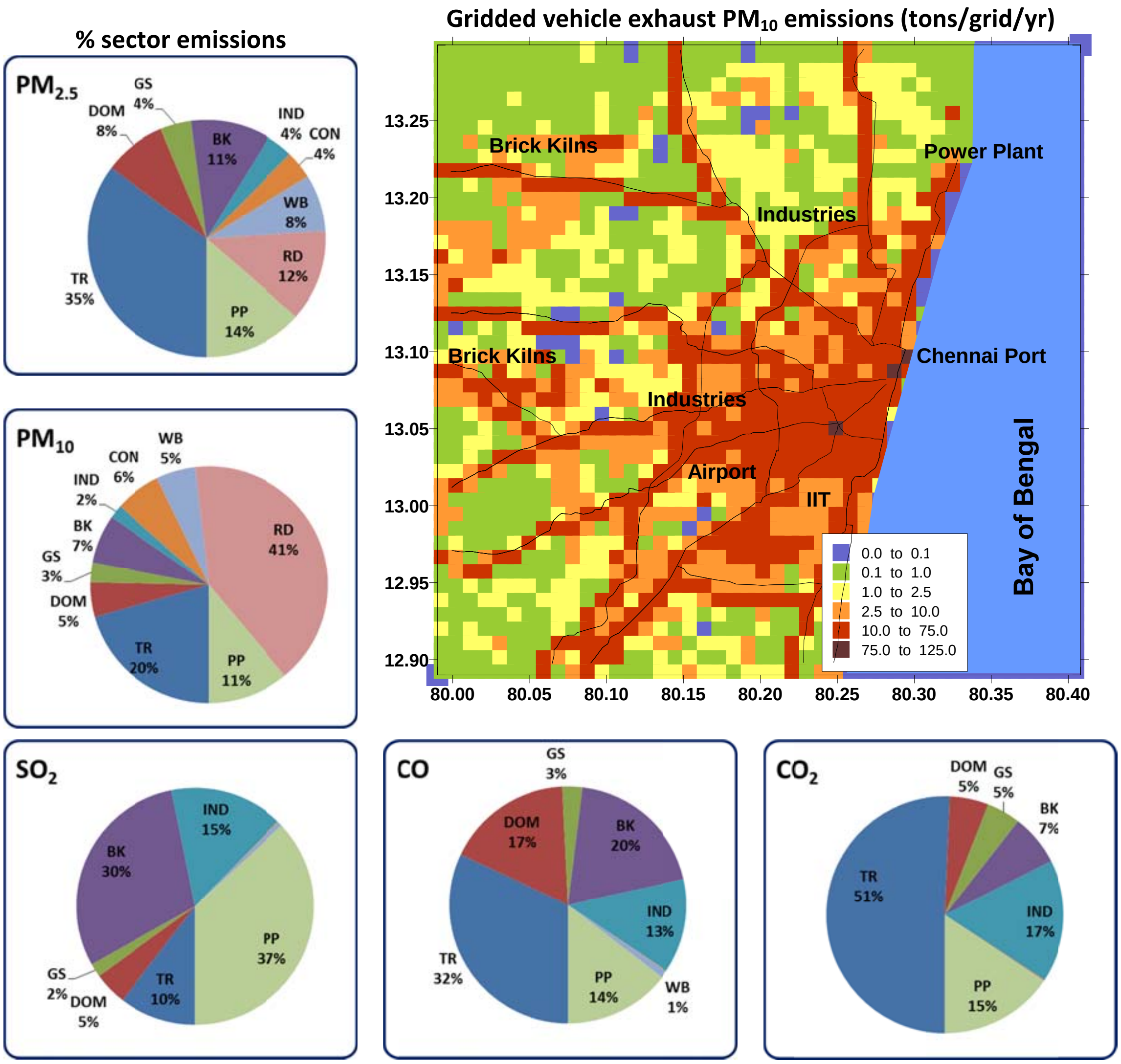
IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

Notes:

Send questions to simair@urbanemissions.info

An emissions inventory for the city of Chennai was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~50,200 tons of PM_{10}, ~24,600 tons of $PM_{2.5}$, ~18,100 tons of SO_2, ~262,900 of NO_x, ~1,002,000 tons of CO, and ~31.6 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 11: Multi-pollutant emissions inventory for Chennai city



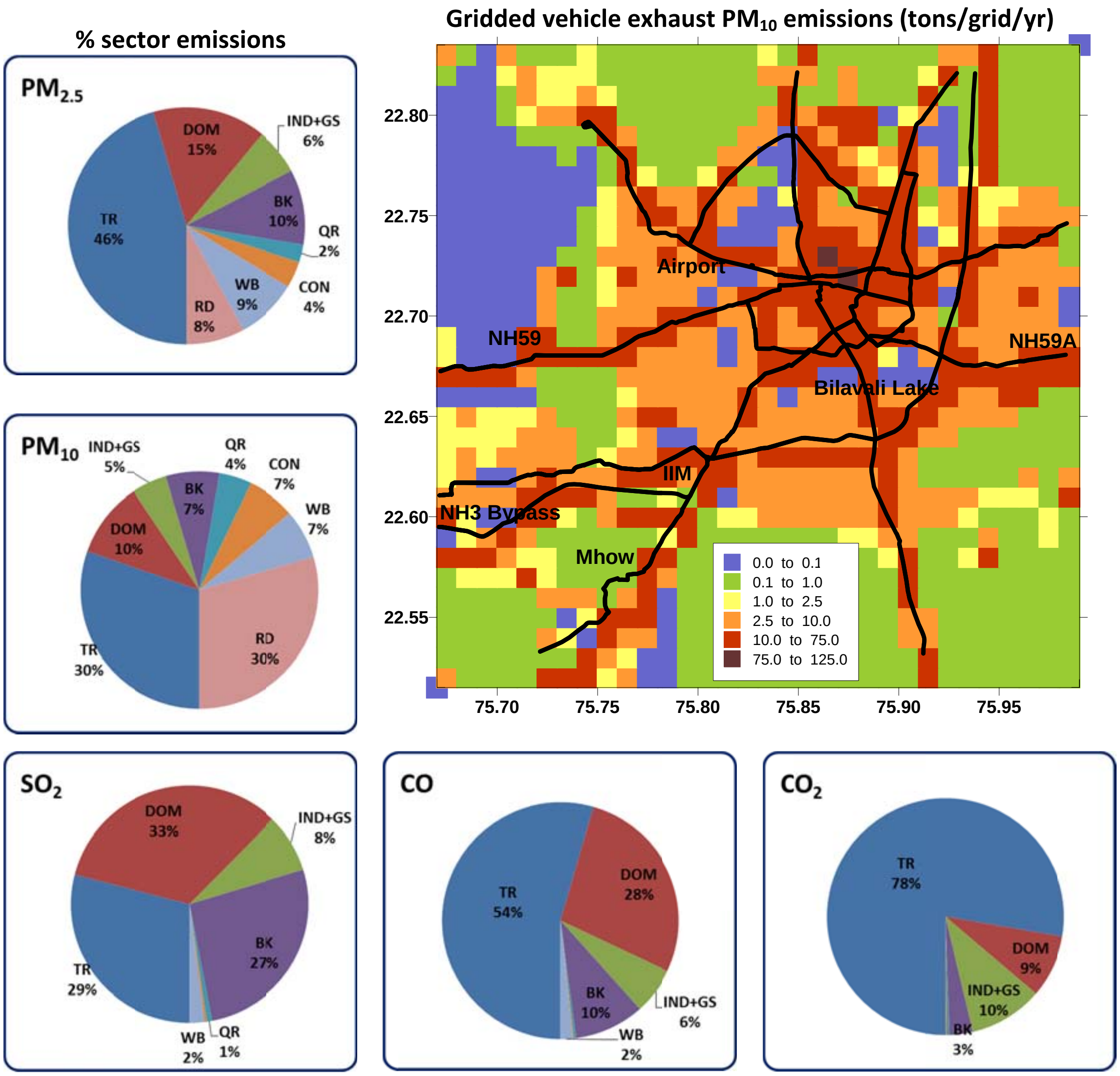
IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

Notes:

Send questions to simair@urbanemissions.info

An emissions inventory for the city of Indore was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~18,600 tons of PM_{10}, ~10,400 tons of $PM_{2.5}$, ~2,800 tons of SO_2, ~147,300 of NO_x, ~276,500 tons of CO, and ~9.4 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 12: Multi-pollutant emissions inventory for Indore city

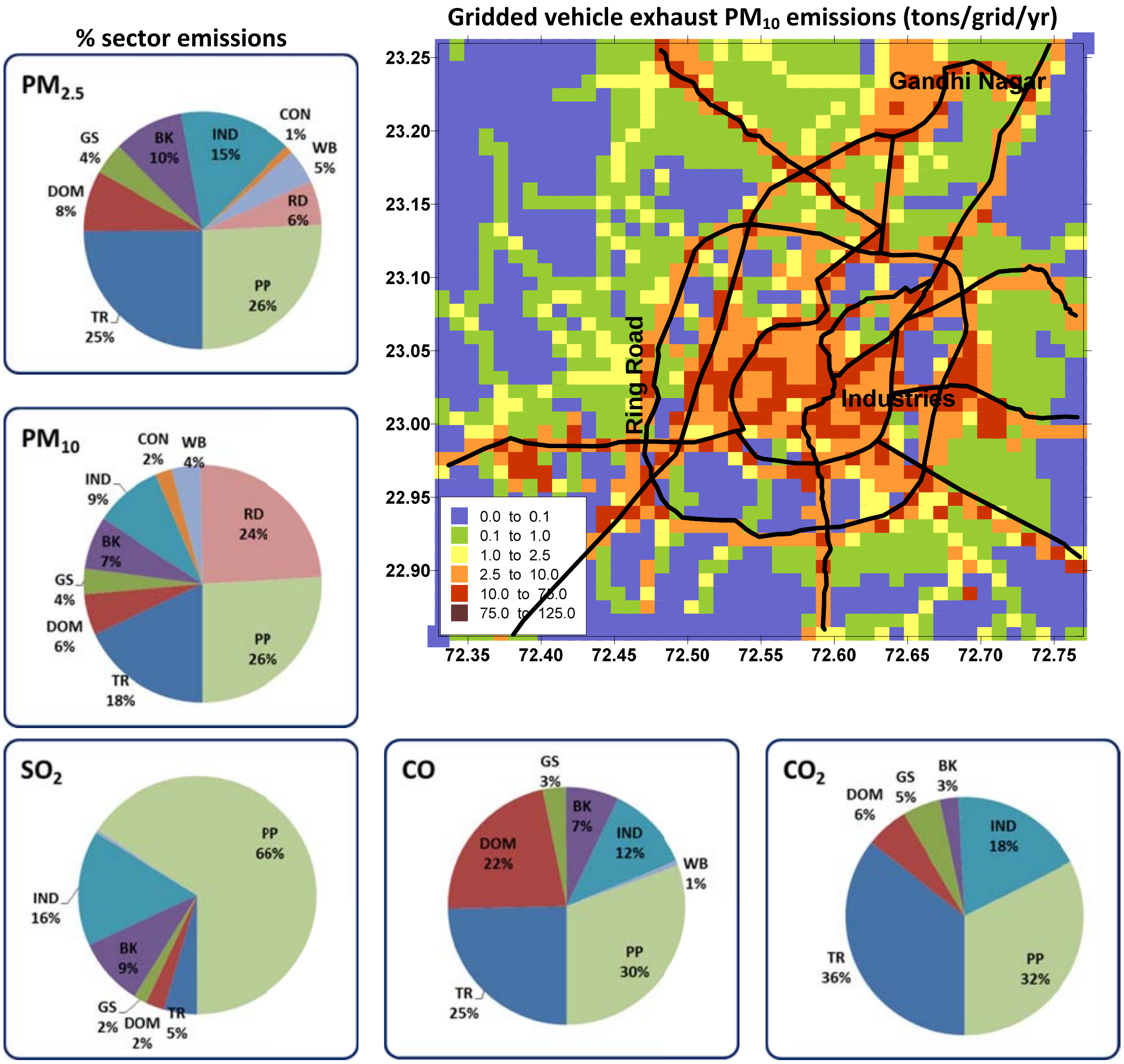


IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

Notes:
Send questions to simair@urbanemissions.info

An emissions inventory for the city of Ahmedabad was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~31,900 tons of PM_{10}, ~19,300 tons of $PM_{2.5}$, ~15,100 tons of SO_2, ~186,300 of NO_x, ~707,000 tons of CO, and ~22.4 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 13: Multi-pollutant emissions inventory for Ahmedabad city



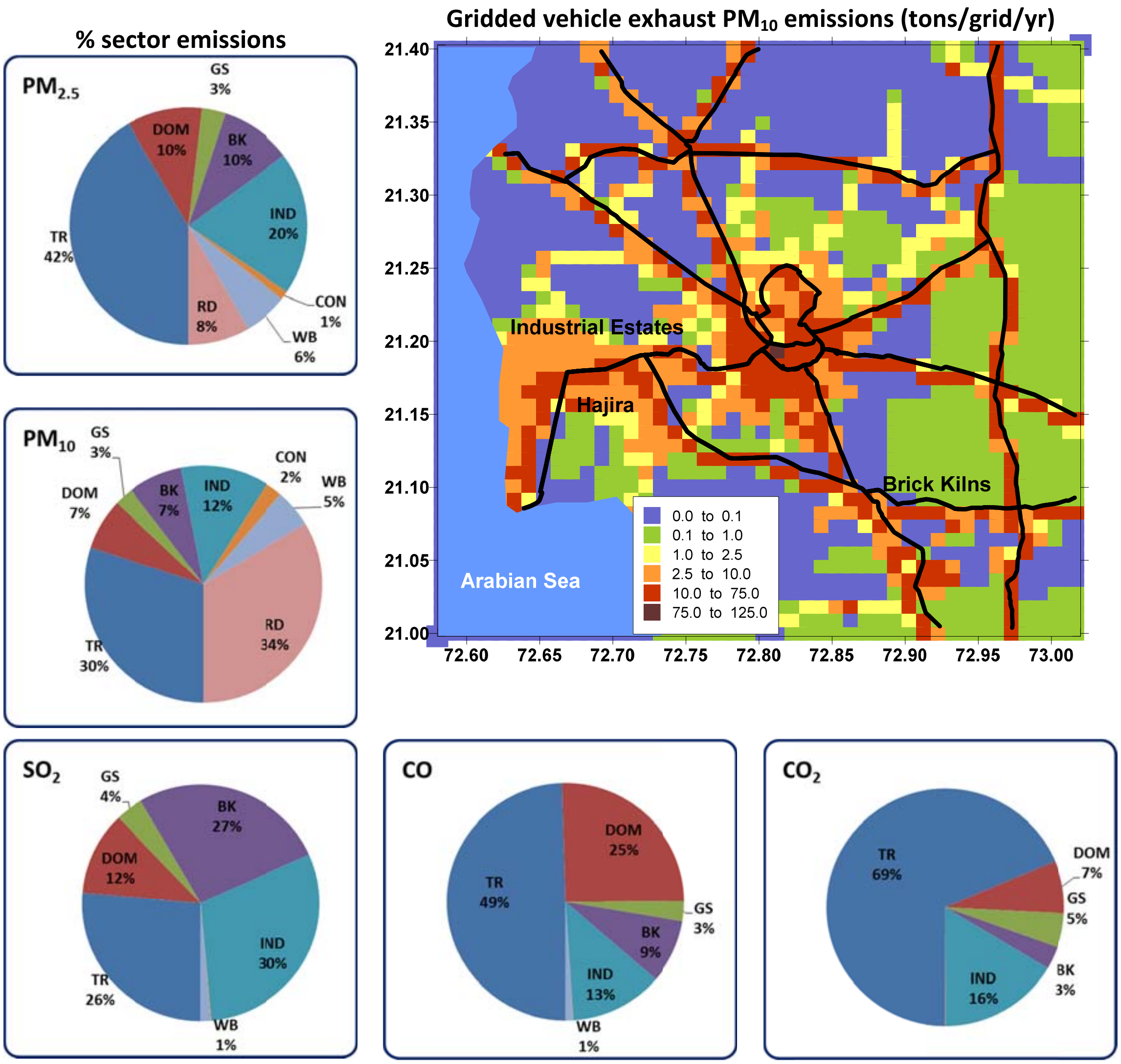
IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

Notes:

Send questions to simair@urbanemissions.info

An emissions inventory for the city of Surat was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~20,000 tons of PM_{10}, ~12,000 tons of $PM_{2.5}$, ~3,400 tons of SO_2, ~146,500 of NO_x, ~372,000 tons of CO, and ~11.8 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 14: Multi-pollutant emissions inventory for Surat city



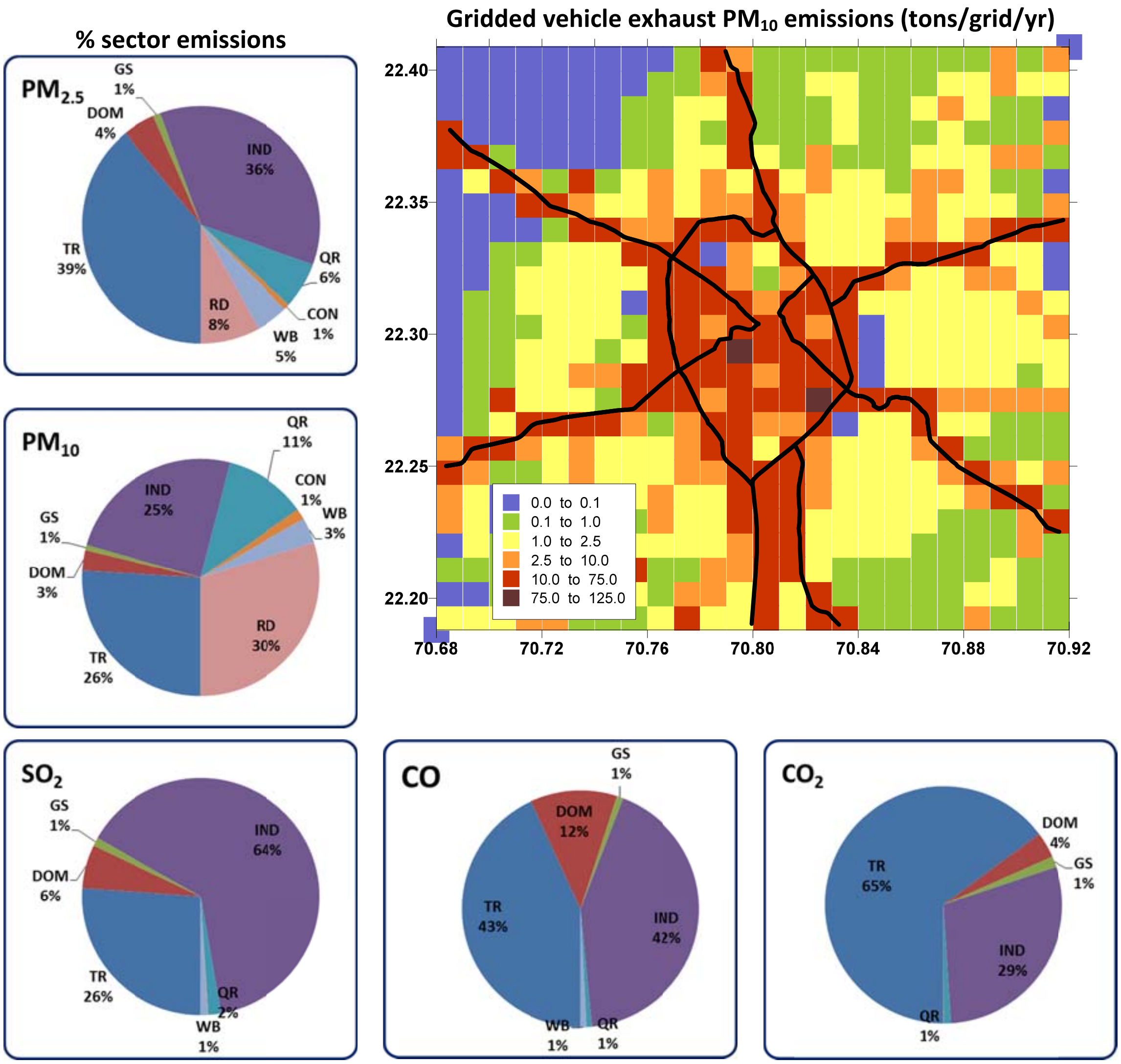
IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

Notes:

Send questions to simair@urbanemissions.info

An emissions inventory for the city of Rajkot was developed for all known sources ranging from the vehicle exhaust (passenger and freight), re-suspension of road dust, domestic and industrial fuel combustion, in-situ diesel generators, and waster burning. Annual emissions for the base year 2010 are estimated at ~14,000 tons of PM_{10}, ~7,800 tons of $PM_{2.5}$, ~2,200 tons of SO_2, ~91,800 of NO_x, ~237,000 tons of CO, and ~7.4 million tons of CO_2. The city level emissions inventory is further segregated into 1km x 1km grids. Gridded vehicle exhaust emissions are presented here.

Figure 15: Multi-pollutant emissions inventory for Rajkot city



IND = industries; PP = power plants; DOM = domestic; TR = transport; RD = road dust; WB = waste burning; CON = construction activities; BK = brick kilns; GS = diesel generator sets; LFB = landfill burning

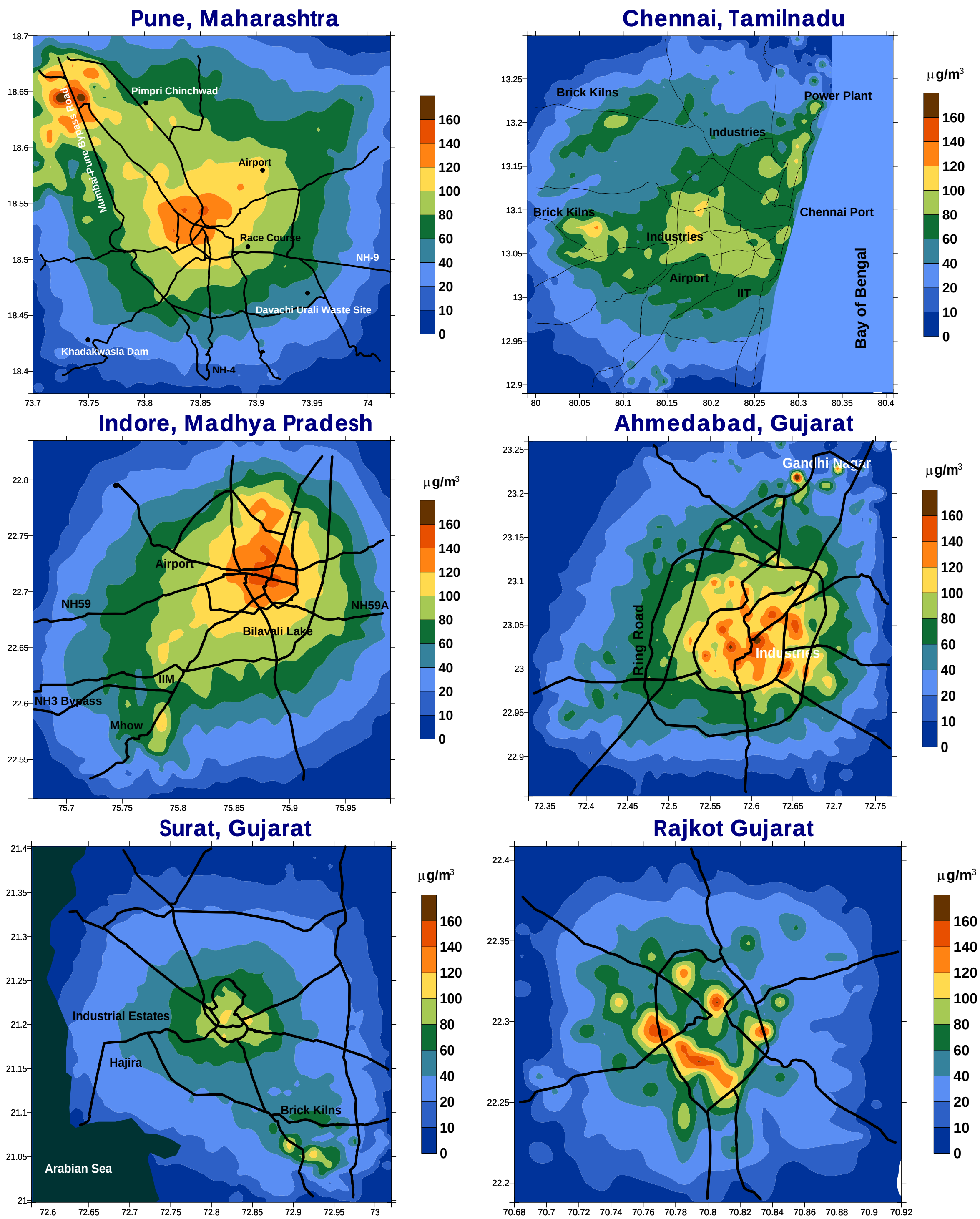
Notes:

Send questions to simair@urbanemissions.info

Dispersion Modeling & Health Impacts of Air Pollution

The dispersion modeling was carried using the ATMoS model (the Atmospheric Transport Modeling System), previous utilized for similar studies in Asia. The modeled annual average PM_{10} concentrations are presented in the figure below.

Figure 16: Modeled Annual Average PM_{10} Concentrations



The modeled concentrations in the central district area of each city are then compared with the measured concentrations presented in **Table 03**. It is important to note that this is not a direct point to point comparison, rather comparison of results over a year and for an area. In the central district areas, the annual average concentrations for PM_{10} are above the national ambient standard of 60 $\mu g/m^3$. Due to limited information on the $PM_{2.5}$ monitoring data, there are no comparisons available at this time. The $PM_{2.5}$ fractions (in emissions) are vetted with the emissions factors pertinent to the sectors and the dispersion modeling is conducted in a manner similar to PM_{10}, with different physical and chemical characteristics. As and when, more monitoring data is available from these cities, the $PM_{2.5}$ results will be re-visited for calibration and further analysis. In the above figure most of the city district areas exceed the annual average standard of 40 $\mu g/m^3$ for $PM_{2.5}$ concentrations.

Table 03: Summary of 2010 PM_{10} emissions, and modeled and measured concentrations

City	Domain size km x km	Emissions tons/year	Measured $\mu g/m^3$	Modeled $\mu g/m^3$
Pune	32 x 32	38,400	60-160	80-140
Chennai	44 x 44	50,200	60-120	60-100
Indore	32 x 32	18,600	60-170	80-150
Ahmedabad	44 x 44	31,900	80-100	60-140
Surat	44 x 44	20,000	75-100	50-120
Rajkot	24 x 24	14,000	80-120	50-140

The dispersion modeling results for PM_{10} annual average concentrations, overlaid on the gridded population at the same resolution are utilized for calculating the health impacts presented in the table below. The dose-response functions for various endpoints (listed in the table) were well documented in the studies across the world. It is important to note that total population listed in the table is for the entire modeling domain, which extends beyond the city limits.

Table 04: Health impacts of air pollution in 2010

Mortality & Morbidity in 2010	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
Domain size (km x km)	32 x 32	44 x 44	32 x 32	44 x 44	44 x 44	24 x 24
Study Domain Population (million)	6.5	8.5	3.3	7.8	5.0	1.4
PM_{10} emissions (tons/yr)	38,400	50,200	18,600	31,900	20,000	14,000
Estimated Premature Deaths	**3,600**	**3,950**	**1,800**	**4,950**	**1,250**	**300**
Adult Chronic Bronchitis	10,800	11,800	5,400	14,800	3,750	950
Child Acute Bronchitis	79,250	86,600	39,300	108,300	27,400	6,800
Respiratory Hospital Admission	5,000	5,460	2,500	6,800	1,700	450
Cardiac Hospital Admission	1,350	1,480	670	1,850	470	120
Emergency Room Visit	97,800	106,900	48,500	133,700	33,800	8,400
Asthma Attacks (million)	1.2	1.3	0.6	1.7	0.4	0.1
Restricted Activity Days (million)	10.4	11.3	5.1	14.2	3.6	0.9
Respiratory Symptom Days (million)	49.7	54.1	24.5	67.6	17.1	4.2

It is important to note the differences in the population and geographical sizes of the study domains when comparing the results between the cities and with the previous studies. The domains selected in this study are typically larger than the main district areas, surrounding satellite locations with significant industrial loads to account for the non-transport sector, which is often neglected in the in-city based observations and analysis. For example, for the Pune domain, the satellite city of Pimpri Chinchwad is included, for the Ahmedabad domain, the city of Gandhi Nagar is included, and for the Chennai domain, the all the neighboring industrial estates with brick kiln clusters (at least 20-30 km away from main district area) are included. With the increase in the study domain sizes, the population size and the exposure estimates also increase and this is reflected in the estimates presented in **Table 04**.

The main correlation between the emissions, pollution, exposure, and possible health impacts is simple and straight. Most of the emissions in the cities are low lying sources, which tend to affect the immediate vicinity more than the areas 20-30 km away from the source locations. This is particularly true for the sources like vehicle exhaust, road dust, residential burning, garbage burning, and emissions from the diesel generator sets. Even from the construction sector, the types of technology differed from city to city. Only in Chennai, the brick kilns are designed with stacks, which allow for the pollution 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 low when compared to the transport and industrial activities, because the high stacks which disperse most of the pollution to vicinities outside the cities.

The land-sea breeze is a significant quotient in these studies. Comparatively, of the six cities, Chennai and Surat are the most industrial and also the coastal cities, with significant emissions from this sector and yet experience the lowest impacts relative to their geographical and population sizes. This is primarily due to the breezes – Westerly winds for Chennai and Easterly winds for Surat, dispersing most of the pollution the industries.

The dose response functions themselves are also subjective and represent a conservative estimate based on the studies around the globe. In 2010, the six cities account for an estimated annual 15,200 premature deaths due to exposure to air pollution above the WHO guidelines. These levels are very significant and comparable to the levels being experienced in the cities across Asia. Based on willingness to pay rates, these health impacts cost (in crores of INR) ~1,780 in Pune, ~1,960 in Chennai, ~890 in Indore, ~2,440 in Ahmedabad, ~620 in Surat, and ~155 in Rajkot. These estimated are subjective to data available in the cities and presented here to provide an estimate to compare against possible costs of interventions to control air pollution in these cities. The kind of questions that can be answered following this analysis are, for example, (1) what level of interventions are possible to reduce the health costs associated with the pollution exposure, based on the current know-how of the emissions and their strengths to control (2) do the estimated health costs warrant an immediate response to the pollution control?

Air Pollution in 2020 and Scenario Analysis

The emissions, dispersion, and health impacts analysis was extended to the year 2020, with assumptions for economic growth. In case of the transport sector, the passenger vehicles were extrapolated at ~8%, motorcycles at ~10%, and the remaining private sector vehicles like short buses, commercial vehicles, etc., at ~1%. The industrial sector is estimated to grow at ~10%. It is also assumed that the emission standards will improve in the coming decade, including an improvement of on-road conditions for the vehicle movement, which will inherently reduce the deterioration rates and thus the emission loads. Hence, vehicle numbers are increasing at ~10%, the emissions are expected to taper off. In 2020, the six cities account for an estimated annual 21,400 premature deaths due to exposure to air pollution above the WHO guidelines.

Table 05: Health impacts of air pollution in 2020 – baseline scenario

Mortality & Morbidity in 2020	**Pune**	**Chennai**	**Indore**	**Ahmedabad**	**Surat**	**Rajkot**
Domain size (km x km)	32 x 32	44 x 44	32 x 32	44 x 44	44 x 44	24 x 24
Study Domain Population (million)	7.6	10.5	4.3	10.3	6.2	1.9
PM_{10} emissions (tons/yr)	38,000	55,100	21,000	31,800	23,200	18,500
Estimated **Premature Deaths**	**4,300**	**6,000**	**2,500**	**7,850**	**2,050**	**670**
Adult Chronic Bronchitis	12,900	17,800	7,500	23,400	6,100	2,010
Child Acute Bronchitis	94,500	130,400	54,500	171,500	44,900	14,700
Respiratory Hospital Admission	6,000	8,200	3,400	10,800	2,800	930
Cardiac Hospital Admission	1,600	2,200	930	2,900	770	250
Emergency Room Visit	116,650	161,000	67,200	211,650	55,400	18,200
Asthma Attacks (million)	1.4	2.0	83.0	2.6	683.3	0.2
Restricted Activity Days (million)	12.3	17.0	7.1	22.4	5.9	1.9
Respiratory Symptom Days (million)	59.1	81.5	34.0	107.1	28.0	9.2

Notes:

Please send questions & comments to simair@urbanemissions.info

Six "what-if" interventions were modeled for 2020 to study the associated benefits in terms of health and CO_2 emissions (1) an increase in the non-motorized (NMT) shares (2) an increase in the public transport shares (3) alternative fuels for public transport and the 3-wheelers (4) a reduction in the silt loading on the roads (5) a technology improvement in the brick kilns and (6) a facility to bypass heavy duty trucks away from the city limits. A summary of the combined benefits for the city in terms of health and CO_2 emissions, up on implementation of these six interventions is presented in **Table 06**.

Table 06: Benefits of air pollution in 2020 – under control scenarios

Co-benefits in 2020	Pune	Chennai	Indore	Ahmedabad	Surat	Rajkot
Estimated PM_{10} emissions reduced under what-if's (tons/yr)	13,900	17,400	6,200	8,800	8,200	7,900
% compared to 2020 baseline	37%	31%	30%	27%	35%	42%
Premature deaths saved	1,700	1,270	630	1,390	590	290
% compared to 2020 baseline	39%	21%	25%	18%	29%	42%
Mortality cost savings (million USD)	71	53	26	57	24	12
Morbidity cost savings (million USD)	114	87	44	94	40	20
Estimated CO_2 emissions reduced under what-if's (million tons/yr)	3.0	5.7	1.8	2.5	2.4	1.4

In conclusion, the results of this study are intuitive. Policies that promote public transportation and allow for NMT result in lower pollution levels and lower greenhouse gas emissions. Promoting alternative transport options is not only environmentally sustainable but it is also a socially progressive policy. The brick kiln sector, though outside the city administrative limits, has a significant role in reducing air pollution and providing the co-benefits. Because of the mix of fuels (including biomass), other pollutants like Black Carbon, have a vital role to play in the climate policy. The garbage burning and linked toxic emissions need an immediate management solution. The dust re-suspension on the roads due to the vehicular movement is the low-hanging fruit for immediate improvements in city's air quality[1].

[1] To access the full report with details on methodologies utilized for developing emissions inventory, including the emissions factors for various sectors, dispersion modeling, dose-response functions for health impacts, and assumptions for 2020 scenario analysis, please send an email to simair@urbanemissions.info

www.urbanemissions.info