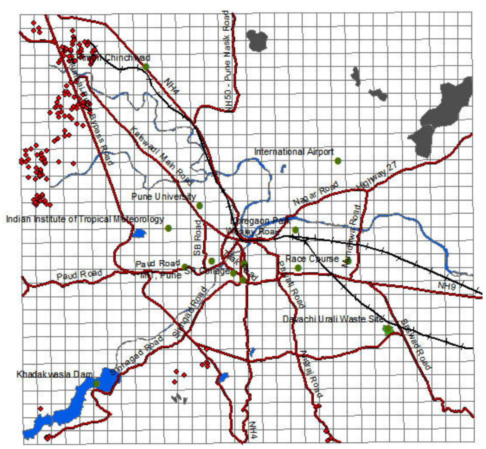
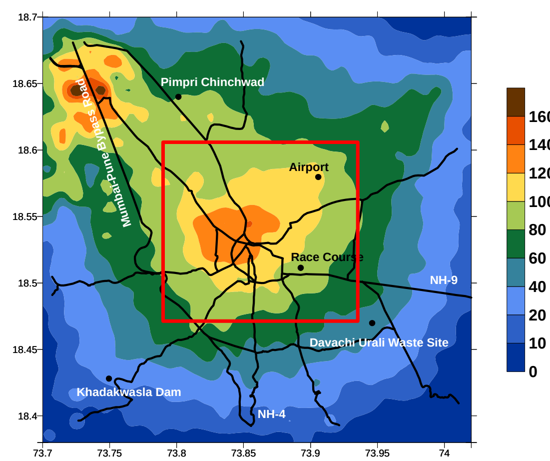
Simple Interactive Models for Better Air Quality

www.sim-air.org

# Urban Air Pollution Analysis in India

- Pune (Maharashtra)
- Chennai (Tamil Nadu)
- Indore (Madhya Pradesh)
- Ahmedabad (Gujarat)
- Surat (Gujarat)
- Rajkot (Gujarat)





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September, 2011

UrbanEmissions.Info, New Delhi, India (2011)

## Table of Contents

# List of Figures

## List of Tables

# Executive Summary of Urban Air Pollution Analysis in 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) | 36,600 | 56,400 | 17,900 | 35,100 | 19,950 | 14,000 |
| 2010 $PM_{2.5}$ emissions (tons/yr) | 16,650 | 26,000 | 9,900 | 17,500 | 12,000 | 7,750 |
| 2010 $CO_2$ emissions (mil tons/yr) | 11.9 | 30.6 | 8.6 | 22.4 | 11.6 | 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 |

## Chapter 1.0

# Scope of this Study

Air pollution is responsible for an increasing number of mortality and morbidity cases in Indian cities. In a recent study, based on published information on air quality monitoring from the Central Pollution Control Board (Delhi, India) and hospital admissions records from cities across India, the city of Delhi was declared the "Asthma Capital" of India.[1] 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.

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).

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[1] Read more on the "Delhi - Asthma Capital of India"
@ http://mailtoday.intoday.in/index.php?id=18601&option=com_content&task=view&sectionid=23

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

## *1.1 Integrated Air Quality Management*

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. The methodologies employed in developing an emissions inventory and further analysis is presented in relevant sections of this report.


**Figure 1.1: Location of the six cities**

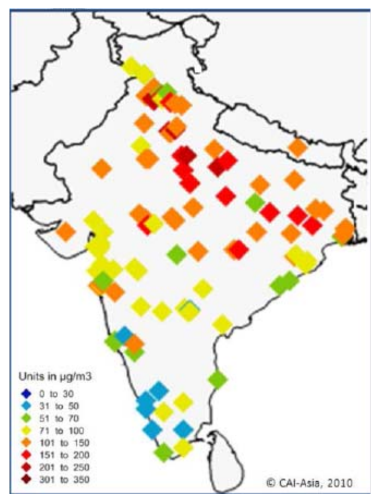
To conduct integrated air quality management in the six cities, the Simple Interactive Models for better air quality (SIM-air) program was utilized. The SIM-air program (**Figure 1.2**) is a family of open-source analytical tools to establish baseline emissions inventory, to conduct dispersion modeling, 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[2]. 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).

[2] The details of the SIM-air program and the tools are available @ http://www.urbanemissions.info

Due to inherent challenges in collecting necessary data, disclosure issues with various agencies or lack of institutional and technical capability to maintain such information, few cities have developed or have made their emission inventories publically available in India. In this study, we acknowledge this challenge and uncertainty involved in such inventories. This is a "*learning while building*" exercise and the emissions inventories developed through this exercise can be further improved as more capacity is built within the collaborating groups (with planned training events in the future). During the study period, information available from various local, national, and international academic groups were utilized to establish these baselines, understand current trends in the ambient pollution levels, and analytical tools were used to assess health impacts[3].

***Box 1.1 Recent studies in India to understand air pollution sources and strengths***

Air quality monitoring is the primary activity for most air quality management institutions. In India, ~350 monitoring stations are operated by the Central Pollution Control Board (CPCB) and the State Pollution Control Boards (SPCBs). A summary of the annual average $PM_{10}$ concentrations measured in 2008 is presented here[4]. When compared to the national annual average standard of 60 $\mu g/m^3$ for $PM_{10}$, more than 60 percent of these cities are experiencing critical levels.




While the data from these monitoring stations is location specific, representative of the pollution sources surrounding the monitors, they do not give any specific information about the sources nor the source contribution to the ambient pollution measured. There is an acute need for apportioning these contributions in order to better understand air pollution in the country and improve air quality management[5].

In 2011, the Ministry of Environment and Forests of India (MoEF) and CPCB, completed and published a detailed study on source apportionment and emissions inventory (for their study domains) for six cities in India – Pune, Chennai, Bangalore, Mumbai, Kanpur, and Delhi. This work was conducted for the base year 2006-07 providing necessary background information on the sources of air pollution, an emissions inventory for the criteria pollutants (for the study domains), the results of a source apportionment study based on monitoring data, and an action plan to control air pollution[6]. A summary of results from Pune and Chennai, the two cities overlapping with this study is presented in the later sections.

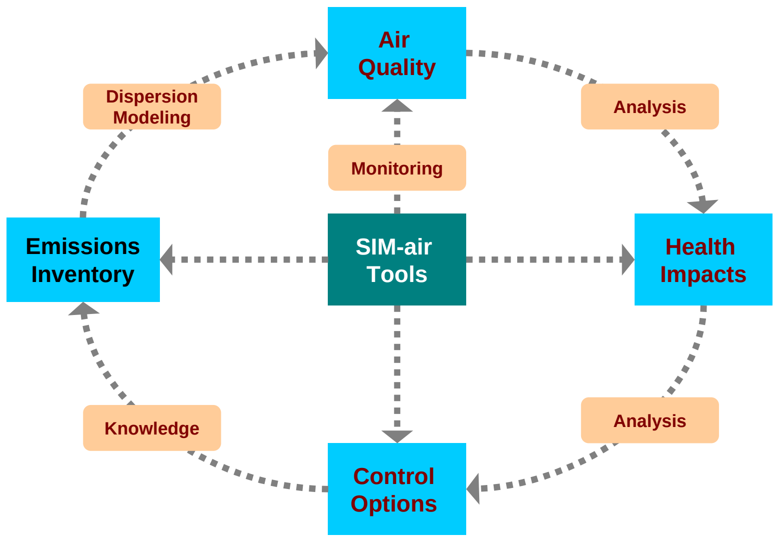
In this study, the emissions inventory and health impacts analysis is conducted for the base year of 2010, following the schematics presented in **Figure 1.2** and the emissions are projected to

[3] Examples of emissions inventories available in the public domain
Global Emissions Inventory Activity @ http://www.geiacenter.org/
Emissions Database for Global Atmospheric Research @ http://www.mnp.nl/edgar/
Greenhouse Gas and Air Pollution Interactions and Synergies @ http://gains.iiasa.ac.at/index.php
[4] CAI-Asia, 2010, "India Air Quality Profile 2010" @ http://cleanairinitiative.org/portal/node/6591

2020 to evaluate the impacts and the potential for pollution control – in terms of health and carbon benefits of six interventions

1. an increase in the non-motorized transport (cycling and biking) shares by ~20 percent
2. an increase in the public transport shares by ~20 percent (for the trips)
3. an alternative fuel for the public transport and 3 wheelers
4. a potential 50 percent reduction in the road dust
5. a technology change in the brick kilns improving the efficiency and reducing the emissions by ~50 percent
6. a reduction of ~20 percent of the truck movement in the city limits

**Figure 1.2: Schematic framework of the SIM-air program**




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 responses functions established through epidemiological studies. The methodology details along with a database of dose response coefficients and references are presented in the later sections.

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[5] A detailed overview of the source apportionment techniques – top-down based on the monitoring techniques and bottom-up based on the fuel consumption and activity levels – is presented in "Tools for Improving Air Quality Management - A Review of Top-down Source Apportionment Techniques" by Johnson TM, Guttikunda SK, Watson J, Russell AG, West J, Bond T, and Artaxo P., including a summary of the applications from Asia, Africa, and Latin America. Full report is available @ http://www.esmap.org/esmap/node/1159

[6] Detailed report on the CPCB's source apportionment study from the cities in India is available @ http://cpcb.nic.in/Source_Apportionment_Studies.php

A source apportionment and co-benefits of air pollution management for Hyderabad was conducted and published in 2007-08 @ http://urbanemissions.info/model-tools/sim-air/hyderabad-india.html

## Chapter 2.0

# Particulate Pollution & Co-Benefits

The five main pollutants responsible for the majority of the health impacts in Indian cities are particulates (PM), sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), and ozone ($O_3$). Each of the pollutants has an ambient standard (related to the pollution observed at various locations) and an emissions standard (related to the weight of the pollution at the source)[7]. Other pollutants with regulatory standards are the volatile organic compounds (VOCs). Of these pollutants, PM, $SO_2$, CO, $NO_x$ and VOCs are considered the primary pollutants, as they are directly emitted at the source, while ozone is considered a secondary pollutant, as it is formed due to chemical reactions among the primary pollutants. Given a mix of $NO_x$ and VOC emissions, in the presence of strong sunlight during the day, this leads to a buildup of ozone through photolysis[8].

Consequences of exposure to these pollutants range from premature mortality due to aggravated morbidity effects such as asthma, chronic bronchitis, and oxygen deficiency in blood. A detailed review of the impacts of outdoor air pollution in the developing countries was conducted by the Health Effects Institute (USA)[9]. Other health impacts include eye irritation, respiratory illness and impacts on reproductive health; ecological impacts include loss of productivity and slower photosynthesis among vegetation; structural impacts include corrosion of metal, accelerated erosion on buildings and monuments; aesthetic impacts include bad smell, reduced visibility, and accumulation of soot and dust on buildings. While these impacts are

[7] Read more on the national ambient air quality standards in India @ http://cpcb.nic.in/National_Ambient_Air_Quality_Standards.php

[8] Refer to the books "Atmospheric Chemistry and Physics" by Seinfied and Pandis, and "Fundamentals of Atmospheric Modeling" by Mark Jacobson, which provide detailed discussion on the photochemistry of $NO_x$, VOCs, and ozone, and more on the air pollution modeling

[9] See a list of publications summarizing the impacts of outdoor air pollution on human health based on epidemiological studies for the particulates and other primary pollutants conducted across the world is distributed by the Health Effects Institute, USA @ http://www.healtheffects.org/

mostly experienced in the urban centers, regional impacts include the loss in the agricultural yield due to acid rain and ozone exposure, and global impacts include increase in emissions that have an impact on climate change.

Each of the pollutants is associated with a range of health impacts. For example, PM is the leading cause of respiratory illnesses, ozone pollution causes eye and lung irritations, $SO_2$ (with precipitation) results in acid rain, irritation along the respiratory track and bronchitis, $NO_x$ enhances the symptoms for chronic bronchitis, and CO reduces the oxygen supply to the brain (and is in some cases fatal). We experience health impacts due to air pollution from all the pollutants. However, the health impacts due to PM are considered the most harmful, due to its size, composition, direct linkages to aggravating chronic and acute respiratory diseases[10].

Studies in India suggest that acute respiratory infection (ARI) in children below 5 years of age is the largest single disease category, accounting for about 13 percent of the national burden of disease[11], and children living in households using solid fuels have 2-3 times more risk of ARI than unexposed children. In 1995, air pollution in China from fuel combustion was estimated to have caused 218,000 premature deaths (equivalent to 2.9 million life-years lost), 2 million new cases of chronic bronchitis, 1.9 billion additional restricted activity days, and nearly 6 billion additional cases of respiratory symptoms[12]. The main pollutant in both China and India is believed to be fine PM. Recent studies put the risk of exposure to urban air pollution at ~900,000 premature deaths in Asia[13].

In this study, emissions inventory, pollution modeling, and health impacts assessments are calculated using PM as the primary indicator.

While PM pollution is measured and estimated as a single entity, the composition of PM is complex and accounts for contributions from other pollutants. By restricting the impact assessments to PM, we avoid any double counting of impacts between pollutants. A typical chemical composition of PM is presented in **Figure 2.1**, which consists of direct emissions from sources such as vehicle exhaust, industry, and domestic fossil fuel combustion; in the form of metals, crustal elements, soot (also known as black carbon) and secondary contributions due to the chemical transformation of gaseous pollutants into aerosols such as $SO_2$ to sulfates, $NO_x$ to nitrates, and VOCs to secondary organic aerosols (SOAs). Similarly, the contribution to ozone pollution is also accounted in the form of SOAs which form during the photolysis reactions between $NO_x$ and VOC.

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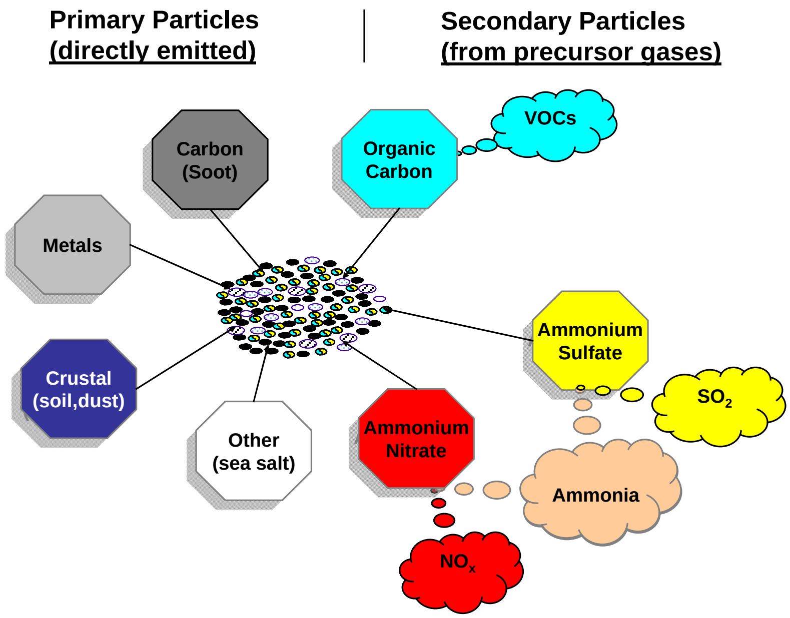
[10] A detailed explanation on the science and composition of the PM pollution is presented in SIM-air Working Paper No.10 “What is Particulate Matter: Composition and Science” and No.16 “Urban Particulate Pollution Source Apportionment - Part 1. Definition, Methodology, and Resources” @ http://www.urbanemissions.info

[11] Comparative Quantification of Health Risks @ http://www.who.int/publications/cra/en

[12] Lvovsky, et al. 2000. “Environmental Costs of Fossil Fuels: A Rapid Assessment Method with Application to Six Cities.” Environment Department Paper No. 78, The World Bank, Washington DC, USA

[13] A summary of the mortality and morbidity health impacts, estimated and surveyed, reported from cities and countries across the world, along with a methodology to estimate health impacts of outdoor air pollution are presented in “Estimating health impacts of air pollution, SIM-air working paper series, SIM-06-2008, available @ http://urbanemissions.info/sim-series-06.html

**Figure 2.1: A typical chemical composition of particulate pollution**




The PM size is also critical for estimating and studying its impact on human health. Generally referred size fractions are

- Total suspended particulates (TSP, with aerodynamic diameter <~30 microns (μm)
- $PM_{10}$ (with an aerodynamic diameter of less than 10 μm, also referred to as coarse)
- $PM_{2.5}$ (with an aerodynamic diameter of less than 2.5 μm, also referred to as fine)[14]
- Ultrafine PM are those with a diameter of less than 0.1 micron

The PM size fractions affect the atmospheric lifetime, spatial distribution, temporal variability, and health impacts of particles. In general, smaller the particle size, higher the damage. For example, the $PM_{2.5}$ size fraction is considered more harmful than the $PM_{10}$ size fraction, because the $PM_{2.5}$ particles can travel farther into the lungs and can cause more damage than the $PM_{10}$ particles[15].

The lifetime of the particles also varies by size and shape. Coarse particles have an average life time (resuspension before they settle on a canopy or wet deposited due to precipitation) between minutes to hours, while the fine particles average between days to weeks. Also, the travel distances for coarse particles range from 1 to 10s of kilometers and the fine particles average from 100s to 1000s of kilometers.

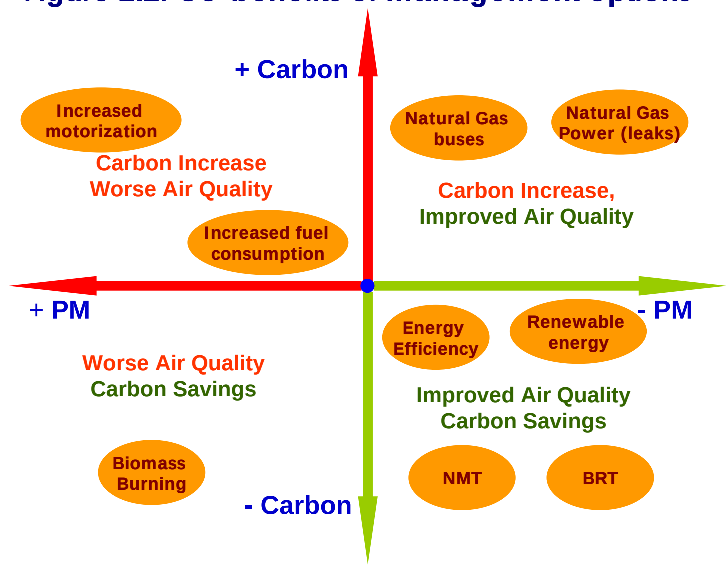
[14] In India, $PM_{2.5}$ was added to the list of criteria pollutants in November, 2009, and the SPCBs are required to monitor $PM_{2.5}$ along with $PM_{10}$ at all their monitoring stations. However, the capacity to do so is still limited and only a handful of the cities are monitoring and reporting $PM_{2.5}$ pollution levels.

[15] While the $PM_{2.5}$ is considered more harmful and an important fraction of the PM pollution, in this study, the emissions and health impacts analysis is limited to $PM_{10}$ due to data constraints in the monitoring data. The monitoring data from the cities is available only for the $PM_{10}$ fractions. While we recognize the constraint in the monitoring data and all the modeling and comparisons are carried out for the $PM_{10}$ pollution, the final emissions inventories and modeling data is available for both the fractions for further use.

## *2.1 Co-Benefits of Particulate Pollution Control*

A co-benefits approach[16] is increasingly becoming a starting point for discussing integrated programs benefiting both climate change and air quality. **Figure 2.2** depicts a scenario where the co-benefits can aide decision making over a variety of control measures. For example, policies designed to reduce the impact of transport on air quality by tackling congestion and encouraging a shift to public transport, walking, and cycling also reduces $CO_2$ emissions. Measures to improve energy efficiency and cut energy demand, reduces air pollutants and GHG emissions alike.

**Figure 2.2: Co-benefits of management options**[17]



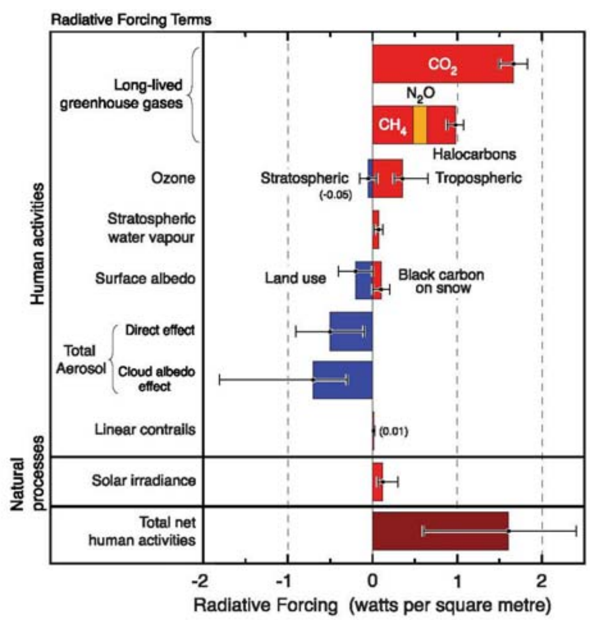

In most developing countries, the co-benefits approach is being recognized as a practical and effective tool in technical, policy, economic, and institutional perspectives. With the growing awareness for clean air, besides the pressure to support infrastructure needs, local impacts of air pollution will have a higher priority over global impacts of GHGs. However, this shouldn't suggest that the concept of low carbon society takes a back seat. The interventions that cities are trying to implement, including improving public transport (road and rail) or promoting non-motorized transport and increasing the energy efficiency in the industries reduce pollutants that contribute to both local as well as global environmental impacts.

In an urban environment, the health effects due to air pollution (mortality and morbidity) are the primary concern. At the same time, some known fractions of PM pollution (such as Black Carbon – **Figure 2.1**) and the secondary pollutants such as sulfates (from SO2) and ozone, also affects regional and global atmospheric chemistry and the radiation balance. **Figure 2.2** summarizes the radiative forcing of greenhouse gases (GHGs) and various types of aerosols[18]. The presence of large quantities of aerosols and the linked physical and chemical interactions are known to change the earth's radiation balance, affecting local and global temperatures and possibly precipitation. The level of interactions between various types of aerosols and climatic

[16] The theme of the 5th Better Air Quality Conference for Asian Cities, the largest air quality conference of Asia is "Co-Benefits", www.baq2008.org
[17] Source: Modified from presentation by Dr. Cornie Huizenga, Executive Director, CAI-Asia, Manila, Philippines
[18] Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis, Summary for Policymakers*

conditions, along with the presence of the greenhouse gases like $CO_2$, $N_2O$, and $CH_4$ is an emerging science[19].

**Figure 2.3: Radiative Forcing of Climate between 1750 and 2005**




At the global level, the **Figure 2.3** shows that although GHGs are quite important in the overall picture, pollutants that are usually considered only in the air quality domain, such as aerosols and ozone, also have considerable affect on climate change. Note that the sources of GHGs and the local air pollution are the same – fossil fuel combustion. Thus, in an urban environment, an intervention introduced to control air pollution, the combined benefits (also known as co-benefits) include considerable reductions in the GHG emissions (like CO2) and health benefits (due to reduction in PM) and aide in the reduction of the climate radiative forcing. In this study, we consider the PM pollution in a city as the primary indicator and the $CO_2$ emission reductions of select interventions as a co-benefit. Due to the nature of the analysis in this study, which focuses on the health impacts of PM pollution in a city, no independent analysis was conducted for black carbon (or other aerosol fractions) and their impact of climate radiative forcing; which can be extended in future studies.

[19] "Climate Impacts of Black Carbon – A Review and Policy Implications" – A report by the Princeton University. Full report is available @ http://www.bioenergylists.org/sellersprincetonbc

## Chapter 3.0

# Cities at a Glance

The six cities selected for this study (presented in **Figure 3.1**) are Pune (Maharashtra); Chennai (Tamil Nadu); Indore (Madhya Pradesh); and Ahmedabad, Rajkot, and Surat (Gujarat). The study domain, geographical conditions, population, general source characteristics from industrial and power generation, and vehicle and road statistics are presented in **Table 3.1** and some of the geographical characteristics for each city are presented in **Figure 3.2**. 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.

In elevation, except for Pune and Indore (both at ~550 meters), remaining cities are close to the sea level (ranging between 6 to 50 meters). 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. The domain are designated at 44 km x 44 km for Chennai, Ahmedabad, and Surat; 32 km x 32 km for Pune and Indore; 24 km x 24 km for Rajkot - the smallest of the six cities. For example, 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

**Figure 3.1: Location of the six cities**

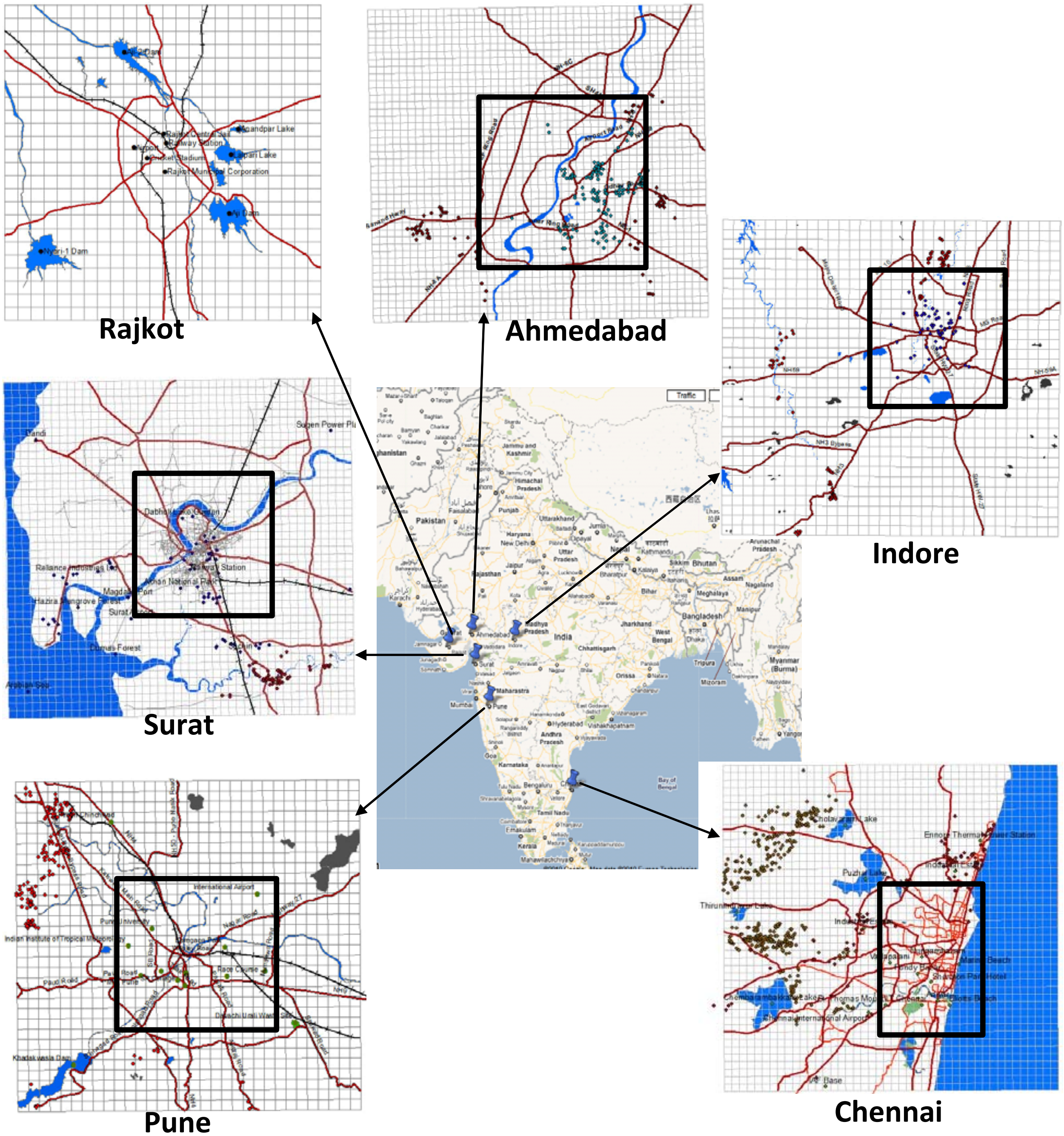
processes, use of diesel in the in-situ power generator sets, and the vehicle exhaust from the trucks moving in and out of the quarries. If only the main district area is considered for the emissions and pollution analysis, this important source will be missed. Similarly, the city of Chennai is expanded farther to the West to include the brick kiln clusters, an important source of criteria and GHG pollutants from manufacturing and freight movement. The emissions and pollution analysis was conducted at 1 km grid resolution for all the cities. 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.

**Table 3.1: Cities at a glance – geographical and transport characteristics**

| | 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 |
| Power plants | NO | YES (2) | NO | YES (2) | YES | NO |
| Installed capacity (MW) | - | 1,080 | - | 1,100 | 500 | - |
| Dominant fuel | NA | Coal | NA | Coal | Gas | NA |
| Industrial Estate | Medium | Large | Small | Medium | Large | Medium |
| Brick Kilns – Bull Trench | NO | YES | NO | NO | NO | - |
| Brick Kilns (number) | 400 | 600 | 120 | 320 | 200 | - |
| Annual average $PM_{10}$ ($\mu g/m^3$) | 60-160 | 60-120 | 60-170 | 80-100 | 75-100 | 80-120 |
| Number of monitoring stations | 5 | 6 | 3 | 6 | 3 | 2 |
| $PM_{2.5}$ 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 |
| % HDV of trucks | 26% | 50% | NA | 14% | 23% | 47% |
| % 2 Wheelers in total fleet | 75% | 79% | 77% | 74% | 80% | 82% |
| % Cars in total fleet | 14% | 15% | 11% | 15% | 10% | 12% |

*NA = not applicable; HDV = heavy duty vehicles*

**Figure 3.2: Geographical domains of the six cities**

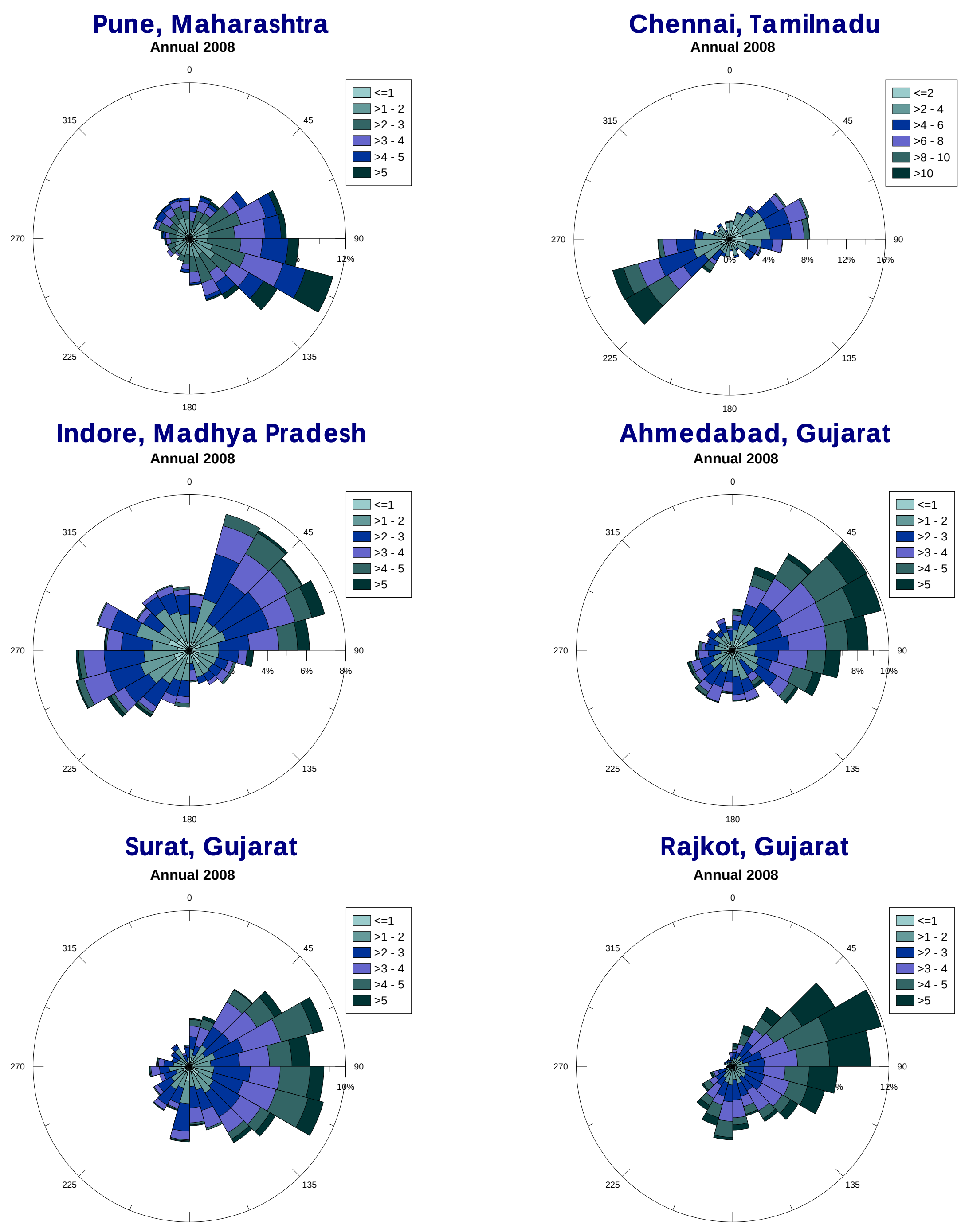



*In each of the geographical study domains presented above, except for the city of Rajkot, the thick dark square represents the main district area with most of the city population; the dots represent the brick kilns and industrial units; the red lines represent the main roads and highways passing through the city*

## *3.1 Meteorological Conditions*

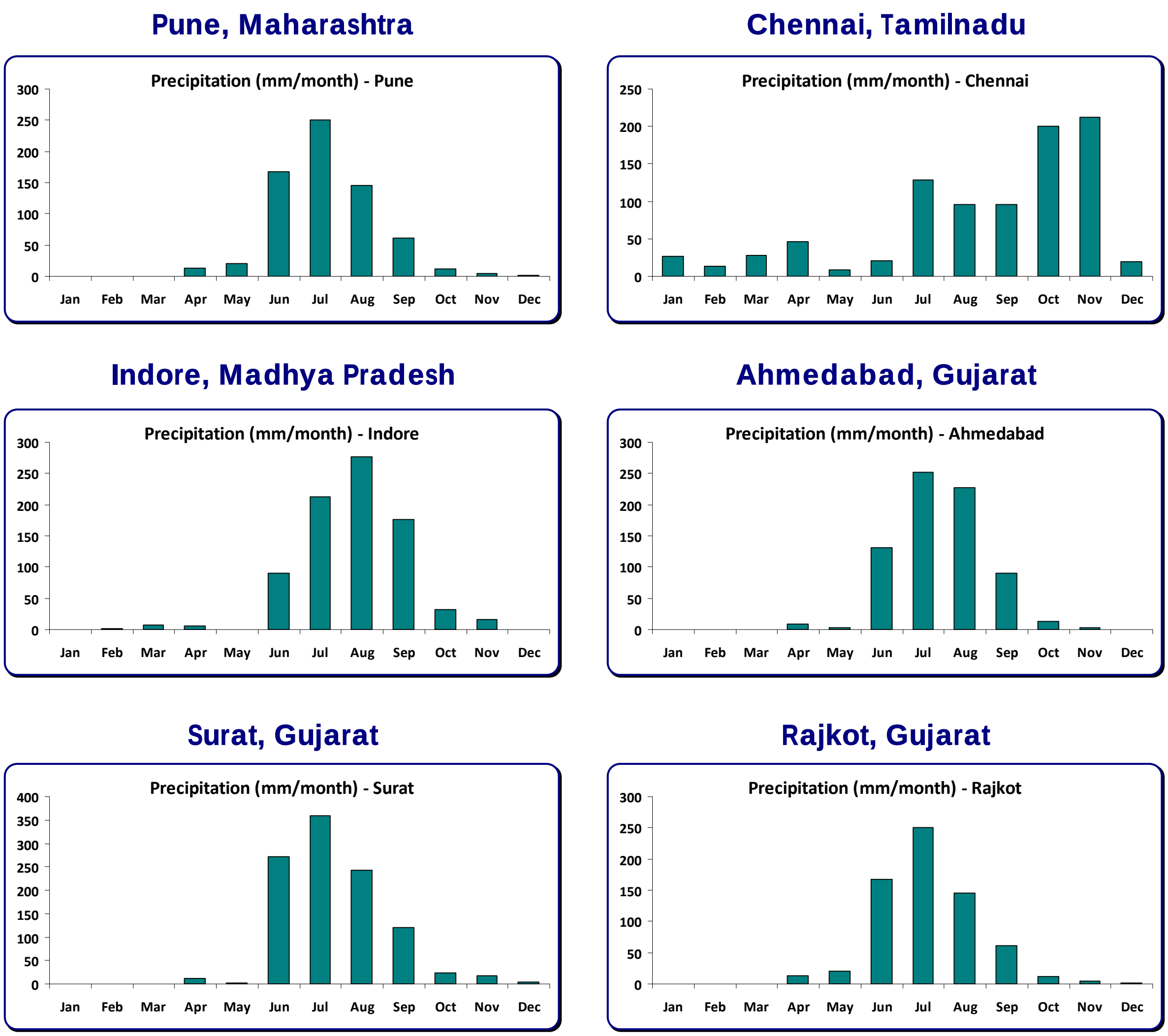
The meteorological conditions – wind speeds, wind directions, precipitation, and the mixing layer heights, prevalent in each of the cities are presented here.

**Figure 3.3: Annual wind speed and wind directions (2008)**



The meteorological data presented in **Figure 3.3** for annual wind speeds and directions, **Figure 3.4** for monthly precipitation and **Figure 3.5** for mixing layer heights are obtained from the NCEP Reanalysis fields, an open-source database maintained and distributed by NCAR[20]. The meteorological data for precipitation, wind speeds and wind directions are available for the period from 1948 to 2010. For this study, data from year 2008 is extracted for the grid cells covering the city boundaries of Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot[21].

**Figure 3.4: Monthly precipitation patterns (2008)**

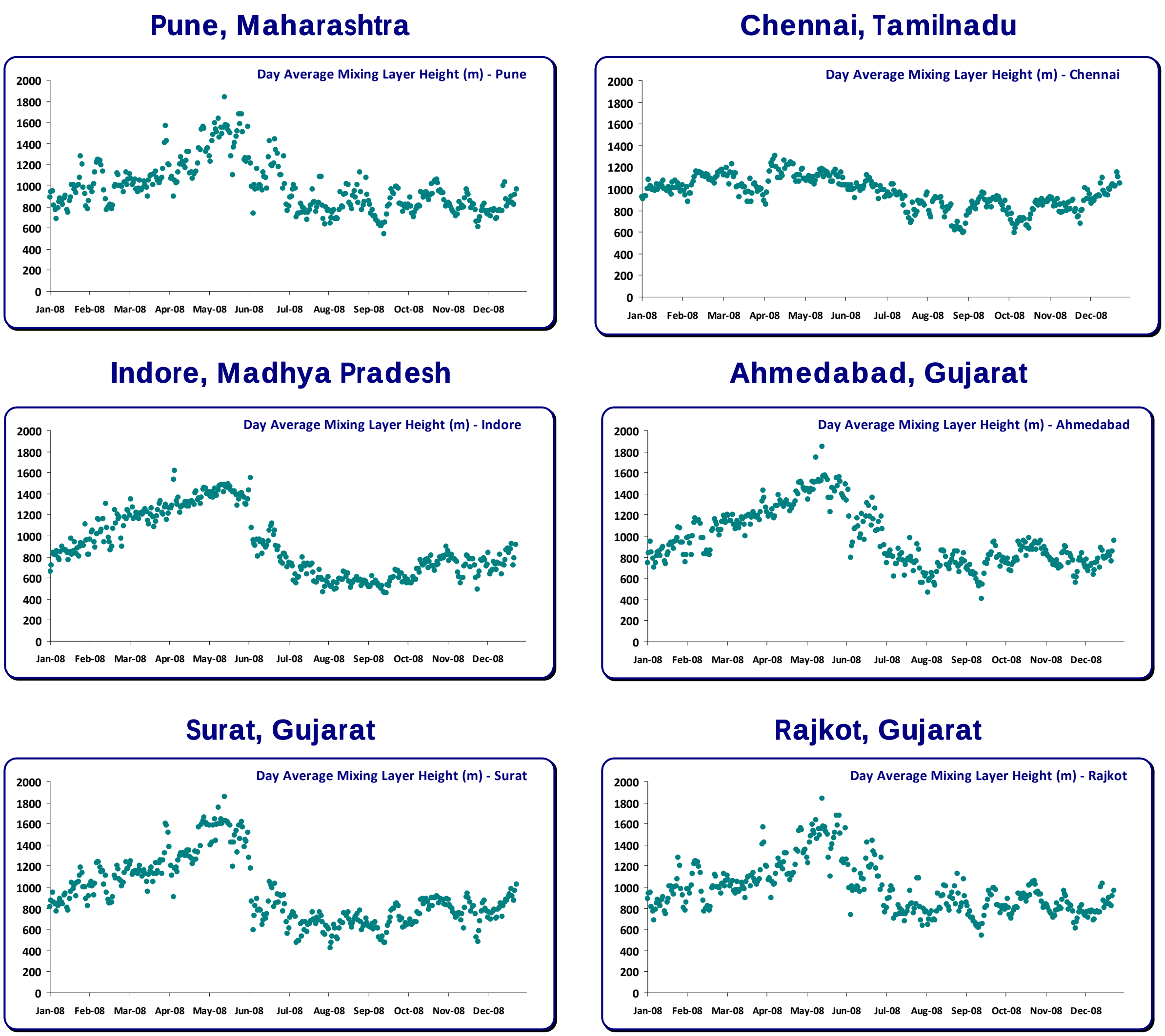



[20] NCEP/NCAR Reanalysis data for a number of meteorological conditions is available for a period starting from 01/01/1948 @ http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html The meteorological processing is conducted before the dispersion modeling.

[21] To calculate mixing layer height, the NCEP reanalysis data is re-gridded and multiple parameters are utilized, such as 3D wind and temperature, surface wind, temperature, and pressure, and 2D surface heat flux, and precipitation fields.

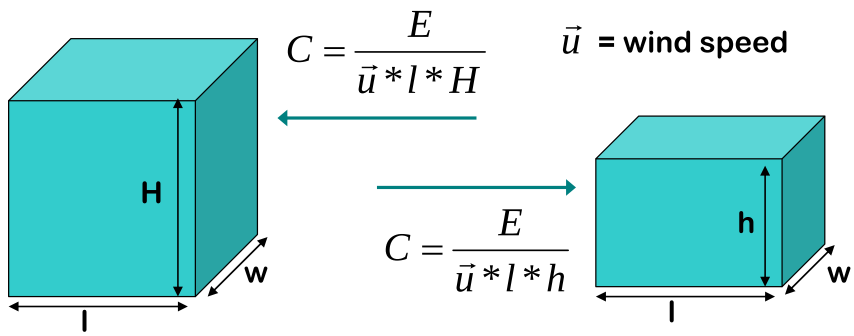
The port cities of Chennai and Surat are the wettest and as illustrated by the wind rose functions (in **Figure 3.3**), they also experience the strongest land-sea breeze affects. These strong winds blowing away from the city, for the most part of the year, result is dispersing a significant amount of the pollution from the industries and the power plants located along the coast. The precipitation fields (in **Figure 3.4**) are vital in dispersion modeling, as precipitation accounts for the wet deposition of pollution and entrainment of suspended particles; and reduces the ambient pollution levels naturally. The wet surface conditions are also hinder re-suspension of the dust particles on the roads.

**Figure 3.5: Daily mixing layer heights (2008)**




The mixing height plays a critical role in dispersion of the emissions over the seasons. The winter months are more polluted than the summer months for two reasons – one, precipitation is usually higher during the summer monsoon and two, the mixing layer is lower during the winter months. Mathematically, this is illustrated in **Figure 3.6** as a box model. By definition, the ambient concentration is defined as mass over volume. Assuming that the emissions are equally mixed in an urban environment under the mixing layer, for the same emissions, a lower mixing height means higher ambient concentrations. Similar to the mixing layer height, the wind speed is also very relevant. The higher wind speeds are responsible for driving part of the pollution out of the city limits and thus reducing the average contribution of the local emissions. On the other hand, the emissions from regions outside of the city also contribute to the local pollution, which is coined as long range transport component, affecting the background concentrations in the city.

**Figure 3.6: Box model illustration of the impact of the mixing layer height**




The mixing layer heights in **Figure 3.5**, except for Chennai, follow a typical pattern of highs in the summer and lows in the winter months. The mixing layer height is vital for the dispersion of emissions in a city. In the winter months, a lower height hinders dispersion and thus exacerbates the ambient pollution levels, unlike the summer months. In the case of Chennai, land-sea breeze and stronger winds (compared to other cities) result in a more uniform mixing layer height over the seasons. Meteorological parameters are also available at the seasonal level (upon request).

## *3.2 Particulate Pollution*

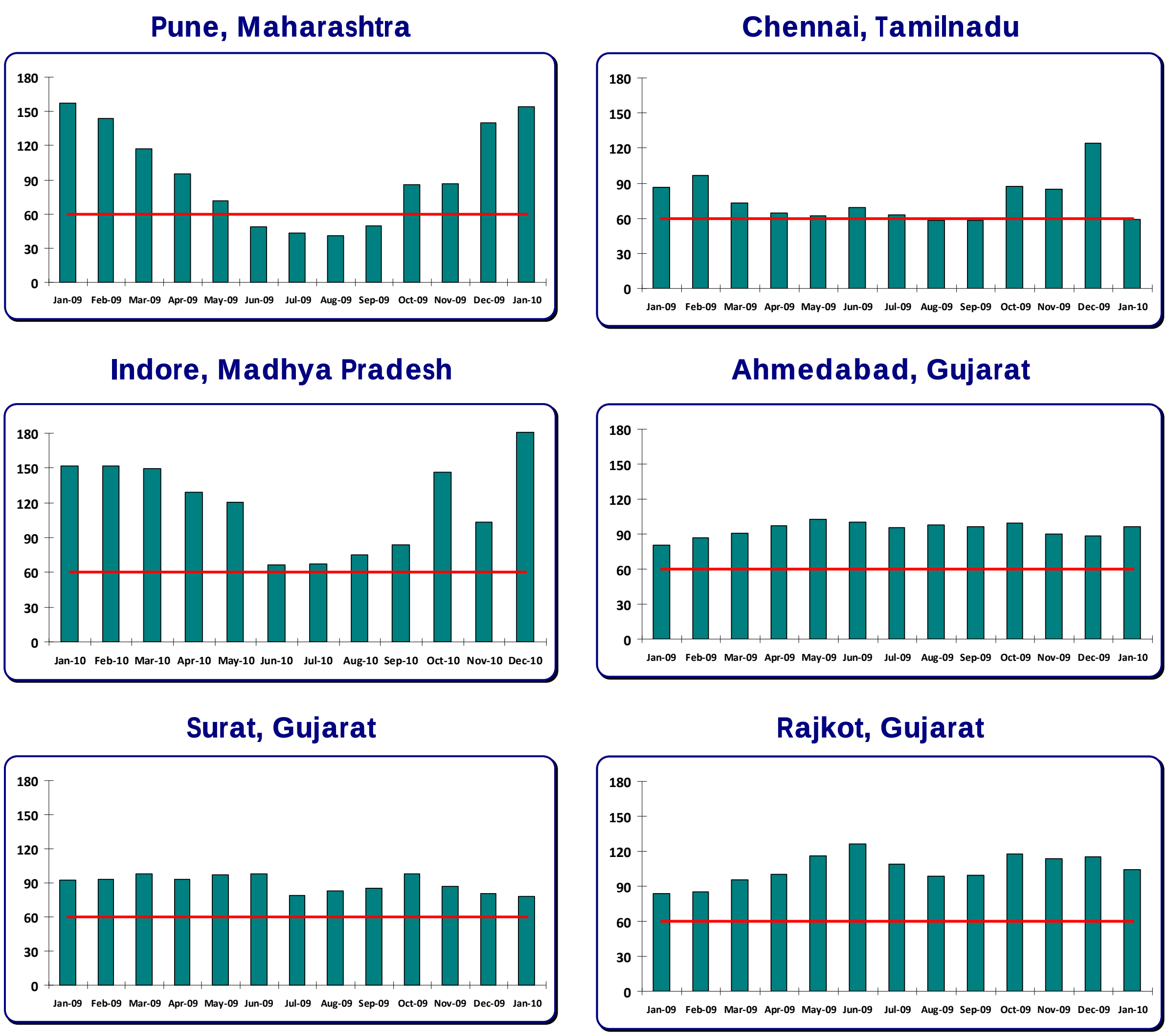
The Central Pollution Control Board operates a network of approximately 400+ stations in 130 cities across India, measuring ambient levels of criteria pollutants such as $SO_2$, $NO_x$, and $PM_{10}$. A majority of the stations are manually operated, which results in a discontinuity of data from these stations. In November, 2009 the MoEF and CPCB proposed new protocols for the States to improve monitoring at these stations and improve their capacity to support policy decisions. New pollutants like $PM_{2.5}$, Ozone, and some carcinogenic volatile organic compounds such as Benzene, were added to the monitoring list, which adds strength to data collection efforts. In major cities, continuous monitors are now operational, which provide additional information on

**Figure 3.7: National ambient monitoring network in India**

these pollutants. The range of average $PM_{10}$ concentrations measured in Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot is presented in **Table 3.1** (all the stations are operated by the state pollution control boards) and a summary of the monthly average concentrations from all stations in each city is presented in **Figure 3.8**. All six cities exceed the annual ambient standard of 60 $\mu g/m^3$.

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 $\mu g/m^3$.

**Figure 3.8: Monitored monthly average $PM_{10}$ concentrations**



The following section includes a discussion of the major sectors for each city and provides an overview of the city's characteristics in a comparative framework.

## *3.3 Industrial Estates*

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[22] have grown substantially[23]. 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 (MIDC)[24]. Similar IT parks constructed under the SEZ schemes include the Magarpatta city to the east of the city with close to 5,000 households residing in the area.

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[25]. 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[26].

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

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[22] Automotive companies like Tata Motors, Mercedes Benz, Force Motors (Firodia-Group), Kinetic Motors, General Motors, Volkswagen, and Fiat have manufacturing facilities in and near Pune. Several automotive component manufacturers like Saint-Gobain Sekurit,TATA Autocomp Systems Limited, Robert Bosch GmbH, ZF Friedrichshafen AG, Visteon, and Continental Corporation also set up facilities in and around Pune.

[23] Details of the research work at ARAI are available @ https://www.araiindia.com. ARAI played an integral part in testing and establishing the emission factors for 62 vehicle categories in the Indian fleet, as part of the six city particulate pollution source apportionment studies conducted by Ministry of Environment and Forests and Central Pollution Control Board of India. Details of the source apportionment studies are available @ http://cpcb.nic.in/Source_Apportionment_Studies.php

[24] The Economic Times, "Hinjewadi: The land of opportunity", December 7th, 2007 @ http://economictimes.indiatimes.com/articleshow/2604416.cms

[25] The Business Line, August 31st, 2010, "Nissan to export Micra thru Ennore port soon" @ http://www.thehindubusinessline.in/2010/09/01/stories/2010090151270200.htm

[26] The Ennore port in Chennai @ http://www.ennoreport.gov.in/

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.

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[27].

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[28].

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

[27] JNNURM, City Development Plan for Ahmedabad, Gujarat
[28] JNNURM, City Development Plan for Surat, Gujarat

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.

## *3.4 Transport*

The vehicle fleet characteristics are presented as a summary in **Table 3.1** and detailed break-up of the fleet in **Table 3.2**. 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 3.1**).

In case of Pune[29] 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.

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 and fleet percentages are presented in **Figure 3.9**.

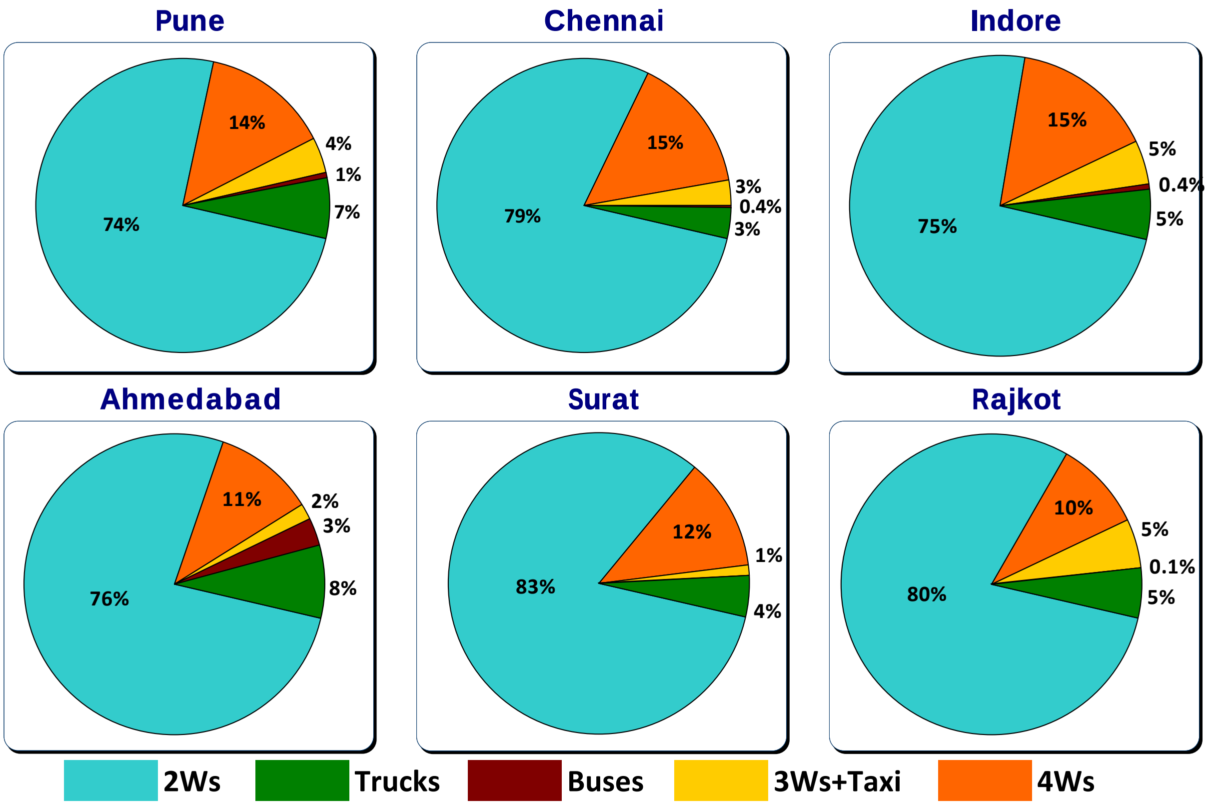
[29] Further statistics on the vehicle counts prior to 2004 and traffic management are available @ http://www.punepolice.gov.in/statistic.htm#gipovdtp5y
The vehicle fleet compositions utilized in this analysis matched to the numbers presented in Environmental Status Report for Pune city 2009-10 (in Marathi) available @ http://punecorporation.org/pmcwebn/index.aspx

**Table 3.2: 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** |

For comparative purposes in **Table 3.1**, 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.

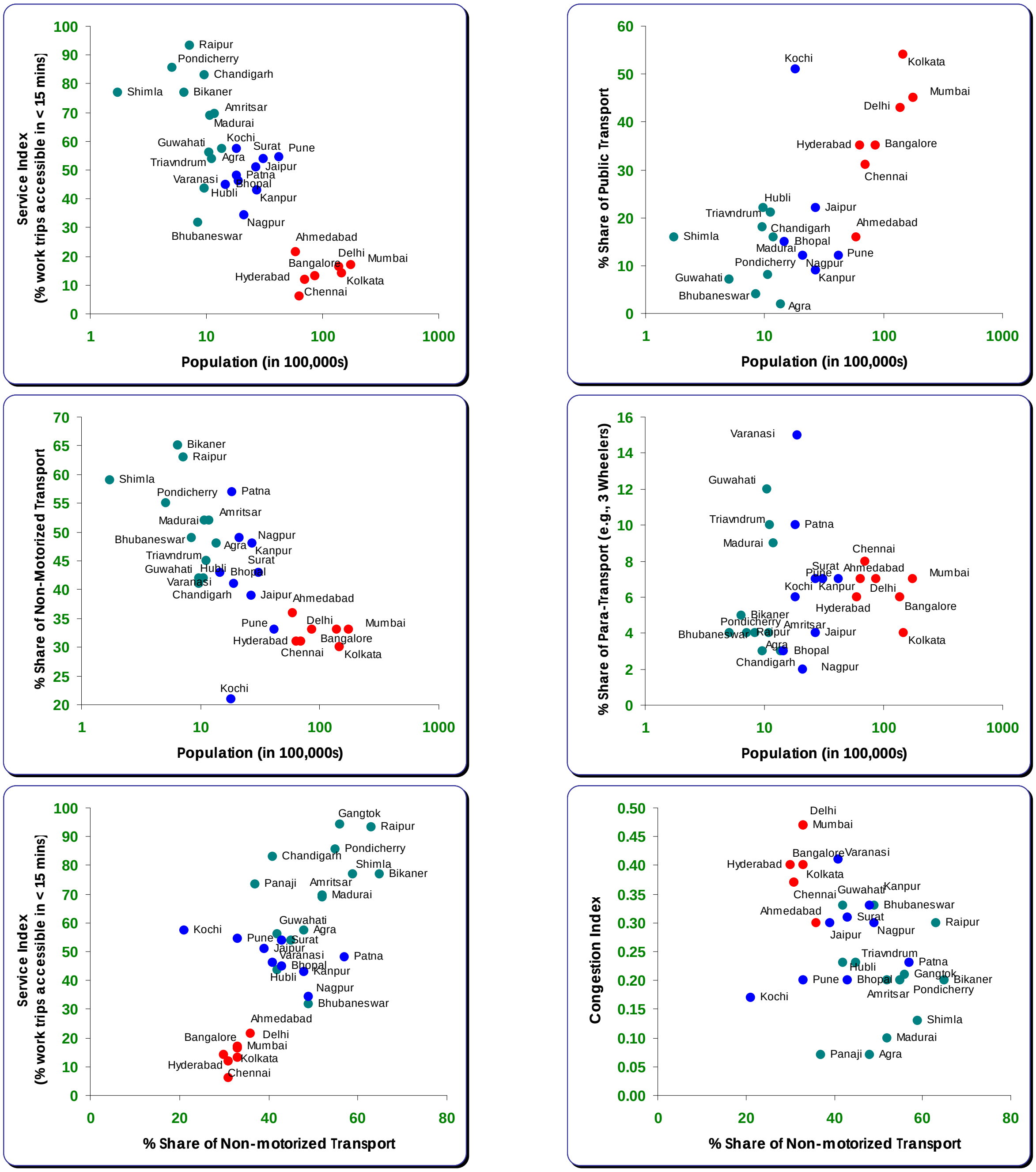
**Figure 3.9: Vehicle fleet composition in the six cities**




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.

The public transport systems in the Tier 1 and Tier 2 cities are expanding. This was also highlighted in the studies conducted by the Ministry of Urban Development of India, that as the cities are expanding, the collective need for public transportation systems is further realized and implemented. A summary of the data is presented in **Figure 3.10**. The big cities have at least doubled their administrative boundaries in the last decade. This, combined with increasing incomes, has been the impetus for transport demand to increase exponentially. **Figure 3.10**, **top left panel**, presents the relationship between the city population (on log scale) and city travel service index (defined as the percentage of work trips accessible in less than 15 minutes of travel time). The megacities (red dots) fair poorly compared to the medium size cities (blue dots) and then the tertiary cities (turquoise colored dots).

## Figure 3.10: Passenger travel statistics in India[30]




**Color code: red = mega cities; blue = secondary cities; turquoise = tertiary cities**

[30] Data is sourced from the report "Traffic and Transportation Policies and Strategies in Urban Areas in India" by Ministry of Urban Development, Government of India, May, 2008 @ http://urbanindia.nic.in/moud/theministry/ministryofurbandevelopment/main.htm

As the cities are expanding geographically, the need for motorized (self or public) transport is becoming imminent. Important messages in **Figure 3.10**:

- As cities grow, access to the work place in less than 15 minutes travel time decreases
- As cities grow, the share of public transport in the form of buses (percent of passenger trips) increase
- As cities grow, the share of non-motorized transport (NMT) in the form of walking and cycling (percent of passenger trips) decreases
- As cities grow, the share of para-transit (including 3-wheelers) increased, but not at the same rate as the other modes.
- Lower the share of non-motorized transport in the city, lower the service index (% trips accessible in less than 15 minutes travel time)
- Lower the share of NMT in the city, higher the congestion index, primarily due increase in the personal transport

The access to public transport is growing, but not enough to support the growth in travel demand. **Figure 3.10**, **top right panel**, presents the share of passenger trips covered by the public transport against the population in the cities. The access to the public transport is high in the megacities, and expected to grow under the JNNURM funds[31]. However, delays in the bus manufacturing sector to supply the necessary number of buses (currently standing at ~70,000 buses) is hindering further promotion of public transport[32]. In India, the growth rate for the motor vehicles (passenger cars and 2-wheelers) is approximately 10 to 12 percent[33]. While the share of personal transport is growing, it is important to focus on the NMT (walking and cycling) together, which forms a major portion of the passenger trips, especially the short trips < 3 km.

An intervention that some cities are trying to implement is the Bus Rapid Transport (BRT) systems. A number of cities across the world have successfully implemented this design into the public transport systems – with world's best practices coming from Bogotá, Colombia and Curitiba, Brazil. Similar efforts have been attempted in Pune (with limited success) and Ahmedabad.

The Youth Commonwealth games were hosted in Pune and for the event, the city undertook a foray into BRT systems with the aim to encourage the use of public transportation, in particular buses. Though the program was implemented with much enthusiasm, faulty design and problems in implementation meant that the project did not turn out as planned. The pilot was restricted to a limited area, enforcement of lanes for only busses was inadequate, the design of

[31] Jawaharlal Nehru National Urban Renewal Mission (JNNURM) @ http://jnnurm.nic.in/

[32] Down to Earth, October, 2008, "City bus: In demand, out of supply" @ http://www.downtoearth.org.in/cover.asp?foldername=20081031&filename=news&sid=45&page=1&sec_id=9&p=1
Times of India, February 8th, 2009, "BRTS dreams may go bust" @ http://timesofindia.indiatimes.com/articleshow/msid-4096144,prtpage-1.cms
The Hindu, May 13th, 2009, "Delhi Govt. faces cancellation of bus funding under JNNURM" @ http://www.hindu.com/thehindu/holnus/004200905131452.htm

[33] Times of India, May 12th, 2009, "On growth track: Auto sales zoom 11% in April, 2009", report from SIAM – Society of Indian Automobile Manufacturer @ http://timesofindia.indiatimes.com/Car-sales-up-420-bikes-jump-1211-in-April/articleshow/4508229.cms

bus stops in the center of the road caused problems for commuters and in some cases, was responsible for accidents, and the number of low-floor-buses was much below the original planned fleet. As a result of, the BRT system is all but dismantled in Pune City[34]. Ahmedabad launched its BRT system in 2009[35]. The project was approved in November, 2006 for the first phase of 12.5 km from RTO to Pirana. The network is now being expanded with an expected total length of BRTS corridor of ~88 km by March, 2012.

## *3.5 Construction*

**Figure 3.11: An ariel 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 3.1**). The clusters are presented in the **Figure 3.2** as red dots. The type of kilns also varies significantly between the cities – from scove or clamp kilns to bull-trench kilns. The former is an inefficient method of baking bricks, which is the common sight for 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 3.11**. 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.

In the brick manufacturing industry, along with the emissions associated with coal and biomass burning at the kilns, emissions associated with the transfer of soil from the quarries to the manufacturing units, and transfer of bricks from the manufacturing sites to the construction sites, form a significant portion. The use of the light duty and heavy duty vehicles in and around the brick kiln clusters is highlighted while spatially allocating the transport sector emissions to the 1 km grids over the study domains. Around Pune, the total estimated brick production is ~1,800 million per year with an estimated coal consumption of 0.27 million tons[36]. The brick kiln cluster to the northwest of the city has ~400 active units. Of the six cities, largest brick manufacturing clusters are located outside the Chennai district, counting ~600. The total installed capacity in the six cities is estimated at ~3,000 million per year.

[34] India Together, 2007, "Pune's BRT stumbles at start" @ http://www.indiatogether.org/2007/jan/eco-brtpune.htm
[35] A Note on the BRT System in Ahmedabad , Mr. Sudhir Gota, CAI-Asia, Manila, Philippines
[36] UNDP/GEF, 2007, "Energy Efficiency Improvements in the Indian Brick Industry", project document

The pollution from the fossil and biomass fuel usage at the brick kilns is a growing problem around the cities. During the agricultural harvest season, the kilns use a mix of biomass and coal for heating and in the off season, past the harvest season, the heating is supported primarily by coal. Burning of fossil and biomass fuels release significant amounts of $SO_2$, $NO_x$, PM, and $CO_2$. In the vicinities of the urban centers, the PM, $SO_2$, and $NO_x$ emissions have an immediate affect on the ambient air and human health. The black Carbon (BC) emissions, a fraction of PM emissions, have a prominent role in the climate science. BC, a short-lived species, can help counteract the impacts of growing GHGs and support the climate policy dialogue at the global scale[37]. The use of coal and

**Figure 3.12: An aerial view of quarry operations along the Pune-Nashik highway**


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 3.2**) at Moshi near Pune-Nashik highway. An aerial view of the quarry operations is presented in **Figure 3.12**, 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[38]. The health risks associated with constant exposure to the dust particles in these areas is under study[39]. In this study, the quarry locations are mapped to account for the resuspension of dust due to crushing and handling of rock and emissions from the truck movement and in-situ diesel generator usage.

## *3.6 Power Plants*

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

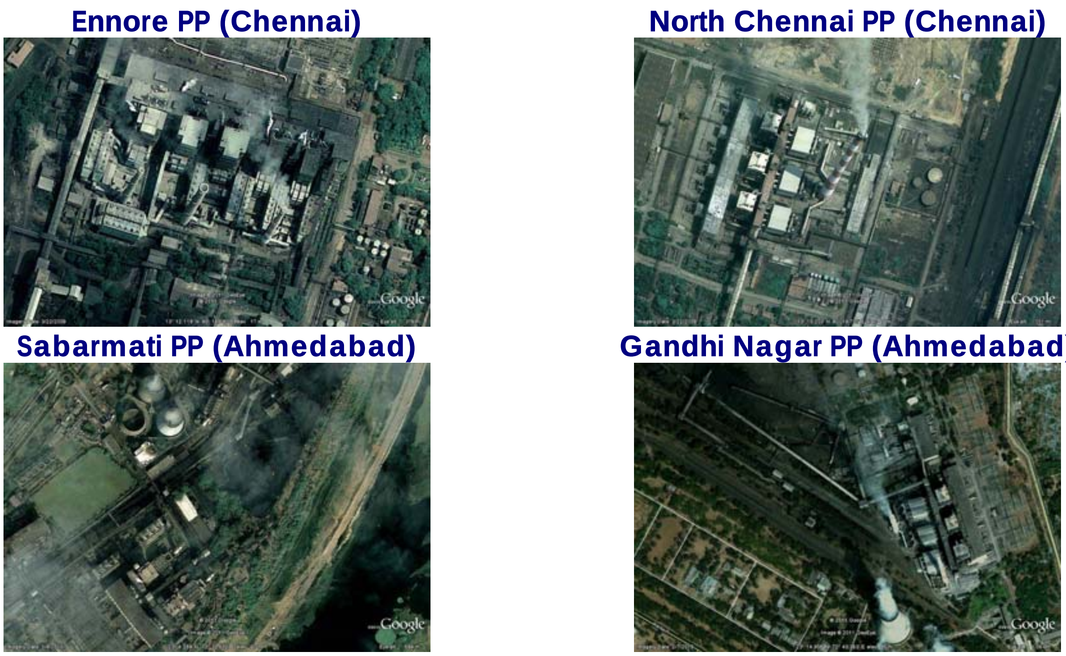
[37] "Climate Impacts of Black Carbon – A Review and Policy Implications" – A report by the Princeton University. Full report is available @ http://www.bioenergylists.org/sellersprincetonbc

[38] Pune Mirror, February 6th, 2011, "Quarrying Mafia at it Again" @ http://www.punemirror.in/article/2/2011020620110206061931035 49f862d/Quarrying-mafia-at-it-again.html

[39] Express India, January 4th, 2008, "Bastu Rege, coordinator of Santulan, an NGO, that conducts pashan shalas (schools) for children at stone quarries says that these kids face constant health risks due to the environmental pollutants. Rege, who is instrumental along with others in opening 70 such schools in Pune district with 2,500 children living at stone quarries, says that the children often suffer from skin diseases, sore eyes and gastroentritis due to unhygienic water."
@ http://www.expressindia.com/latest-news/Children-in-stone-quarries-hit-by-lung-disease/257713/

Sabarmati power station (**Figure 3.13**) 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 3.13: An aerial view of power plants**

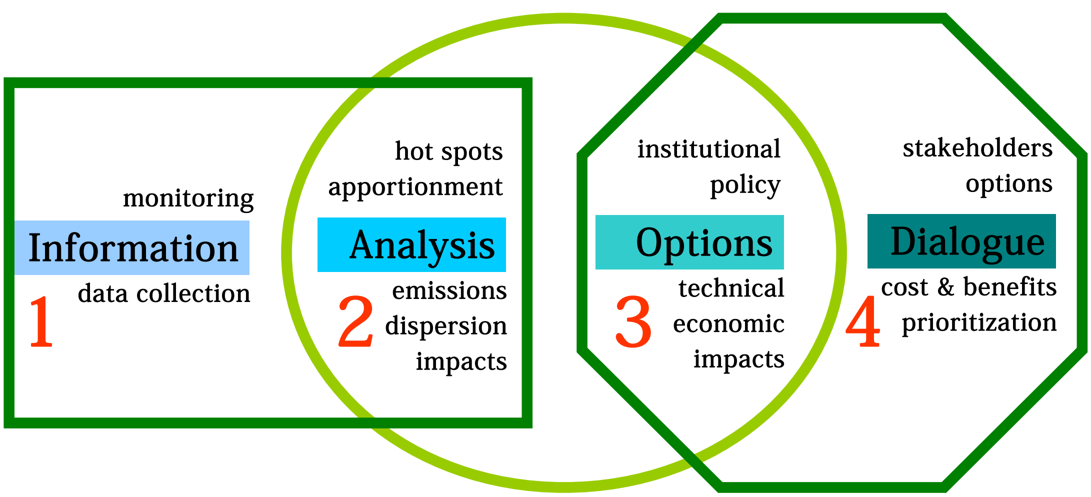


## Chapter 4.0

# Emissions Inventory and Dispersion Modeling

The Simple Interactive Models for better air quality (SIM-air) tools were utilized to establish the baseline emissions inventory for each city, followed by dispersion modeling to assess health impacts and baseline and select interventions for some emission sources[40]. The SIM-air family of tools is developed on an open-source platform, in a plug-n-play mode to support emissions and pollution analysis in the cities. The tools are supported by publicly available information from all known sources of emissions (for example those available in Geographic Information Systems (GIS) such as road maps, population maps and industrial locations).

**Figure 4.1: Urban air pollution analysis steps**




[40] The details of the SIM-air program and the tools are available @ http://www.urbanemissions.info. Previous urban applications of SIM-air tools include Hyderabad and Delhi (India); Bangkok (Thailand); Lagos (Nigeria); Antananarivo (Madagascar); Shanghai and Shijiazhuang (China); Hanoi (Vietnam); Dhaka (Bangladesh); and Ulaanbaatar (Mongolia).

In this study, the analysis steps undertaken are presented in **Figure 4.1**, starting with

- Information – 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.
- 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, activities (such as industries, hotels, hospitals, apartment complexes, institutions, and markets), and followed by dispersion modeling to convert the emissions into ambient concentrations, utilizing the meteorological conditions presented in the previous chapter. The grid cells with concentrations exceeding the threshold values, along with population data per grid cell, were then utilized to evaluate the health impacts. Further details on each of these steps are presented in the following sections.
- Options – for the select interventions (presented in **Chapter 1**), the emissions, concentrations, and health impact reductions were evaluated following same methods utilized for baseline calculations.
- Dialogue – the baseline and intervention results will be disseminated (to be determined) to the city stakeholders

## *4.1 Previous Studies*

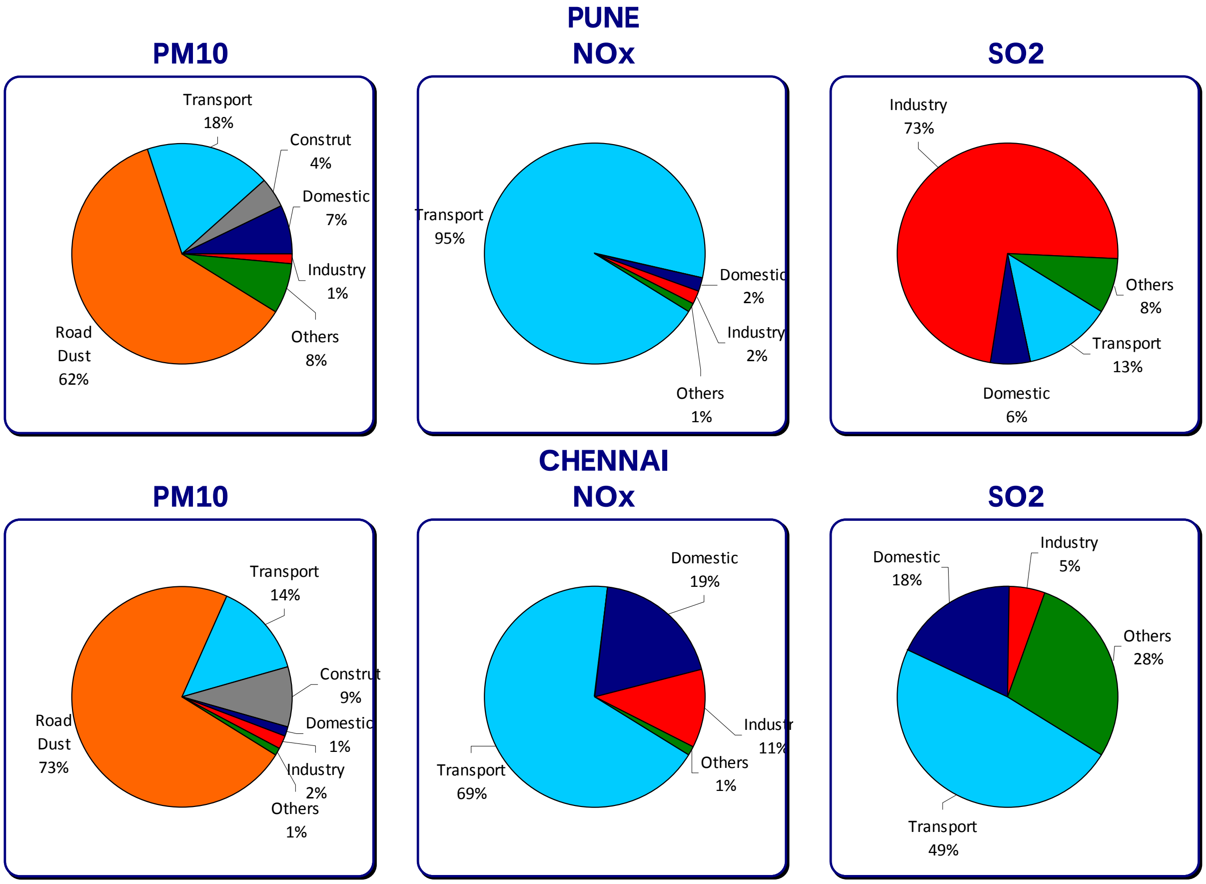
For the city of Pune, an emissions inventory was developed by the Air Quality Management Cell, an independent organization associated with the zonal pollution control board of Pune. This work was carried out as part of the PREIS program[41] with technical support from the United States Environmental Protection Agency (USEPA) to improve air quality management practices in India. As part of this effort, significant training and field study activities have been undertaken in the City of Pune.

Following the PREIS study, in 2006-07, Ministry of Environment and Forests (MoEF) and Central Pollution Control Board (CPCB) of India, carried out particulate pollution source apportionment study in six cities – Delhi, Kanpur, Chennai, Mumbai, Pune, and Bangalore[42]. As part of the study, an emissions inventory was also developed (and published in January, 2011). The emissions estimated under for Pune account for 32.3 tons $PM_{10}$ per day, 41.4 tons per day of $NO_x$, and 7.1 tons per day of $SO_2$. The emissions estimated under the CPCB study for Chennai district account for 11.02 tons $PM_{10}$ per day, 12.1 tons per day of $NO_x$, and 1.3 tons per day of $SO_2$. The low lying sources like the road dust and vehicle exhaust tend to contribute more to the ambient pollution compared to the elevated sources, which tend to travel longer distances.

[41] Pune Regional Emissions Inventory Study (PREIS) @ http://www.unipune.ac.in/dept/science/environmental_science/es_webfiles/preis.htm

[42] A summary report of the particulate pollution source apportionment studies carried out in Pune, Chennai, Kanpur, Delhi, Mumbai, and Bangalore is available @ http://moef.nic.in

**Figure 4.2: Contribution of major sources to emissions inventory (2006-07) from CPCB/MoEF study**




In CPCB's study, it is important to note the methodology employed in developing these inventories. The inventory is for the base year of 2006-07 and represents only the sources in the main city district. This does not include the areas surrounding the main district where the industrial activity is generally larger than the in-district activities. The inventories were primarily surveyed and estimated for an area of 2km x 2km around the monitoring site selected for the source apportionment study and then extrapolated to the city district area. This could lead to some bias in the final inventory, as the modeled concentrations will not account for the long-range transport of emissions within the vicinity of the city districts. For example, in case of Chennai, there two large coal-based thermal power plants with a generation capacity of ~1100 MW and a number of petrochemical refineries and other manufacturing which fall outside the city administrative district, are not included in the inventory. In case of Pune and Chennai, the inventory does not account for the brick kiln emissions. In both the cities, the clusters are ~20 km away from the city district boundaries, though they are known to contribute to ambient air pollution in the city limits.

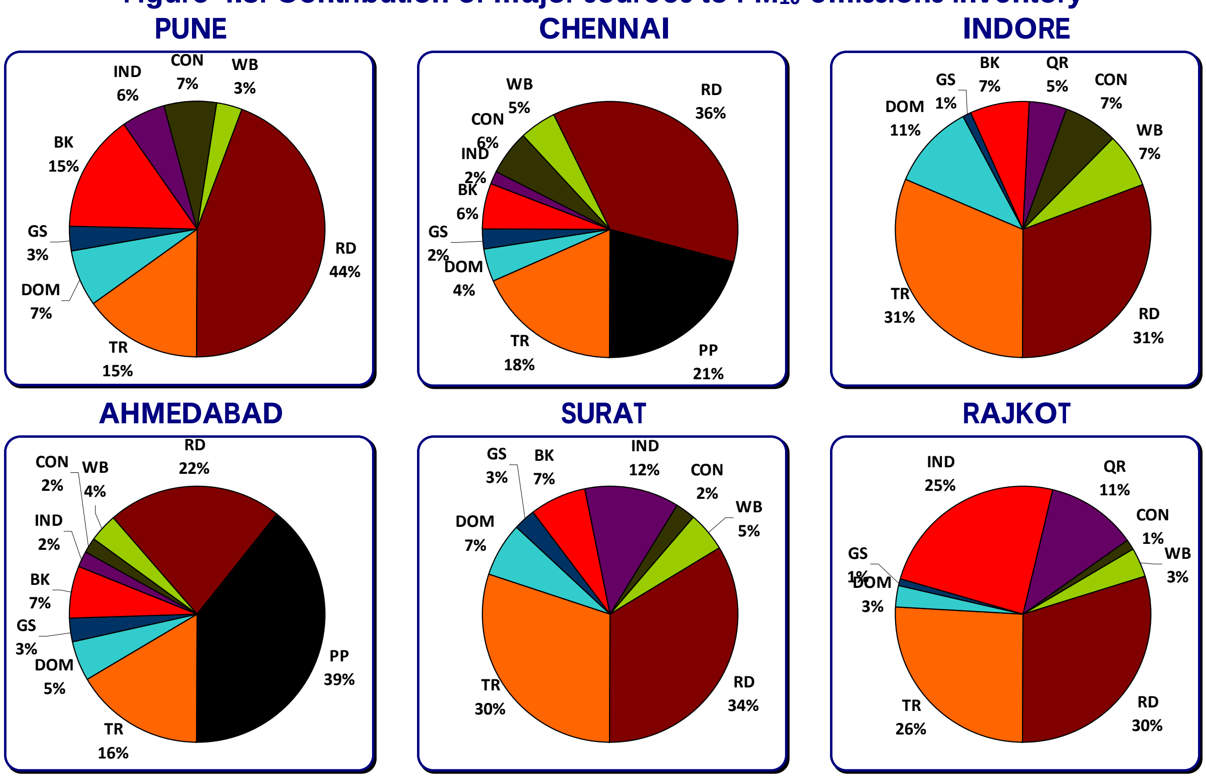
## *4.2 Emissions Inventory for 2010*

In this study, an emissions inventory is established using bottom-up consumption patterns for various sectors and using appropriate emission factors from the past and relevant literature. 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.

**Table 4.1: Summary of 2010 emissions inventory for the six cities (numbers rounded)**

| City | PM2.5 (tons) | PM10 (tons) | SO2 (tons) | NOx (tons) | CO (tons) | CO2 (million tons) |
|---|---|---|---|---|---|---|
| **Pune** | 16,650 | 36,600 | 3,600 | 127,350 | 438,200 | 11.9 |
| **Chennai** | 26,000 | 56,400 | 15,100 | 268,200 | 857,500 | 30.6 |
| **Indore** | 9,900 | 17,900 | 2,550 | 146,600 | 263,300 | 8.6 |
| **Ahmedabad** | 17,500 | 35,100 | 10,500 | 175,300 | 510,150 | 22.4 |
| **Surat** | 12,000 | 19,950 | 3,350 | 146,450 | 371,400 | 11.6 |
| **Rajkot** | 7,750 | 14,000 | 2,200 | 91,750 | 236,700 | 7.4 |

**Figure 4.3: Contribution of major sources to $PM_{10}$ emissions inventory**




TR = transport; BK = brick kilns; GS = generator sets; DOM = domestic fuel combustion; CMQ = construction material processing at quarries; RD = road dust; WB = open waste burning

**Figure 4.4: Contribution of major sources to $PM_{2.5}$ emissions inventory**

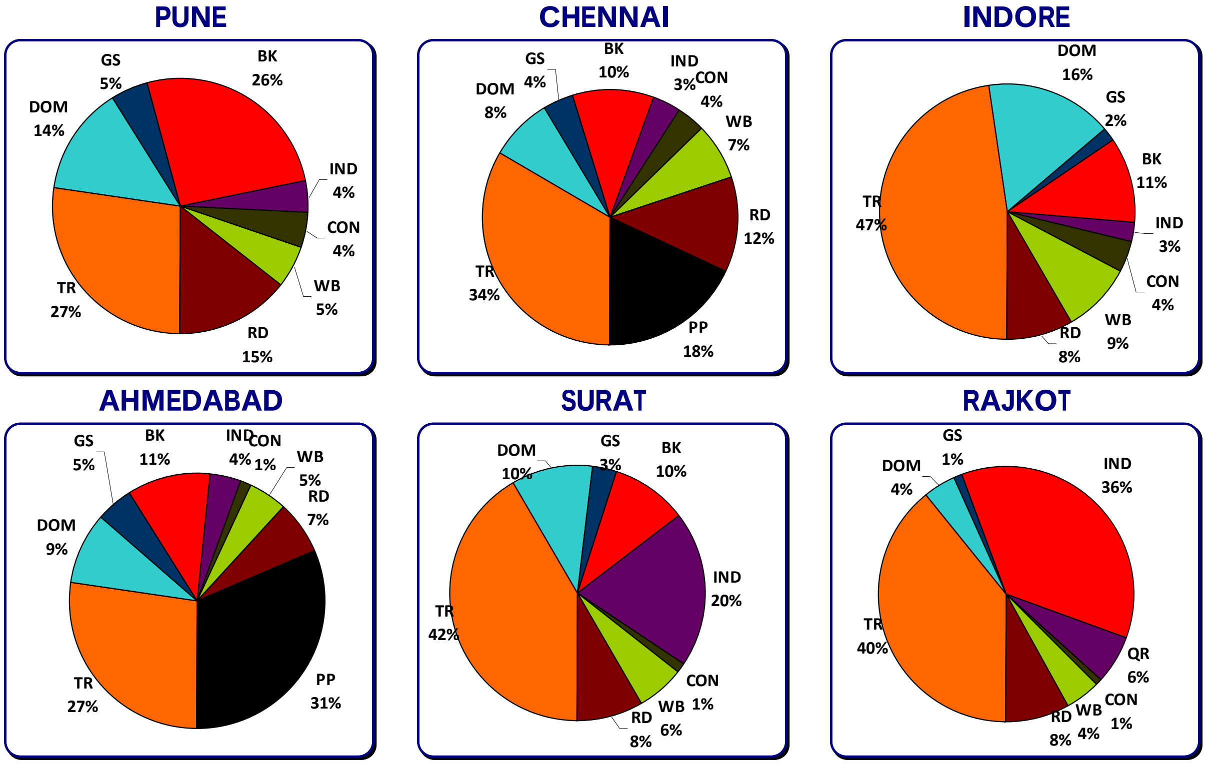
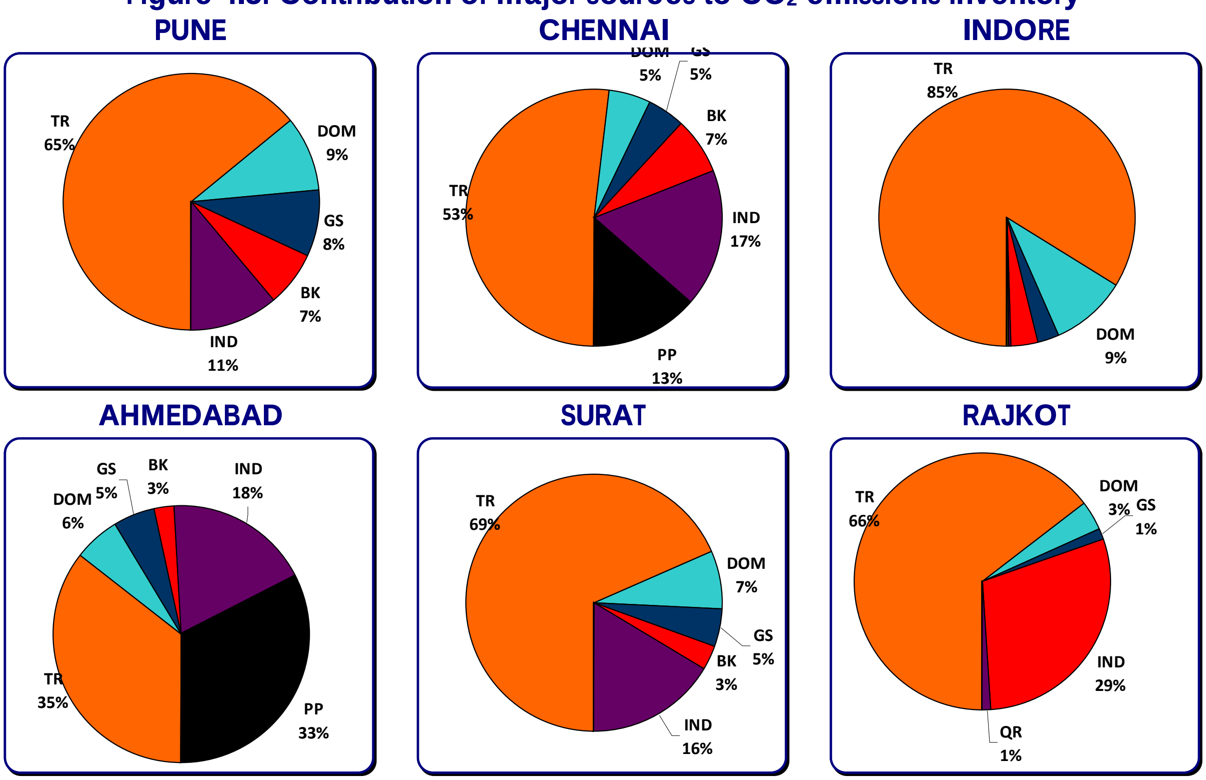



**Figure 4.5: Contribution of major sources to $CO_2$ emissions inventory**

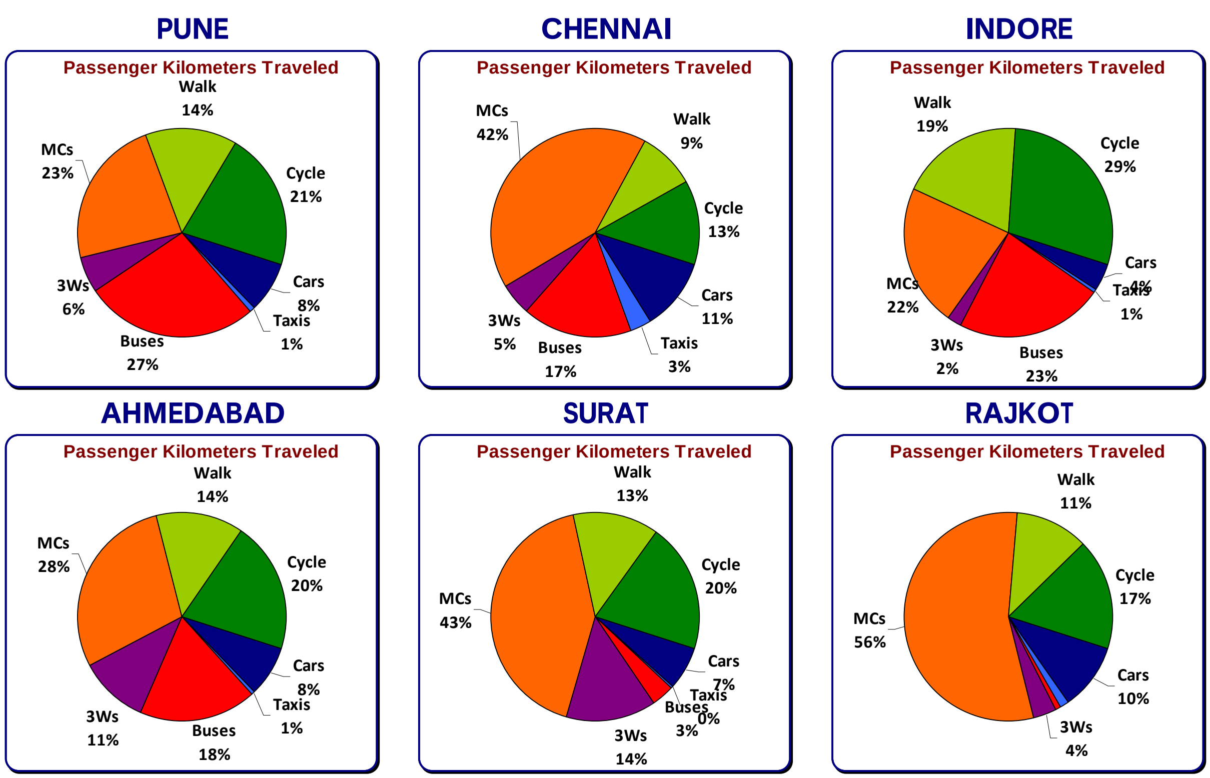



TR = transport; BK = brick kilns; GS = generator sets; DOM = domestic fuel combustion; CMQ = construction material processing at quarries; RD = road dust; WB = open waste burning

Some interesting notes 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 resuspension 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.

**Figure 4.6: Estimated percent passenger kilometers traveled**



***The transport sector is the major contributor***. In this study, inventory analysis is carried out for the motorized "in-city" passenger vehicles and the freight transport, covering the current trends in five modes of transport (passenger cars, motorcycles, 3 wheelers, buses, and trucks) and estimated the energy consumption and emissions using the information existing studies, the factors developed by ARAI as part of the CPCB source apportionment study, and academic publications[43]. **Table 3.2** presents a summary of the vehicles registered in the six cities and a summary of the shares of vehicles in **Figure 3.7**.

The changing geographical setting in the city and need for better mobility is leading the traffic demand and related congestion, reflected in the double digit growth rate in the number of registrations of cars and multi-utility vehicles, and motor cycles (2-wheelers). While the number of 2-wheelers, 3-wheelers, and 4-wheelers dominate the vehicle numbers, majority of the population is still served by the public transport and/or use the non-motorized transport[44].

**Table 4.2: Summary of vehicular emission factors from CPCB/MoEF study[45]**

| Vehicle | Fuel | CO | HC | NOx | CO2 | PM |
|---|---|---|---|---|---|---|
| 2-Wheelers | Petrol – 2 Stroke | 3.62 ± 2.50 | 2.87 ± 1.78 | 0.028 ± 0.011 | 25.9 ± 6.5 | 0.054 ± 0.019 |
| 2-Wheelers | Petrol – 4 Stroke | 1.33 ± 0.85 | 0.55 ± 0.19 | 0.297 ± 0.113 | 29.6 ± 9.7 | 0.016 ± 0.009 |
| 3-Wheelers | Petrol | 1.98 ± 0.79 | 2.36 ± 2.17 | 0.318 ± 0.150 | 64.9 ± 7.8 | 0.048 ± 0.036 |
| 3-Wheelers | Diesel | 8.55 ± 12.6 | 0.63 ± 0.83 | 0.890 ± 0.510 | 145.2 ± 24.8 | 0.545 ± 0.580 |
| 3-Wheelers | CNG | 0.84 ± 0.21 | 1.16 ± 1.27 | 0.345 ± 0.219 | 67.7 ± 14.1 | 0.066 ± 0.072 |
| 3-Wheelers | LPG | 3.04 ± 1.90 | 2.31 ± 1.81 | 0.06 ± 0.028 | 61.3 ± 9.6 | 0.425 ± 0.417 |
| Cars | Petrol | 2.91 ± 1.67 | 0.36 ± 0.28 | 0.369 ± 0.348 | 127.0 ± 28.8 | 0.007 ± 0.006 |
| Cars | Diesel | 0.52 ± 0.33 | 0.19 ± 0.07 | 0.534 ± 0.207 | 151.0 ± 13.7 | 0.118 ± 0.077 |
| Cars | CNG | 0.50 ± 0.40 | 0.53 ± 0.22 | 0.426 ± 0.375 | 141.0 ± 9.3 | 0.003 ± 0.002 |
| Cars | LPG | 4.75 ± 2.87 | 0.54 ± 0.43 | 0.350 ± 0.212 | 135.0 ± 6.5 | 0.001 ± 0.000 |
| MUVs | Diesel | 1.29 ± 0.96 | 0.79 ± 0.62 | 1.220 ± 0.829 | 213.0 ± 37.7 | 0.361 ± 0.242 |
| LCVs | Diesel | 3.24 ± 0.36 | 1.63 ± 0.55 | 2.543 ± 0.458 | 353.0 ± 41.0 | 0.709 ± 0.265 |
| Buses | Diesel | 8.40 ± 4.86 | 1.10 ± 1.03 | 11.13 ± 3.572 | 752.0 ± 144. | 1.080 ± 0.725 |
| Buses | CNG | 3.72 ± 0.00 | 3.75 ± 0.00 | 6.210 ± 0.000 | 806.0 ± 0.00 | 0.00 ± 0.00 |
| HCVs | Diesel | 12.6 ± 9.40 | 1.50 ± 1.59 | 11.57 ± 3.210 | 799. ± 53.1 | 1.602 ± 0.512 |

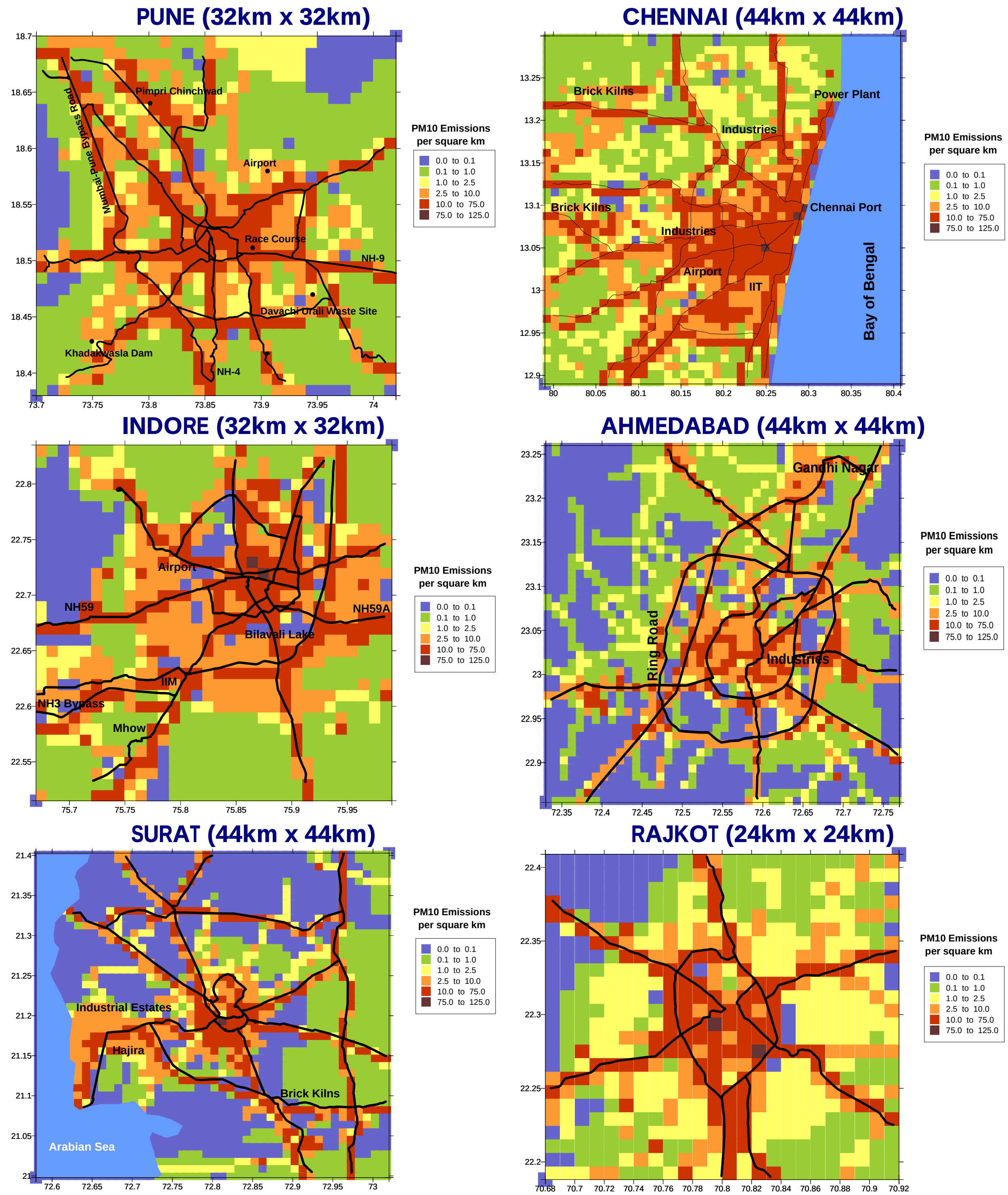
*MUVs = multi-utility vehicles; LCVs = light commercial vehicles; HCVs = heavy commercial vehicles*

[43] An analysis of the "Emissions from India's Intercity and Intracity Road Transport" is presented by the Clean Air Initiative for Asian Cities (CAI-Asia). A draft report from May, 2009, is available @ http://www.cleanairnet.org/caiasia/1412/article-73353.html
A study of basic transport and air quality indicators was carried out by WRI/EMBARQ in 2009 @ http://www.embarq.org/en/book/export/html/427
ADB, 2006, "Energy Efficiency and Climate Change considerations for on-road transport in Asia" @ http://www.cleanairnet.org/caiasia/1412/articles-70656_finalreport.pdf

[44] Times of India, May 12th, 2009, "On growth track: Auto sales zoom 11% in April, 2009", report from SIAM – Society of Indian Automobile Manufacturer @ http://timesofindia.indiatimes.com/Car-sales-up-420-bikes-jump-1211-in-April/articleshow/4508229.cms

[45] A detailed report on the emission factors for the Indian vehicle fleet is available @ http://cpcb.nic.in/Source_Apportionment_Studies.php

**Figure 4.7: Estimated gridded vehicle exhaust emissions**



The methodology employed in calculating the emissions is presented in **Annex 1**. The emissions estimation results include an inventory for the criteria pollutants – PM, SO2, NOx, CO, VOCs and CO2 (presented **Table 4.1**), percentage shares of passenger kilometers traveled (presented in **Figures 4.6**), percentage shares by vehicle type and fuel. The on-road vehicle exhaust emissions are then distributed to the grids @ 1 km resolution using GIS based databases for the highways, main roads, and arterial roads (presented in **Figure 3.2**). The gridded emissions inventory from the transport sector is presented in **Figure 4.7**. For each vehicle type, the emissions are weighted by road type to allow for appropriate spatial distribution of the emissions. For example, the emissions from the truck movement are mostly distributed to highways, compared to the motorcycles, whose movement is expected more along the arterial roads, hot spot locations, industrial estates, and populated areas. The idling emissions due to congestion on the roads are distributed to the roads (weighted to the road density over the grids) and a fraction over grids overlapping with hot spot locations like hotels, hospitals, markets, apartment complexes, and cinemas.

***The road dust emissions*** are calculated for different road types – highways, main roads, and arterial roads, based on the estimated vehicle kilometers traveled. The methodology utilized for the analysis is based on the US EPA AP-42 and customized for the silt loading and speed conditions in each city[46]. Of the total road dust emissions, major contribution comes from trucks, buses, and cars, although the vehicle fleet is dominated by the motorcycles. This is because of the empirical relationship between resuspension of dust with vehicle weight and speed.

It is important to note that re-suspension of the road dust is suppressed during the rainy season and this is accounted for in the dispersion modeling of the emissions where meteorology is an important factor for dispersing and depositing pollutants. The monthly precipitation pattern over the city is presented in **Figure 3.4**. The silt loading on the roads in most of the cities is substantial enough to induce re-suspension of the roads and higher the fleet size, like in the case of Pune and Chennai, higher are the emissions. In case of Chennai, the port activities along with a large industrial area, which account of ~10,000 heavy duty vehicles moving in and out of the city account for the bulk of the re-suspended dust.

***Among industries emissions, brick kilns and the quarries dominate***. The growing number of brick kilns and technology in place for firing bricks make this sector one of the inefficient fuel users. The boom in the construction industry is leading the official and unofficial brick manufacturing operations and accounts for a total estimated brick production of ~3,000 million per year with an estimated coal consumption of 0.27 million tons[47], along with biomass and other unconventional fuels. Most of the biomass utilized comes from the agricultural waste, especially in the harvest seasons, given the vicinity of the kiln clusters to agricultural lands.

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[46] US EPA - 42 details @ http://www.epa.gov/ttn/chief/ap42/

[47] UNDP/GEF, 2007, "Energy Efficiency Improvements in the Indian Brick Industry", project document

The bottom-up source apportionment results (based on emissions inventory) presented in **Figure 4.3** highlight the contributions from the brick kiln operations at ~15 percent in the residential areas. The proximity of the brick kilns to the agricultural area is an important feature to note. This supports the availability of biomass (especially during the harvest season) to support some of the clay brick burning operations, which is otherwise supported by coal. In Pune, most of the brick baking is conducted as a pile with no chimney to support to movement of the burning emissions whereas in Chennai the same process is supported with a chimney, which allows for release of emissions at higher altitude (and thus farther dispersion).

***The domestic sector emissions include the low income and high income group fuel usage***. These emissions are calculated using the gridded population density from SEDAC[48] called GRUMP database (Global Rural-Urban Mapping Project) available at 30 sec (~500 meters resolution) for the world. The population density maps are overlaid with data from the Census of India to estimate the solid and liquid fuel usage in the low and high income groups for the domains presented[49]. In most cities, LPG is the dominant energy source for cooking. The amount of usage varies, where a 15 kg LPG cylinder (standard size across the country) lasts ~25 days for an average high income household with 4 members to ~50 days for a low income groups (a mix of solid fuels are also in use). In case of food kiosks, which are common in the markets and road side, these cylinders last for less ~10 days.

The inventory totals for the domestic sector include the emissions from residential usage, food kiosks, and possible fuel usage for heating (especially in the winter season). The domestic sector is estimated to account for ~8-20 percent of the annual total $PM_{10}$ emissions among the six cities. These emissions are distributed over the grids in using the population density maps. The high income group emissions are distributed over the populated areas (with the highest density).

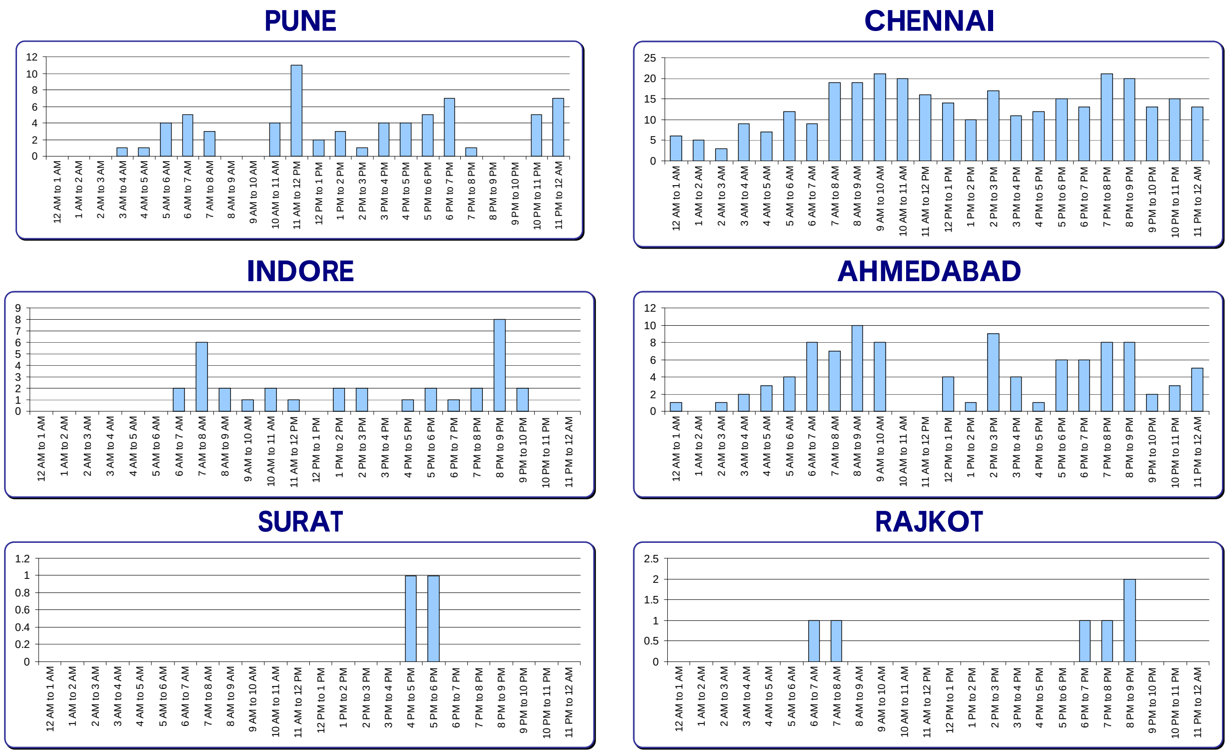
***The diesel generator sets are a common sight*** for most parts of the city and a significant source of criteria pollutant emissions and GHGs. A database of hotspots was estimated using population databases (gridded and district level), which is later used to estimate the emissions. The average emission rates used for diesel generator usage utilized in this study are 60 tons/PJ of $NO_x$, 63 tons/PJ of $PM_{10}$, and 1,256 tons/PJ of CO and ~2.56 kg/lit of diesel consumed. Total emissions from the diesel generator sets account for ~8 million tons of $CO_2$ for the six cities.

[48] Gridded population of the world by SEDAC @ http://sedac.ciesin.columbia.edu/gpw/

[49] The Census of India data is available in the GIS format for all of India at State and Tahsil level and disaggregated into the income groups, fractions of solid and liquid fuel usage

Besides the regular passenger transport statistics to evaluate the emissions from cars, buses, trucks, 2-wheelers, and 3-wheelers, ***statistics for the aviation sector*** were collected for the main airport in each city[50]. A summary of the flight statistics by hour is presented in **Figure 4.8**. Of the six cities, Chennai is the largest international airport with an average departure and arrival of 320 flights, followed by Pune at 120 and the lowest is for the city of Surat with 2 flights per day to Delhi and back.

**Figure 4.8: Daily number of flights at Airports**




The emissions inventory for this sector includes take offs and landing, idling due to the passenger vehicles at the departure and arrival lounges, and the buses (based on diesel) used to shuttle passengers from the terminal to the flights and vice versa. Breakups for only $PM_{2.5}$ and $CO_2$ are presented in this document. Pune is also a hub for military training and operations and a portion of the city is designated as cantonment area, which is not included in the analysis for lack of information to support such calculations.

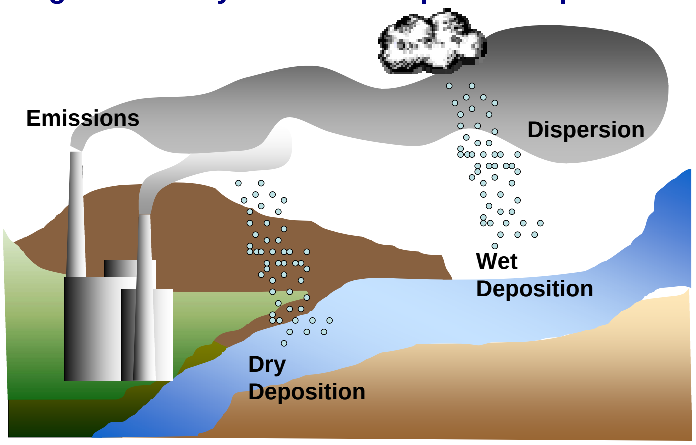
***The power plants*** are the major source of energy consumption and emissions for three of these cities – Chennai, Ahmedabad, and Surat. For each of the power plants, the exact locations of the stacks was obtained, along with statistics of coal consumption and ash productions rates, and thus allocating the point emissions directly to the location.

[50] The flight statistics for each city are obtained from the online resources @ http://www.flightstats.com
This does not include private or chattered flights

## *4.3 Dispersion Modeling of 2010 Baseline Emissions Inventory*

Typically, the emissions are released from (a individual point or an area) source, which after entering the atmosphere, depending on the meteorological conditions like wind speed, wind direction, pressure, temperature, moisture content, etc., interacts with other pollutants, and depending on the local canopy, either deposits on a surface (as dry or wet) or lingers in the air in the form of pollution, which we breathe[51].

**Figure 4.9: Physics of atmospheric dispersion**




The importance of emissions and dispersion modeling and the effect of long range transport of various pollutants are studied extensively at urban, regional, national, and inter-continental levels[52]. Similar to the emissions baseline development, the dispersion modeling is an intense exercise, which requires both computational power and data assimilation. Several modeling systems are available, with varying capacity and complexity to address the physical and chemical aspects of atmospheric transport of pollutant. In this study, the Atmospheric Transport Modeling System (ATMoS) dispersion model is utilized for modeling the air quality using local specific meteorological data[53]. This model was previously utilized for numerous air pollution modeling studies in Asia, including the RAINS and GAINS integrated modeling system, sulfur pollution control in Asia, PM pollution analysis for cities. The details of the model formulation and the input data are presented **Annex 2.0**. The model allows for multi-pollutant analysis in which each of the primary emissions are modeled separately due to differences in their physical and chemical characteristics and aggregated at the end. This includes $SO_2$ to sulfates and $NO_x$ to nitrates[54]. The total $PM_{10}$ concentrations comprise of all the sub-fractions ($PM_{coarse}$+$PM_{fine}$+$SO_4$+$NO_3$) while the total $PM_{2.5}$ comprise of the finer sub-fractions ($PM_{fine}$+$SO_4$+$NO_3$), thus providing a multi-pollutant aspect to the PM pollution. The estimated annual average concentrations of $PM_{10}$ are presented in **Figure 4.10** and PM2.5 are presented in **Figure 4.11**. The smaller bold black box highlights the most populated areas of the domain (the main city district).

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[51] Refer to the books "Atmospheric Chemistry and Physics" by Seinfied and Pandis, and "Fundamentals of Atmospheric Modeling" by Mark Jacobson, which provide detailed discussion on the air pollution modeling and involved steps

[52] Examples of Urban, Regional, and Global scale atmospheris dispersion modeling exercises
MEGAPOLI Study @ http://megapoli.dmi.dk/
Task Force for Hemispheric Transport of Air Pollution @ http://www.htap.org/
Better Air Quality for North America @ http://www.narsto.org/
European Monitoring and Evaluation Programme @ http://www.emep.int/

[53] For details on the Atmospheric Transport Modeling System (ATMoS) visit @ http://www.urbanemissions.info

[54] These rates are specified in the model input file and user has an option to either use the default value or change it accordingly. No chemical transformation is applied to direct PM emissions.

## Figure 4.10: Modeled Annual Average $PM_{10}$ Concentrations

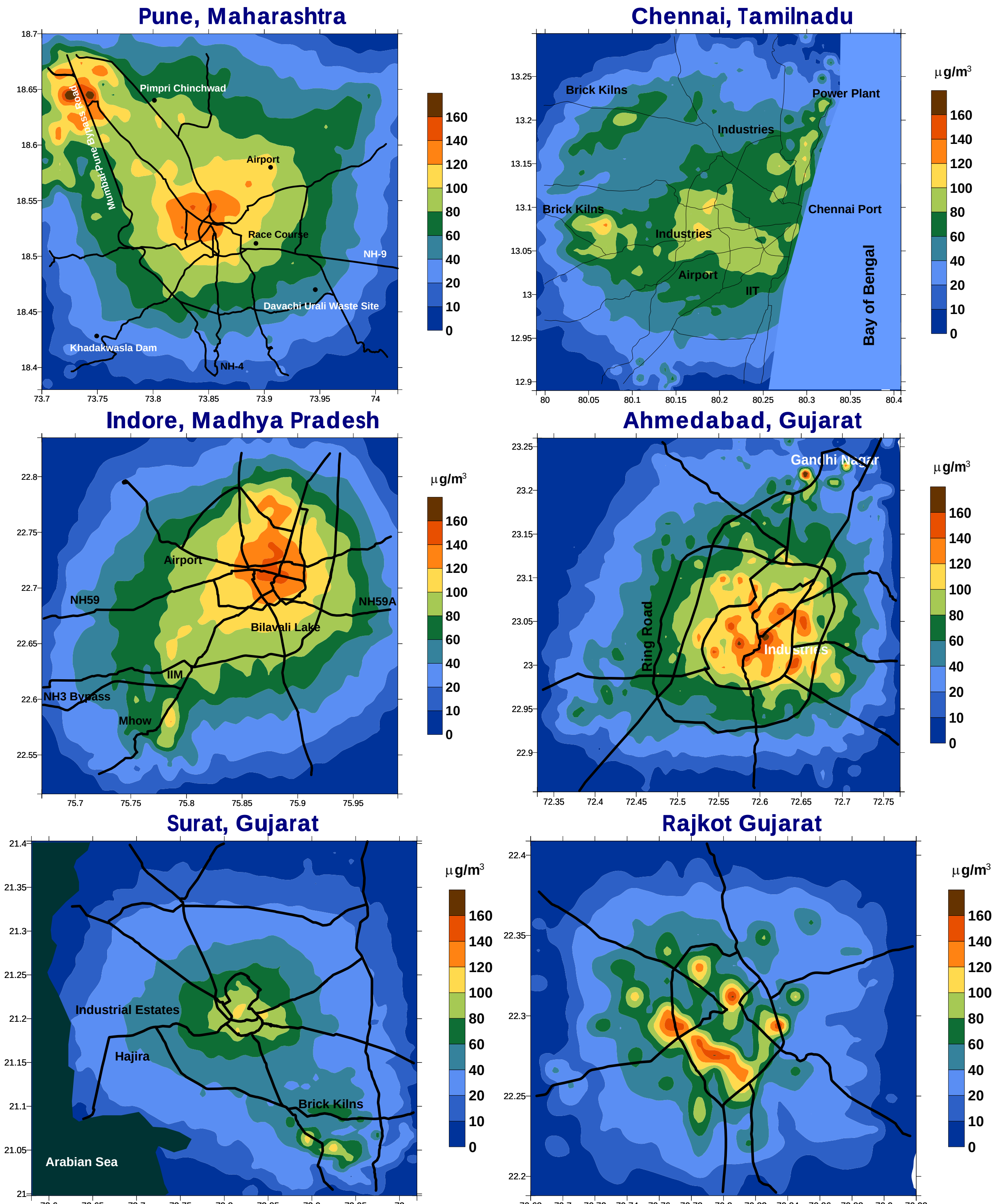
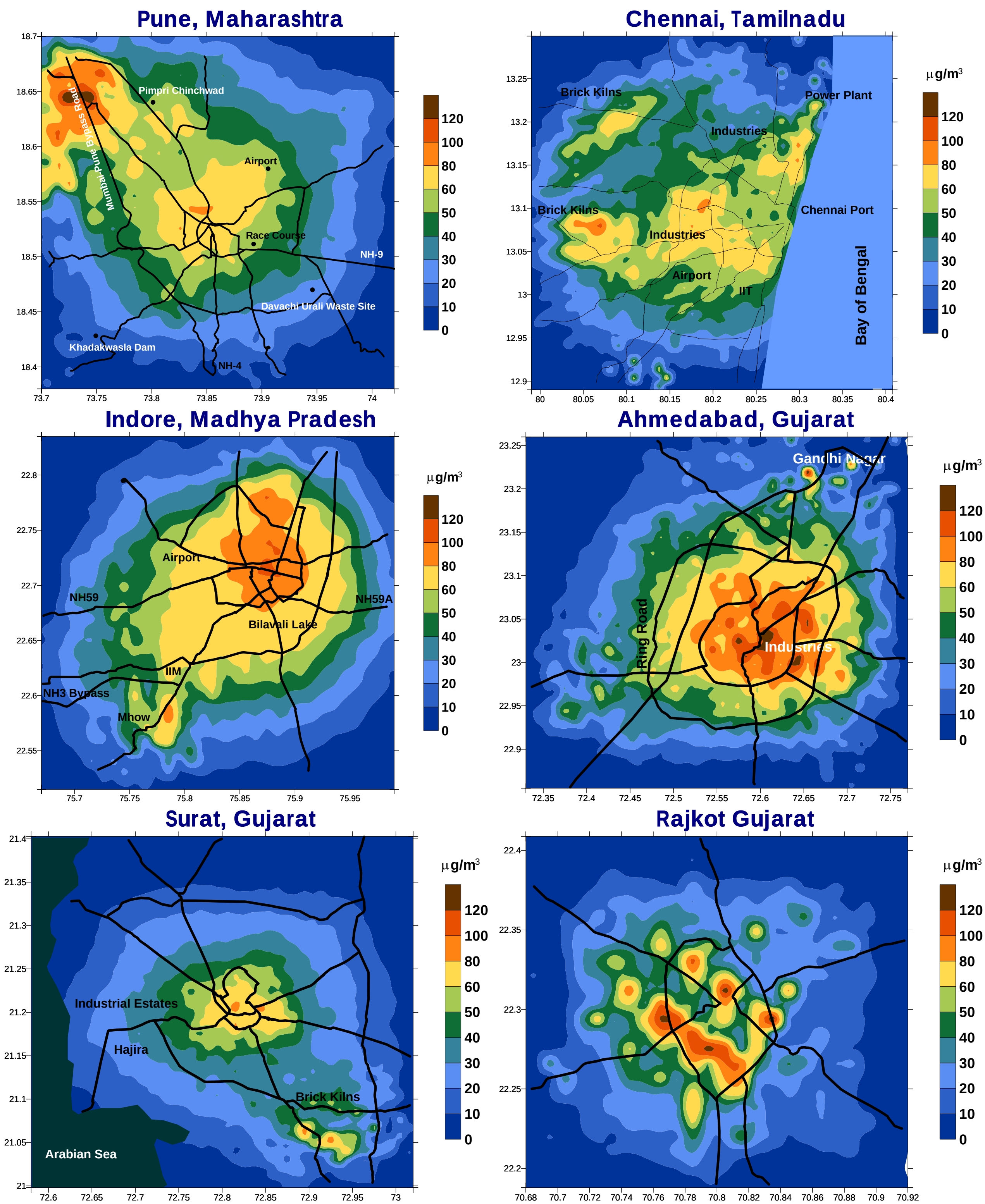


**Figure 4.11: Modeled Annual Average $PM_{2.5}$ Concentrations in**



A summary of the modeled average $PM_{10}$ concentrations from **Figure 4.10** and the measured concentrations presented in **Figure 3.8** are presented in **Table 4.3** and the ranges are comparable. It is important to note that measurements are point values reflecting the pollution from the sources surrounding the sampling location and are usually representative of the sources within ~2-3 km radius. While the data from the stations is limited, these are very useful comparisons. The measurement data is used to calibrate the modeling results and thus support further "what-if" emissions scenario analysis.

**Table 4.3: Summary of the 2010 $PM_{10}$ emissions inventory, modeled, and measured concentrations**

| City | Domain size (km x km) | Total Annual $PM_{10}$ Emissions (tons/yr) | Range of $PM_{10}$ concentrations (μg/m³) | |
|---|---|---|---|---|
| | | | Modeled | Measured[55] |
| Pune | 32 x 32 | 36,600 | 80-140 | 60-160 |
| Chennai | 44 x 44 | 56,400 | 60-100 | 60-120 |
| Indore | 32 x 32 | 18,100 | 80-150 | 60-170 |
| Ahmedabad | 44 x 44 | 35,100 | 60-140 | 80-100 |
| Surat | 44 x 44 | 19,900 | 50-120 | 75-100 |
| Rajkot | 24 x 24 | 14,000 | 50-140 | 80-120 |

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 **Figure 4.11**, most of the main city district areas exceed the annual average standard of 40 μg/m$^3$ for $PM_{2.5}$ concentrations.

The physical location and topography of the city plays a crucial role for emissions and concentration changes presented in **Table 4.3**. For example, the cities of Chennai and Surat are ideally located next to the Bay of Bengal Sea and Arabian Sea respectively, which provides them with an extreme buffer zone to disperse a large amount of the pollution coming from the city sources, especially the large scale industries. For example, in case of the Chennai city, though the estimated annual emissions are the highest of the six cities, the concentrations modeled and measured are in the same range of a city half its size in geography and emissions (like Rajkot). This can be attributed to the land-sea breezes, which are very strong in Chennai, evident in the meteorological fields presented in **Figure 3.3**, with Westerly winds (with a significant amount of time above 10 m/sec). These winds are strong enough to disperse any of the pollution to the sea, from the two large power plants and those from the industrial estate including petroleum refineries and a large port and thus reducing the load of these emissions on local pollution. Similarly, in Surat, though the existence of the largest industrial area (including steel plants, textiles, refineries, and small scale power plants), the pollution is driven to the sea by the strong Easterly winds (**Figure 3.3**) and this reducing the pollution load of these

[55] The measured concentrations are obtained from the CPCB and State Pollution Control Boards. The ranges represent highs and lows of the daily average $PM_{10}$ concentrations over each month (presented in **Figure 3.8**).

emissions on local pollution. The topography plays a different role in case of Pune, where the valleys restrict the movement of the pollution at higher altitudes and then thus creating atmosphere for higher concentrations for most part of the year.

## *4.4 Percentage Sectoral Contributions*

The percentage contributions of various sectors to the modeled annual average concentrations provide an interesting background for urban air quality management. These estimates are dependent on the spatial distribution of emissions from each of the sectors. In case of industrial emissions, specific location information was gathered for known industries, brick kilns, quarries, and power plants, whose emissions are then allocated directly to the respective 1km x 1km grid (presented in **Figure 3.2**). The spatial distribution of the vehicular and road dust emissions along with road density (for highways and arterial roads)[56] is utilized for spatially gridding the emissions and thus obtaining the contribution distributions. These databases were developed on a GIS platform for easy viewing, understanding, and studying the spatial patterns (vehicle exhaust distribution patterns are presented in **Figure 4.7**). In the dispersion model, provision is made to evaluate the contribution of each sector to the total ambient pollution (to PM) based on the emissions inventory. A summary of the range of estimated percent contributions to the annual average $PM_{10}$ concentrations is presented in **Table 4.4**. Note that the ranges for each sector are for the main city district area and the spatial spread of these contributions include pollution from sources inside and outside of the city district limits

**Table 4.4: Summary of percent contributions to annual average $PM_{10}$ concentrations**

| City | Pune | Chennai | Indore | Ahmedabad | Surat | Rajkot |
|---|---|---|---|---|---|---|
| Vehicle exhaust | 8-16 | 10-20 | 15-25 | 10-20 | 10-30 | 10-40 |
| Road dust | 30-50 | 10-30 | 15-25 | 10-20 | 10-30 | 10-30 |
| Industries (+kilns) | 10-30 | 5-30 | 10-30 | 10-50 | 10-30 | 10-70 |
| Power plants | - | 0-5 | - | 0-15 | - | - |
| Domestic | 8-20 | 15-40 | 20-40 | 5-10 | 5-15 | 0-10 |

In 2006-07, MoEF and CPCB conducted particulate pollution source apportionment studies in Delhi, Mumbai, Pune, Chennai, Bangalore, and Kanpur. Details of the source apportionment results and the emissions inventories were published in January 2011[57]. In this study, we overlap with the cities of Pune and Chennai and though both the studies aim at establishing source contributions to ambient pollution, there are major differences in the approaches. The study conducted by MoEF/CPCB is a top-down source apportionment (their results for the cities of Pune and Chennai are summarized in **Figure 4.13**), which is based on monitoring and receptor modeling, while this study is a bottom-up source apportionment (results for the cities of Pune and Chennai are presented in **Figure 4.14**), which is based on activity levels, fuel consumption, and source modeling.

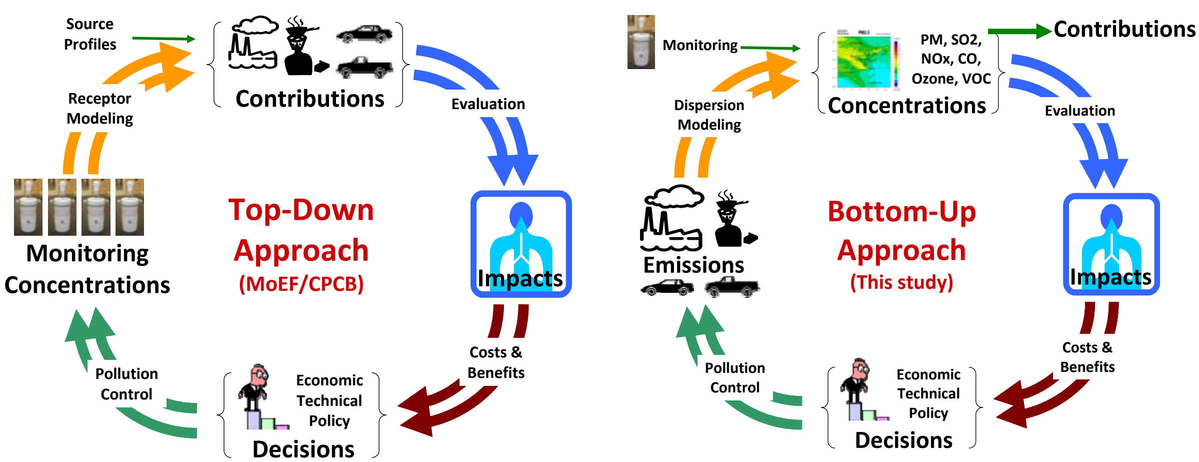
[56] Previous studies include those surveyed and presented as part of the JNNURM city development reports, available @ http://jnnurm.nic.in/nurmudweb/missioncities.htm for the cities Delhi, Pune, Chennai, Ahmedabad, Surat, and Rajkot,

[57] A summary report of the particulate pollution source apportionment studies carried out in Pune, Chennai, Kanpur, Delhi, Mumbai, and Bangalore is available @ http://moef.nic.in

While both represent source contributions to ambient air pollution, it is important to understand the differences and advantages of these results (also see **Annex 3.0**), which are established using two different concepts.

- In a source apportionment study (carried out primarily for PM pollution) where the concentrations of PM are measured over a period of time, the samples of which are chemically analyzed in a lab for bio-markers for various sources and statistically estimate the contribution of various sources (results in **Figure 4.13** from MoEF/CPCB study).
- In the later, an emissions inventory is developed using consumption data, multiplied by an appropriate emission factor. The emissions inventories are then processed through a dispersion model in order to estimate the contributions to ambient pollution, which would be an appropriate number to compare (results presented in **Figure 4.14**); instead of comparing the percentages from an emissions inventory to those from a source apportionment study.

**Figure 4.12: Schematics for estimating sectoral contributions[58]**




- Both the processes have their differences and we should note the limitations while interpreting the results for policy decisions. For example, The percent contributions established using top-down source apportionment study are specific to the vicinity of the sampling location – usually represent the source contributions from a 2-3km radius, and should not be generalized for the entire city.
- Given the confidence levels in the emissions inventory, meteorology, and the dispersion modeling, a study (like this one) can present the possible contributions over an entire city.

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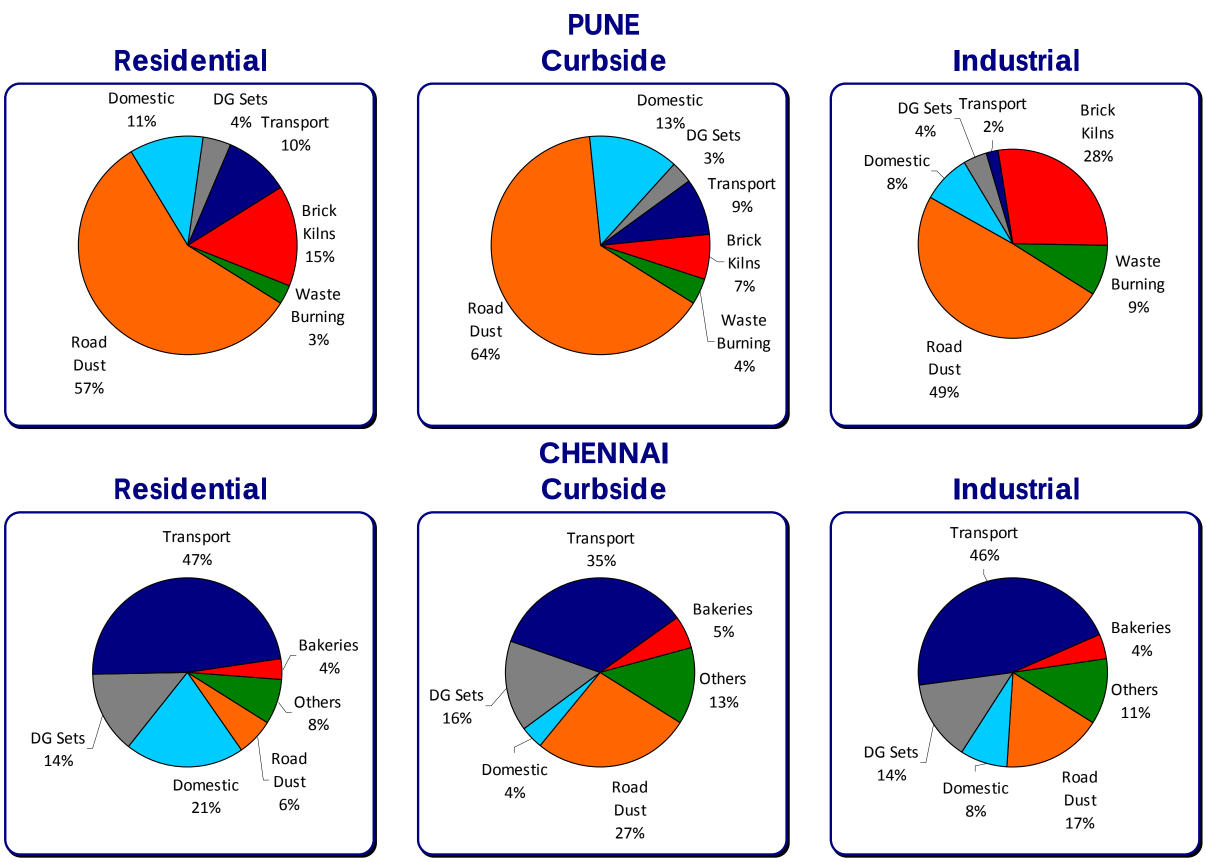
[58] A detailed overview of the techniques to source apportionment and a summary of results from studies across the world are presented in, Johnson and Guttikunda et al., 2011, "***Tools for Improving Air Quality Management - A Review of Top-down Source Apportionment Techniques and Their Application in Developing Countries***" The World Bank, Washington D.C., USA.
Full document is available for download @ http://www.esmap.org/esmap/node/1159

- While accounting for sources around a sampling site, we have to differentiate between the ground level sources such as vehicle exhaust, road dust, domestic fuel burning, etc., which tend to impact the ground level concentrations more than the elevated sources like power plants and industries where the stack height allows for an elevated release of emissions and disperse more.
- The studies can also compliment each other in the long run. (a) for the top-down study, when source profiles are being generated, the same can be used to verify the emission factor for various sources, which can be used for emissions inventory development (b) following dispersion modeling, we can establish the hot-spot locations around the city, which can be used for sampling and source apportionment (c) the receptor modeling can provide insights into missing sources, which can be investigated while developing an emissions inventory

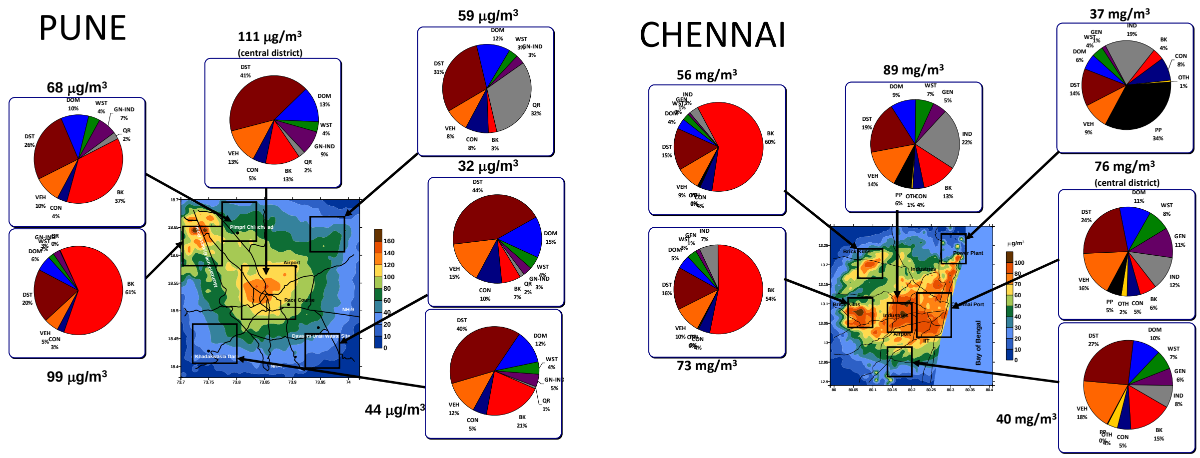
**Figure 4.13: Contribution of major sources to $PM_{10}$ pollution based on MoEF/CPCB source apportionment studies (2006-07)**




From the source apportionment for the Pune city (**Figure 4.18**), it is evident that the major contributor to the pollution problems is re-suspension of road dust due to constant vehicular movement and for Chennai, the vehicular exhaust emissions. The major difference between the two cities is the meteorology and geography. In case of Chennai, high moisture content and local land-sea breezes keep the re-suspension of dust at bay compared to those observed in

Pune. This is also reflected in the modeled estimated presented **Figure 4.10** and **Figure 4.11** for $PM_{10}$ and $PM_{2.5}$ respectively. The modeled source contributions following the procedures in **Figure 4.12** are presented in **Figure 4.14** for the cities of Pune and Chennai. In the figures, several regions are selected across the city for which the concentrations (presented in the figure) and source contributions are averaged.

**Figure 4.14: Modeled 2010 $PM_{10}$ source contributions averaged over select regions across the city**




When comparing the results with **Figure 4.13**, we should consider only the shares for the central districts (marked in **Figure 4.14**). Major differences between the two studies which we should consider while comparing the two results are

- The base year for analysis in MoEF/CPCB study (**Figure 4.13**) is 2006-07 while this study is conducted for the base year 2010 (**Figure 4.14**). During this period, these cities have experienced a significant growth in consumption patterns, number of industries, public and private ventures (especially in Pune, associated with the Information-Technology sector), vehicle ownership, and infrastructure (such as roads and residential construction). The inventories developed under study reflect these changes and though the shares are qualitatively comparable, there are significant quantitative differences for the same reasons.
- While there was an improvement in the fuel quality used (now set at Euro IV standards for major cities) and more stringent emission standards for new vehicles (now set at Euro III for major cities), there an increase in the emissions from the transport sector, from 2006 to 2010, because of an increase in the number of vehicles. Note that these higher standards apply only to newer vehicles which form a fraction of the overall fleet.
- The modeling domains in the two studies are significantly different. While an emissions inventory and source apportionment study was conducted covering only the main district areas for both the cities, this study was conducted for a larger area (for all cities), thus accounting for long-range transport of elevated sources, such as brick kilns and power plants, which are located at least 20 km away from the central district.

- The advantage of this methodology is to be able to account for sources and their contributions for a wider area of consideration (as shown in **Figure 4.14**), thus allowing for a holistic pollution control plan, specific to various locations.
- The vehicle contributions are highlighted in Figure 4.13, mainly because of the sampling locations and their proximity to the roads. The low lying sources like road dust and vehicle exhaust tend to contribute more to the ambient pollution compared to the elevated sources, which travel longer distances before settled on the ground.

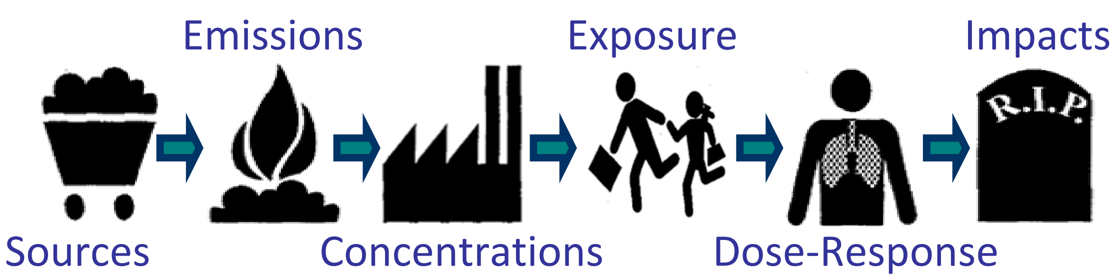
Overall, the conclusion of the 2006-07 study carried by the MoEF and CPCB is that the transport sector (directly and indirectly) is responsible for most of the ambient PM pollution in Pune, followed by contributions from the brick kiln industry, open waste burning, and domestic sector. In this study, the percentage contributions from various sectors have remained similar with additional sectors like brick kilns and quarries contributing to the local pollution problems.

## Chapter 5.0

# Health Impacts of Air Pollution

An important objective of this study was to assess the baseline health impacts of current air pollution trends in the cities (based on the estimated emissions inventory and concentration profiles over the city) and compare future scenarios for potential co-benefits between health impacts and carbon emissions (for six interventions presented in **Chapter 1.0**).

**Figure 5.1: Schematics of information to assess health impacts**




Among the criteria pollutants, PM is a well established endpoint for assessing the health impacts in a city. Epidemiological studies in developed and developing countries have shown that elevated ambient PM levels lead to an increased risk of mortality and morbidity (a summary of reference studies is presented in **Annex 3.0**). Health effects range from minor irritation in eyes and upper respiratory system to chronic respiratory disease, heart disease, lung cancer, and leading up to pre-mature death. The PM concentrations (for $PM_{10}$ and $PM_{2.5}$) represent a mix of sources – primary and secondary, which becomes a common denominator for the criteria pollutants, without double counting the possible impacts of mix of pollutants (chemical composition and contributions of pollutants to PM concentrations is presented in **Figure 2.1**).

In this study, the modeled $PM_{10}$ concentrations[59] (presented in Figure **4.10**) were utilized to assess the health impacts following the methodology presented in **Equation 5.1**.

$$\delta E = \beta * \delta C * \delta P$$ **Equation 5.1**

Where,

$\delta E$ = number of estimated health effects (various end points for mortality and morbidity).

$\beta$ = the dose response function (DRF) for particular health endpoint; this is defined the change in number cases per unit change in concentrations. This is established based on epidemiological studies conducted over a period of time, analyzing the trends in hospital records and air pollution monitoring.

$\delta C$ = the change in concentrations; the concentrations modeled above a certain threshold value. Although, WHO claims that there is no threshold over which the health impacts are measured. In general, the impacts are felt at the minute fluctuations of the pollution. In this study, the threshold is set at 20 $\mu g/m^3$

$\delta P$ = the population exposed to the incremental concentrations above; this could be on a grid by grid basis (used in this study) or for the city or region on a whole, depending on the level of information available.

The Health Effects Institute (USA) conducted a detailed literature survey on the impact of outdoor air pollution on human health[60] includes an extensive list of references for follow-up on the dose response functions for various end points and methodologies to conduct epidemiological studies to develop these dose response functions. Main Conclusion of their latest study under the PAPA program is that the dose response functions for $PM_{10}$ and $PM_{2.5}$ are the very similar throughout the world and states that "*the study's finding of a 0.6% increase in mortality for every 20$\mu g/m^3$ of exposure to particulate air pollution is strikingly similar to comparable western results (which range from 0.4% to 0.6%) and provide increased confidence in the new Asian results.*". Also see reports from California Air Resources Board on PM and health impacts.

[59] The finer fraction of PM (less than 2.5 micron) is considered more harmful of the PM fractions and more studies are now highlighting the importance of $PM_{2.5}$ in health impact studies. In this study, while we calculated the $PM_{2.5}$ concentrations, presented in Figure 4.11, due to limited measurements available from the cities, these numbers were not calibrated for further use. Hence, all the health impacts are calculated using $PM_{10}$ as a measurable endpoint and the results will be updated in the future simulations, as and when the measurements of $PM_{2.5}$ are more prevalent in these cities. More details on the modeled $PM_{2.5}$ annual and seasonal patterns are available up on request.

[60] Health Effects Institute (USA), 2004, "Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review" @ http://pubs.healtheffects.org/view.php?id=3
PAPA – Public Health and Air Pollution in Asia @ http://www.cleanairnet.org/caiasia/1412/article-48844.html
California Air Resources Board (2008) "Methodology for Estimating Premature Deaths Associated with Long-term Exposure to Fine PM in California" @ http://www.arb.ca.gov/research/health/pm-mort/pm-mort.htm

**Table 5.1: Average dose response functions for morbidity end points**

| Mortality and Morbidity Health Endpoint | Dose response function[61] (β) | Willingness to Pay (INR) | Willingness to Pay (USD)[62] |
|---|---|---|---|
| Premature Deaths | 0.0000134 | 1,880,000 | 41,700 |
| Adult Chronic Bronchitis | 0.000040 | 50,000 | 1,100 |
| Child Acute Bronchitis | 0.000544 | 20,000 | 450 |
| Respiratory Hospital Admission | 0.000012 | 2,000 | 45 |
| Cardiac Hospital Admission | 0.000005 | 500,000 | 11,100 |
| Emergency Room Visit | 0.000235 | 4,000 | 89 |
| Asthma Attacks | 0.002900 | 1,000 | 22 |
| Restricted Activity Days | 0.038280 | 500 | 11 |
| Respiratory Symptom Days | 0.183000 | 30 | 1 |

The morbidity calculations for concentrations exceeding the national ambient standard are also included in this study and the dose response functions utilized are presented in **Table 5.1**. For the final health impacts analysis, the population data is taken from global GRUMP database, distributed by SEDAC and the mortality and morbidity cases are estimated for the modeled annual average concentrations (in **Figure 4.10**) exceeding the WHO health guideline value of 20 $\mu g/m^3$. The estimated health impacts based on the modeled annual average concentrations is presented in **Table 5.2**. The health impacts are then valuated based on willingness to pay methodology, presented in **Table 5.3**.

**Table 5.2: Estimated Mortality and Morbidity due to air pollution for 2010 (numbers rounded to nearest zero)**

| Mortality & Morbidity | 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 |
| Land-Sea Breeze | NO | YES | NO | NO | YES | NO |
| 2010 $PM_{10}$ emissions (tons/yr) | 36,600 | 56,400 | 17,900 | 35,100 | 19,950 | 14,000 |
| **Premature Deaths** | **3,600** | **3,950** | **1,800** | **4,950** | **1,250** | **300** |
| Mortality per ton of PM10 | 0.1 | 0.07 | 0.1 | 0.14 | 0.06 | 0.02 |
| 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 |

[61] The dose response coefficient is defined as the number of effects/1μg/m3 of change in concentration/per capita
[62] Conversion utilized 1 USD = 45 INR

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. A summary of the health impacts across the world is presented in **Annex 3.0**.

**Table 5.3: Estimated costs for Mortality and Morbidity due to air pollution for 2010**

| Mortality & Morbidity | Pune | Chennai | Indore | Ahmedabad | Surat | Rajkot |
|---|---|---|---|---|---|---|
| Mortality (INR crores) | 680 | 750 | 340 | 930 | 240 | 60 |
| Morbidity (INR crores) | 1,100 | 1,210 | 550 | 1,510 | 380 | 95 |
| Mortality (million USD)[63] | 151 | 165 | 75 | 207 | 52 | 13 |
| Morbidity (million USD) | 246 | 269 | 122 | 336 | 85 | 21 |

## *5.1 Study Observations*

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 5.2**.

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

[63] For this analysis, conversion of 1 USD = 45 INR is utilized; 1 crore = 10,000,000; 1 million = 1,000,000

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 (see **Figures 3.3 to 3.5**).

The dose response functions themselves are also subjective and represent a conservative estimate based on the studies around the globe. A summary of these studies and references utilized for this analysis are summarized in **Annex 3.0**.

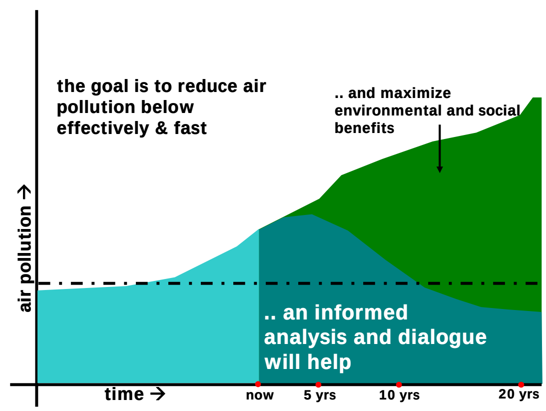
The mortality per ton of emissions presents an interesting perspective to the health impacts analysis. When comparing between Chennai and Ahmedabad, the ratio for the later is at least double and this is primarily due to the meteorology and geographical structure of the city. The winds are at least double in Chennai (**Figure 4.4**) and mostly Westerly to drive emissions (especially from the industries and power plants, which are mostly coastal) out of the city limits. Also, the city spread for Ahmedabad is very densely packed for the emissions over the populated areas, including industries, and hence the higher ratio. In case of Rajkot and Surat, significant portion of the emissions are coming from the industries allocated to the estimates and thus reducing the overall impact on mortality.

The costs associated with the mortality and morbidity is based on willingness to pay methodology and is subjected to scrutiny. The numbers presented in **Table 5.3** are provided as a baseline 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?

## Chapter 6.0

# What-if Scenarios for 2020 & Co-benefits

**Figure 6.1: Maximizing benefits with informed & early action**




For a growing number of cities, the main environmental concern still remains local pollutants such as particulate matter ($PM_{10}$ with aerodynamic diameter less than 10 μm and $PM_{2.5}$ with aerodynamic diameter less than 2.5 μm), $SO_2$, $NO_x$, CO and Ozone. Current trends in environmental regulation and industrial development are converging in a manner that encourages a thoughtful and consistent approach to appropriate control measures which can benefit both the local pollution control and reduction of GHGs to support the climate dialogue. These can range from little or none on small sources (household stoves, small industrial boilers) to advanced controls on modern power plants (e.g., electrostatic precipitators, ESP's) and vehicles (e.g., diesel particle filters)[64].

The objective of this study, given a baseline emissions inventory was developed for the six cities for year 2010, was to evaluate six "what-if" emission scenarios for 2020 – targeting the reduction of local pollution (particularly PM) for health benefits and to reduce GHGs to support climate dialogue. Note that the "what-if" scenarios are being evaluated for health and carbon

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[64] McGranahan et al. (2003) "Air pollution and health in rapidly developing countries", Published by Earthscan Publishers @ http://www.earthscan.co.uk/?tabid=994
Schwela, et. al. (2006) "Urban Air Pollution in Asian Cities: Status, Challenges and Management". Earthscan Publications, UK @ http://www.earthscan.co.uk/?tabid=1455

benefits possible based on the emission statistics estimated for the study domain (presented in **Figure 3.2, 4.3, 4.4, and 4.5 and Table 4.1**) and not necessarily reflect the investment plans for the city. The analysis is carried to evaluate the possible benefits to air quality (related health benefits) and not focused on how the intervention may be implemented or how much it may cost.

A recent GAP conference on "Co-benefits of Air Pollution" concluded that[65]

> *Current science emphasizes the urgent need to address air pollution and climate change in an integrated way. We should no longer treat these two issues separately as we strive to achieve sustainable development and a low carbon society. In both developing and industrialized countries, abatement of air pollution and mitigation of climate change have generally been treated separately. There are, however, large benefits in considering the control options together; such approaches would mostly lead to increased health and/or climate benefits and decreased costs.*

## *6.1 2020 Baseline Scenario Analysis*

For 2020 scenario analysis, first the baseline emissions inventory for projected from 2010 baselines under business as usual conditions and then corrected for the six interventions. For the domestic sector, the gridded population for 2020 was utilized. The industrial sector is estimated to grow at ~10 percent per annum, at the rate of the national GDP. In case of the transport sector, the passenger vehicles were extrapolated at ~8 percent, motorcycles at ~10 percent, and the remaining private sector vehicles like short buses, commercial vehicles, etc., at ~1 percent. 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, though the vehicle population is expected to increase at the rate of ~10 percent, the emissions are not expected to grow at the same rate. The emissions are then processed through the dispersion model to develop the maps similar to those presented in **Figures 4.10 and 4.11**, but not presented in this report.

The emissions inventories for each scenario are then estimated for each city and labeled S1 to S6, processed through the dispersion model, and evaluated for health benefits using the following equation.

$$\delta E = \beta * \delta C * \delta P$$ **Equation 6.1**

Where,

$\delta E$ = number of estimated health effects (various end points for mortality and morbidity).

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[65] Global Atmospheric Pollution Forum, "Climate and Air Pollution Co-benefits" (2008) conference, organized by SEI in Stockholm, Sweden @ http://sei-international.org/projects?prid=140

$\beta$ = the dose response function (DRF) for particular health endpoint; this is defined the change in number cases per unit change in concentrations (described in the previous section).

$\delta C$ = the change in concentrations = the difference between the baseline concentrations for 2020 against the concentrations modeled for each of the scenarios. Unlike the 2010 baseline estimates where the health impacts were evaluated against a threshold value and thus an estimate of number of cases incurred in a particular year, in this case, the difference between the baseline and the scenario concentrations will provide an estimate of the number of cases which can be saved due to the implementation of the scenario.

$\delta P$ = the population exposed to the incremental concentrations above; this could be on a grid by grid basis (used in this study) or for the city or region on a whole, depending on the level of information available.

The estimated health impacts based on the modeled annual average concentrations for year 2020 are presented in **Table 6.1**.

**Table 6.1: Estimated Mortality and Morbidity due to air pollution for 2020 (estimates rounded to nearest zero)**

| Mortality & Morbidity | 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 |
| Land-Sea Breeze | NO | YES | NO | NO | YES | NO |
| 2020 $PM_{10}$ emissions (tons/yr) | 38,000 | 55,100 | 21,000 | 31,800 | 23,200 | 18,500 |
| **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 |

In 2020, the six cities account for an estimated annual 21,400 premature deaths due to exposure to air pollution above the WHO guidelines.

## *6.2 What-if Emission Scenarios*

The what-if scenarios evaluated for co-benefits are

(1) ***An increase in NMT shares, ~20 percent***. Assuming that there is enough infrastructure to support the move from motorized to the non-motorized transport, the shift in the passenger travel kilometers is expected to come in fractions from passenger cars, motorcycles, and buses. In cities with large 3 wheeler population, a fraction of passenger travel is shifted to NMT. For the emissions analysis, the fractions are deducted from the vehicle kilometers traveled from each mode to accommodate for the equivalent increase in the NMT shares for each city.

(2) ***An increase in public transport share, ~20 percent***. This scenario is modeled assuming that the fleet will at least double from the current numbers to accommodate the increase in the passenger kilometers traveled by bus. This shift is modeled assuming 70 percent coming from the motorcycles and 30 percent from the passenger cars. In general, there is an urgent need to update the bus fleet with newer vehicles in most of the cities. However, the supply of new buses has been slow. Two bus manufacturers in India – Tata and Ashok Leyland – together produce nearly 90 percent of standard buses in the country. At their current rate of production they can deliver only about 100 buses a month unless they ramp up production[66]. This rate of supply is inadequate to meet the demand for buses in Indian cities that are investing in public transport. To underscore this point, the demand for buses under the JNNURM funds alone is approximately 70,000 buses for public transport purposes[67].

(3) ***Introducing alternate fuel for public transport and 3 wheeler sectors***. Assuming the fuel supply and infrastructure to support the demand are in place, this scenario is evaluated assuming that the public transport buses and the 3 wheelers will be converted from their current petrol and diesel based fleets to CNG based fleets. This intervention follows the example of the 1998 Supreme Court ruling which led the city of Delhi to take concrete steps to address air pollution in the transport sector[68] and the largest ever CNG switch in the world for public vehicles. More than 100,000 vehicles (including the three wheelers and taxis) were converted to CNG in Delhi over five years[69]. This resulted in significant decrease in the air

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[66] Times of India, February 8th, 2009, "BRTS dreams may go bust" @
http://timesofindia.indiatimes.com/articleshow/msid-4096144,prtpage-1.cms

[67] Times of India, May 13th, 2009, "Low floor buses delayed in Delhi" @
http://timesofindia.indiatimes.com/Delhi/Low-floor-buses-delayed-Bluelines-get-a-breather/articleshow/4521904.cms
The Hindu, May 13th, 2009, "Delhi Govt. faces cancellation of bus funding under JNNURM" @
http://www.hindu.com/thehindu/holnus/004200905131452.htm

[68] More on the Supreme Court ruling @
http://www.cleanairnet.org/infopool/1411/propertyvalue-19513.html
The timeline of implementation (in the transport and industrial sector) and the experience for instituting change which has become a model for other Indian cities, by Narain, et al., 2005, "Who Changed Delhi's Air? The Roles of the Court and the Executive in Environmental Decisionmaking", RFF @
http://www.rff.org/Publications/Pages/PublicationDetails.aspx?PublicationID=17425

[69] More on Delhi Transport Corporation @
http://en.wikipedia.org/wiki/Delhi_Transport_Corporation

pollution. The largest improvement came from the conversion of ~3,000 diesel buses to CNG[70]. Delhi has since 2000 also enforced Euro II emission standards, five years ahead of schedule, and Euro III in 2005 for all passenger vehicles.

(4) ***A reduction in re-suspended road dust, ~50 percent***. The re-suspended dust due to the movement of the vehicles on the roads is by far the largest culprit to the air pollution problem in the cities. In 2020, it is assumed that there is some inherent improvement in the road infrastructure which will reduce the re-suspension on the roads. However, the near doubling of the fleets expected in 2020 allows for the further re-suspension of irrespective of the reduction in silt loadings on the road. For the reduction estimates, the silt loadings on the main and arterial roads are significantly reduced to achieve the possible 50 percent reduction in the re-suspended dust.

(5) ***A change in technology used for baking bricks and improving efficiency by ~50 percent***. The construction is the fastest growing sector in the cities and the demand is expected to further increase in the coming decade. While the technology used for baking bricks in each city varies from chimney style (in Chennai) to no-chimney piled style (in Pune), it is assumed that the technology will be improved to the latest available, such as the Vertical Shaft Brick Kilns (VSBK) which are gradually being introduced in the developing country cities of Dhaka, Kathmandu, and Cairo[71]. In case of Pune, Ahmedabad, Surat, and Indore, where pile style burning is prevalent, the reduction in emissions are expected in the range of 60 percent where as in case of Chennai where the chimney style burning is already prevalent, the change in technology will result in at least 30 percent improvement in efficiency and emissions.

(6) ***A reduction in the truck movement in the city limits, ~20 percent***. The truck movement accounts for the bulk of the pollutants in each of the cities. This includes the in-city freight movement via light duty vehicles and inter-city freight movement via heavy duty trucks. This quotient is more significant for the cities of Chennai and Surat, which host large ports and industrial estates. For the potential emissions reductions and benefit analysis, it is assumed that freight movement will be either supported by the railway services and/or via a bypass and not allowing the trucks to pass through the city. As important assumption here is that lesser the number of truck kilometers traveled through the in-city roads, lesser the emissions, and thus lesser the pollution and its impacts.

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[70] Down to Earth, March 2002, "The Supreme Court Not to Budge on CNG Issue" @ http://www.downtoearth.org.in/full6.asp?foldername=20020331&filename=News&sec_id=4&sid=6

[71] More details on the VSBK technology, the manuals prepared and published by the World Bank (2010) are available @ http://urbanemissions.info/model-tools/sim-air/dhaka-bangladesh.html

## 6.3 Co-Benefits of "What-if" Scenarios

Note that the scenarios evaluated in this study are neither subjected to planning procedures nor investment. Also, the extrapolation of the emissions from 2010 to 2020 is speculative based on the current economic, geographical, and population trends and subject for alternatives in the many studies. The six scenarios are evaluated, assuming that they are mutually independent activities, which may not be the case at the time of implementation. This was assumed for the ease of calculations. For example, the interventions designed to promote public transportation, in some form or the other, is expected to invariably affect the non-motorized transport, especially in the form of short trips and thus effecting the emissions and pollution patterns. However, in this study the public transport and the non-motorized transport benefits are evaluated independently to estimate possible mutual benefits.

**Table 6.2: Estimated co-benefits from 2020 what-if scenarios**

| Mortality & Morbidity | 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 |
| Land-Sea Breeze | NO | YES | NO | NO | YES | NO |
| 2020 $PM_{10}$ emissions (tons/yr) | 38,000 | 55,100 | 21,000 | 31,800 | 23,200 | 18,500 |
| Estimated PM10 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 CO2 emissions reduced under what-if's (million tons/yr) | 3.0 | 5.7 | 1.8 | 2.5 | 2.4 | 1.4 |

## 6.4 Study Observations

A summary of combined benefits from all the scenarios is presented in **Table 6.2**. Overall the benefits are substantial for health and carbon. Of the estimated 21,400 premature deaths under the 2020 baseline, implementation of the six scenarios by 2020 can potentially save 5,870 lives (~27%) annually and induce an estimated annual reduction of ~16.8 million tons of $CO_2$ in the six cities. The details of possible benefits in terms of emissions, concentrations, mortality, and morbidity from the six scenarios and for the six cities, and the associated health cost savings, are available up on request. Important study observations include

- The benefits of the six interventions were evaluated for health (from the reduction of PM, $SO_2$, and $NO_x$ emissions) and $CO_2$ reductions. However, one of the interventions targets only PM pollution and has no direct reductions for $CO_2$ emissions. This is scenario (4) "intervention to reduce road dust". While we were aware of the fact that this scenario will benefit mostly the health sector by reducing PM pollution, it was important to highlight a low-hanging fruit for air quality management in the cities. While the vehicle exhaust and industrial plumes are major sources of air pollution due to fossil fuel burning, we should not neglect their indirect impact – resuspension of dust due to constant vehicular movement, most often from the heavy duty trucks carrying raw material and finished products for the industrial sector.

- It is also the scenario with the highest health benefits of the six interventions. This could be achieved by paving roads, thus reducing the silt loading on the roads or by wet sweeping which would reduce re-suspension of silt and thus lessen exposure effects.
- The contribution of road dust emissions is higher to the $PM_{10}$ totals than the $PM_{2.5}$ totals (**Figure 4.3 and 4.4**). Since, the health benefit calculations are based on the $PM_{10}$ concentrations; it is evident that the largest benefits are expected from this source. If the baseline for comparisons were to shift from $PM_{10}$ to $PM_{2.5}$, the analysis focus will shift from re-suspended road dust to direct vehicle exhaust and other fossil fuel based sources. Nevertheless, it is important that the road dust emissions and exposure impacts are not neglected.
- 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, reduction in their movement in the city limits, and in general in the management of freight movement in the cities. For the cities like Chennai and Surat, where the ports and the industries dominate the geographical settings and the emission loads (for transport and industrial sectors), the freight management can be an effective and faster intervention to control local pollution and reduce GHGs. The port activity is also linked to rail emissions. A significant portion of the freight from Chennai and Surat is moved by rail. An effective mass transport option for freight management is improving the rail links and thus reducing the in-city emissions due to truck movement.
- For the transport sector, all the interventions are interlinked and could lead to unintended consequences, though the scenarios are designed and evaluated independently for the ease of modeling. For example, in case of scenario (2), improving public transport shares in the cities. For three cities, the benefits from moving a share of passenger cars and motorcycle trips to buses (and thus reducing their emissions) didn’t result in any reduction in $PM_{10}$ emissions. This is due to an increase in the road dust emissions from the additional buses. The rate of re-suspension of road dust is generally higher for the buses than the cars and the motorcycles. This is an unintended consequence, which should be addressed in tandem with infrastructure programs such as better roads and pavements and along with improvements in emission standards for these vehicles.
- The brick kilns, which are a common site for all city outskirts, are expected to yield significant benefits in PM and $CO_2$ emissions. However, this intervention is dependent on the city and the national regulators for promoting emerging technologies, but also the social aspects of the workers and owners, who are dependent on day to day wages. For this study, it was assumed that kiln clusters will eventually move to VSBK or similar systems for higher energy efficiency and result in significant health benefits for the locals and carbon emission reductions. A parallel study conducted by Indian and US

research groups concluded that a shift from the current bull-trench style kilns to zigzag or VSBK technologies can yield ~40-50 percent improvements in the heat efficiency and emissions.

- Of the six interventions, one with consistent reductions in PM and carbon emissions is promotion of non-motorized transport. By definition, no-motorization means no combustion, and thus no-emissions to see and no-pollution to breath. Each of the interventions has its limitations, which are not discussed in this chapter. However, any intervention, which promotes non-combustion, is bound to produce better co-benefits than the rest. Promoting NMT is the best of the lot.
- Possible intervention which was not included in this study is waste management. The garbage burning along the roads (when it is left unpicked) and at the landfills is a growing contributor to ambient pollution, carcinogens, and GHGs. This waste can be better managed by either composting the west waste or recycling the possible products, and using the waste (depending on its calorific value) for heat and electricity generation in select locations.
- Another mentionable intervention is the power generation. As the cities are growing, besides the demand for diesel in the transport sector, a good deal of diesel demand growth comes from diesel generators, usually for own use (1 kW to several MW) but also by utilities (a few to tens of MW each) in places such as hospitals, hotels, markets, malls, apartments, institutions, etc, with limited and no supply of electricity.

## *6.5 Study Extensions…*

The primary objective of the study was to establish a baseline emissions inventory for the criteria pollutants and $CO_2$ for the six cities – Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot and help support air quality management planning in these cities in a co-benefits framework, where the interventions can be studied and possibly implemented to benefit both local health (via air pollution reduction) and climate policy (via carbon reductions). Six such interventions were studied for extrapolated emissions into 2020, demonstrating co-benefits. While baselines and analysis was conducted using the literature available and interviews with officials from various departments in the cities, there is room to further this analysis.

- An information dissemination mechanism to share these results with the local officials and decision makers in the air quality management community and thus institutionalizing the analytical framework employed in this study. This will help in improving the databases and further use of such frameworks for preparation of an effective pollution control strategy.
- A sector based analytical framework. In the cities, interventions with the largest and overlapping benefits are (1) public transport (2) non-motorized transport (3) brick kilns and (4) generator sets. Each of these sources, while contribute significantly to the local air pollution and GHGs; they are integral to the central planning programs, interlinked with infrastructure and urban development. While it is important to study their contributions at the city level, programmatically they have more to offer across states and at the national level.

- This study focused on the Tier-1 cities (except for Rajkot). As the cities are growing, the smaller cities are following the examples of bigger cities; both in terms of growth factors and in terms of interventions introduced for better environment. All this is linked to having relevant information at hand for the policy makers to make the right decisions. These analytical programs should be replicated in other cities to inform decision making and to promote co-benefit frameworks, where cities can benefit from possible local pollution reduction and climate policy funds for implementing these interventions.

# Annex 1.0 Methodology for Transport Emissions

A methodology presented in **equation A1.1** was utilized to estimate the emission trends with air quality and health as the primary indicator. The fundamental equation for calculating the emissions is based on the activity level, which for the transport sector is equivalent of "*Emissions = Number of Vehicles * Vehicle kilometers traveled (km)* Emission Factor (gm/km)*". The age mix of vehicles is deduced from the information available on the vehicle counts from the previous years and anticipated retirements for each mode. The emissions inventory estimated using this methodology does not include road dust resuspension.

$$
\begin{aligned}
NV_{t+1} &= NV_t * (1 + growth) \\
NV_{total} &= \sum_{age=0}^{age=20} NV_{age} \\
EF_{age} &= EF_{new} * (1 + drate)^{\wedge 2} \\
EF_{effective} &= \sum_{age=0}^{age=20} EF_{age} * \frac{NV_{age}}{NV_{total}} \\
Emissions &= NV_{total} * VKT * EF_{effective}
\end{aligned}
$$

**Equation 3.1**

For a given fleet, the total emissions depend on the mix of the vehicles on road, e.g., the make and the age of the vehicles. The age mix of the vehicles is considered to account for the deterioration of the vehicles and the associated emissions, and to account for the average retirement of the vehicles. In this study, an average retirement age of 10 years for the passenger cars, 15 years for the buses, 12 years for the 3 wheelers, and 8 years for the motorcycles is assumed. The average retirement age doesn't mean that all the vehicles are retired instantaneously, but a fraction of the fleet is interchanged for a newer fleet to maintain the assumed age mix. The inventory presented in Table 3 also includes an estimate for idling emissions, assuming an average of ~20 minutes in congestion for passenger vehicles and ~40 minutes for buses per day[72].

For the criteria pollutants, trucks (heavy duty and light duty commercial vehicles) and 2-wheelers (motorcycles, scooters, and mopeds) dominate the emissions, followed by buses and passenger cars. The trucks remain the dominant source of emissions in the Indian cities because of the diesel based fleets and operating under loaded conditions for most of the time. The motorcycle emissions are among the highest in spite of a lower average age for the fleet mainly because of the sheer number of vehicles on road. The passenger car fleet is the newest and adheres to the newer emission norms for petrol and diesel vehicles, which tend to be cleaner on average when compared older fleets of buses and trucks.

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[72] The methodology utilized for calculating the contribution of congestion to air emissions is presented in SIM-air working paper No.18, "Vehicle idling emissions" @ http://www.urbanemissions.info

The fleet average emission factors are established by ARAI India (in Pune) and utilized for the six city source apportionment study conducted by MoEF and CPCB of India. The emission factors were also studies and utilized from the following sources – SEI emissions inventory handbook[73], IIASA GAINS modeling system for co-benefits analysis[74], US-EPA Emissions Factors handbook[75], and HEAT emissions modeling system[76].

The emissions inventory for the transport sector (and others) was calculated in as segregated fashion as possible by vehicle type and fuel type, to allow for analysis of the fuel consumption patterns. The main fuels considered in this analysis are diesel, petrol, liquefied petroleum gas (LPG) and compressed natural gas (CNG). Because of its usage for bus and truck fleets, the role of diesel to local criteria and GHG emissions is the largest. Of the total estimated fuel usage (and for $CO_2$ emissions), the diesel, especially from the trucks is the dominant source of pollution followed by petrol and then the alternative gases like CNG and LPG.

[73] Details available @ http://sei-international.org/news-and-media/1147
[74] Details on the GAINS @ http://gains.iiasa.ac.at/index.php/home-page
[75] US EPA - 42 details @ http://www.epa.gov/ttn/chief/ap42/
[76] HEAT emissions tool @ http://heat.iclei.org

# Annex 2.0 ATMoS Dispersion Model

The Atmospheric Transport Modeling System (ATMoS) model is a UNIX/Linux based air pollution dispersion model, primarily developed for sulfur pollution dispersion modeling as part of the Regional Air Pollution Information System for Asia (RAINS-Asia – software developed and distributed by the International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria), which was later updated to support PM pollution (primary and secondary). This model was previously utilized for numerous air pollution modeling studies in Asia, including the RAINS and GAINS integrated modeling system, sulfur pollution control in Asia, PM pollution analysis for cities. A list of the studies and relevant literature is presented in **Box A1.1**.

***Box A1.1: Applications using the ATMoS Model***

Adhikary, B., 1998, "Analysis of Advanced Control Technologies in Improving Ambient Air Quality and Human Health in Chongqing." B. E Thesis, The University of Iowa, USA.

Arndt, R., et al., 1998, "Seasonal Source-Receptor Relationships in Asia", Atmospheric Environment, 32, 1397--1406.

Calori, G., et al., 1999, "An urban trajectory model for sulfur in Asian megacities. Model concepts and preliminary application" Atmospheric Environment, 33, 3109-3117.

Calori, G., et al., 2001, "Interannual variability in sulfur deposition in Asia", Journal of Global Environmental Engineering, 7, 1-16.

Guttikunda, S. K., et al., 2001, "Sulfur Deposition in Asia: Seasonal Behavior and Contributions from Various Energy Sectors." Water, Air and Soil Pollution, 131, 383-406.

Guttikunda, S. K., et al., 2005, "The Contribution of Megacities to Regional Sulfur Pollution in Asia" Atmospheric Environment.

Heffter, J. L., 1983, "Branch Atmospheric Trajectory (BAT) model", NOAA Technical Momorandum, ERL ARL-121.

Holloway, T., et al., 2002. "Transfer of reactive nitrogen in Asia: development and evaluation of a source–receptor model" Atmospheric Environment

IES (2008). Co-benefits of air pollution and GHG emission reductions in Hyderabad, India. Integrated Environmental Strategies India program, USEPA, Washington DC, USA.

Li, J., et al., 2004. "Curbing Air Pollution in Megacity: Human Health Benefits of Air Pollution Control in Shanghai" Journal of Environment Management, 70, 49-62.

The model has flexible temporal and spatial resolution and can be run for the periods ranging from months to a year. The model produces monthly average concentrations as output and then converted to seasonal and yearly averages for further analysis. The meteorological data for this study is obtained from the NCEP Reanalysis fields, an openly available resource[77]. The meteorological data for the precipitation, wind speeds and wind directions are available for the period from 1948 to 2010 from the NCEP reanalysis data fields. An example data for the year 2008, the grids covering the city of Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot areas for year 2008 are presented in **Chapter 3.0** for wind speeds and directions, mixing layer heights, and monthly precipitation.

**Removal Processing**

While the chemical transformation of the species provides a form of removal of the emissions, two physical processes are included – dry and wet deposition. The wet deposition scheme is activated only during the precipitation period.

A net removal rate at the surface due to dry deposition is calculated using the equation $R_d = \frac{V_d}{z}$ where, $R_d$ is the dry removal rate (per sec), $V_d$ is the dry deposition velocity (m/sec), and z is the surface layer height (m). Constant dry deposition rates are prescribed in the model. Similarly, net removal rate at the surface due to wet deposition is calculated using the equation $R_w = S_p * P$ where $R_w$ is the wet removal rate (per sec), $S_p$ is the precipitation scavenging coefficient and p is the precipitation rate (mm/hr). The rates are average numbers and the methodology of calculation is flexible, depending on the available local information[78].

Utilizing the gridded emissions inventory (presented in the previous section) and the meteorological fields, the dispersion modeling is carried out for annual average concentrations over the study domains for each of the cities.

[77] NCEP/NCAR Reanalysis data for a number of meteorological conditions is available for a period starting from 01/01/1948 @ http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html The meteorological processing is conducted before the dispersion modeling.

[78] An average set of dry and wet deposition rates are presented in the input file of ATMoS-4.0 and user has the option to either keep the defaults or change

# Annex 3.0 Reports of Health Impacts Due to Air Pollution

| Country | City | Mortality reported | Reference |
|---|---|---|---|
| Worldwide | | Climate change causes 315,000 deaths a year | Reuters, May 29th, 2009 |
| Pakistan | | Air pollution kills ~23,000 annually | The News, May 15th, 2009 |
| Worldwide | | 100 million premature deaths could be prevented by cutting global emissions by 50% by 2050 | Guardian, May 12th, 2009 |
| India | | Over 20 million people have asthma and susceptible to higher risks | Hindustan Times, April 25th, 2009 |
| Pakistan | | Pollution kills 55,000 every year | The Nation, April 24th, 2009 |
| United States | | Air pollution shortens life | BBC, April 12th, 2009 |
| UAE | | Air pollution is a major public health issue | Gulf News, April 12th, 2009 |
| Worldwide | | Up to 60,000 premature deaths a year worldwide are due to PM emissions from ocean-going ship engines | Guardian, April 09th, 2009 |
| Bangladesh | Dhaka | Air pollution is causing ~15,000 premature deaths a year | IRIN, April 3rd, 2009 |
| Worldwide | by WMO | Lethal air pollution booms in emerging nations | AFP, March 22nd, 2009 |
| India | Delhi | Country's asthma capital | Mail Today, March 1st, 2009 |
| Indonesia | Jakarta | 50% of the professionals may be literally sick of work due to air quality | Jakarta Globe, February 19th, 2009 |
| Russia | | Air pollution is responsible for 17% of diseases in children and 10% in adults, and affects 44% of the population | Russian News & Information Agency, February 13th, 2009 |
| Uganda | | Do we have to live with pollution? | The New Vision, February 10th, 2009 |
| Afghanistan | Kabul | Air pollution is hastening the deaths of 3,000 every year | IRIN, January 29th, 2009 |
| Bahrain | | More than 10% of the population suffers from asthma and the number is set to rise as air pollution increases | Gulf News, February 08th, 2009 |
| Hong Kong | Hong Kong | Air pollution caused more then 6,600 premature dealths | AFP, January 22nd, 2009 |
| Philippines | Manila | Air pollution kills 5,000 annually | Manila Times, November 07th, 2009 |
| China | Beijing | Pollution sparks health worries | Telegraph, August 07th, 2007 |
| India | Hyderabad | Air pollution causes ~2,500 premature deaths annually | IES, March 15th, 2008 |
| China | | The combined health and non-health cost of outdoor air and water pollution for China's economy comes to around $US100 billion a year | World Bank, July 07th, 2007 |
| Worldwide | by WHO | Air pollution in the world cities is causing some two million premature deaths every year | ENS, October 06th, 2006 |
| Mongolia | Ulaanbaatar | Air pollution causes ~7,000 premature deaths | UE, June 15th, 2007 |
| Worldwide | | Anthropogenic climate change of the past 30 years already claims over 150,000 lives annually | Nature, November, 2005 |

### *Box A3.1: Health Impact Analysis Studies*

1. "Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review" (2004, 2010)
   @ http://pubs.healtheffects.org/view.php?id=3
2. California Air Resources Board (2008) "Methodology for Estimating Premature Deaths Associated with Long-term Exposure to Fine Airborne Particulate Matter in California"
   @ http://www.arb.ca.gov/research/health/pm-mort/pm-mort.htm
3. PAPA – Public Health and Air Pollution in Asia
   @ http://www.cleanairnet.org/caiasia/1412/article-48844.html
4. Lvovsky, et al. 2000. "Environmental Costs of Fossil Fuels: A Rapid Assessment Method with Application to Six Cities." Environment Department Paper No. 78, The World Bank, Washington DC, USA
5. Bell, et al., 2006. "The avoidable health effects of air pollution in three Latin American cities: Santiago, São Paulo, and Mexico City." Environmental Research, 100, March 2006, 431-440.
6. Pope, C. A., III and Dockery, D. W. 2006. Health effects of fine particulate air pollution: Lines that connect. Journal of the Air Waste Management Assoc. 56(6):709-742.
7. Ostro, et al., 1998. "Estimating the Health Impact of Air Pollution: Methodology and an Application to Jakarta." Working paper series, The World Bank, Washington DC, USA
8. Li, J., and S. K. Guttikunda, et. al., 2004. "Quantifying the Human Health Benefits of Curbing Air Pollution in Shanghai." Journal of Environmental Management. 70, pp. 49-62
9. URBAIR Air Quality Management Series, The World Bank, Washington DC, USA
10. HEI, 2004. "Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review." Health Effects Institute, Boston, USA
11. Ostro, et al., 1994. "Estimating the Health Effects from Air Pollutants: A Method With an Application to Jakarta.' World Bank Policy Research Working Paper #1301
12. Xu, et al., 1994, 'Air Pollution and Daily Mortality in Residential Areas of Beijing, China.' Archives of Environmental Health, 49, pp. 216-222
13. SAES, 2000, 'Shanghai Energy Option and Health Impact.' Report prepared by Shanghai Academy of Environmental Sciences and Shanghai Medical University
14. "Cost of Pollution in China", East and Pacific Region, The World Bank, Washington DC
    @ http://go.worldbank.org/FFCJVBTP40