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# Nature of Air Pollution, Emission Sources, and Management in the Indian Cities

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**ABSTRACT**

The global burden of disease study estimated 695,000 premature deaths in 2010 due to continued exposure to outdoor particulate matter and ozone pollution for India. By 2030, the expected growth in many of the sectors (industries, residential, transportation, power generation, and construction) will result in an increase in pollution related health impacts for the most cities. The available information on urban air pollution, their sources, and the potential of various interventions to control the pollution, should help us propose a cleaner path to 2030. In this paper, we present an overview of the emission sources and control options for better air quality in Indian cities, with a particular focus on interventions like urban public transportation facilities; travel demand management; emission regulations for power plants; clean technology for brick kilns; management of road dust; and waste management to control open waste burning. Also included is a broader discussion on key institutional measures, like public awareness and scientific studies, necessary for building an effective air quality management plan in Indian cities.

**KEYWORDS**

**HIGHLIGHTS**
- Air quality monitoring in the Indian cities
- Sources of air pollution in the Indian cities
- Health impacts of outdoor air pollution in India
- Review of air quality management options at the national and urban scale

## 1.0    INTRODUCTION

Air quality is a cause for concern in India, particularly in cities and air pollutants including particulate matter (PM), sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), carbon monoxide (CO), and ozone ($O_3$) often exceed the National Ambient Air Quality Standards (NAAQS). . According to the World Health Organization (WHO), 37 cities from India feature in the top 100 world cities with the worst $PM_{10}$ pollution, and the cities of Delhi, Raipur, Gwalior, and Lucknow are listed in the top 10 (**WHO, 2014**). A similar assessment by WHO, in 2011, listed 27 cities in the top 100. More than 100 cities under the national ambient monitoring program exceed the WHO guideline for $PM_{10}$.

In India, the national ambient standard for CO is better than the WHO guideline. The $NO_2$, $SO_2$, and $O_3$ standards are at par with the guidelines. However, the standards for $PM_{10}$ (Aerodynamic diameter <10 µm) and $PM_{2.5}$ (aerodynamic diameter <2.5 µm) are lagging (comparative details in **Supplementary Material**).

As cities are increasing in size and population, there is a steady demand for motorized vehicles in both personal and public transport sectors. This puts substantial pressure on the city's infrastructure and environment, particularly since most Indian cites have mixed land use. For 40 cities highlighted in **Census-India (2012)**, the key urban characteristics are presented in **Table 1**. The urban population varies from 1.5 million to 17 million. The data shows that regardless of population size, 30 cities are densely populated with 100 persons per hectare or more. Another 30 cities have at least 30% of the households with a motorized two wheeler (MTW) and 19 cities have at least 10% households with a four-wheeler (a car or a utility vehicle). While most cities are supplied with liquefied petroleum gas (LPG) for domestic use, there is still a significant portion of households using other fuels - such as kerosene, biomass, and coal. Of the 40 cities in **Table 1**, 20 have at least 30% of households with a non-LPG cookstove.

In 2010, the Central Pollution Control Board (CPCB) developed the Comprehensive Environmental Pollution Index (CEPI), a methodology to assess air, water, and soil pollution at the industrial clusters in the country (**CPCB, 2009**). While industries typically rely on the grid electricity for operations and maintenance; frequent power cuts often necessitate the use of in-situ electricity generation (using coal, diesel, and heavy fuel oil), which adds to the industrial air pollution load. The study identified 43 clusters with a rating of more than 70, on a scale of 0 to 100, and listed them as critically polluted for further action. Most of these clusters are in and around major cities – most notably Korba (Chhattisgarh), Vapi (Gujarat), Faridabad and Ghaziabad (outside of Delhi), Ludhiana (Punjab), Kanpur and Agra (Uttar Pradesh), Vellore and Coimbatore (Tamil Nadu), Kochi (Kerala), Vishakhapatnam (Andhra Pradesh), Howrah (West Bengal), and Bhiwadi (Rajasthan). The CEPI ratings, where available, are listed by their ranking in **Table 1**.

The global burden of disease (GBD) assessments, listed outdoor air pollution among the top 10 health risks in India. The study estimated 695,000 premature deaths and loss of 18.2 million healthy life years due to outdoor $PM_{2.5}$ and ozone pollution (**IHME, 2013**). Among the health risk factors studied, outdoor air pollution was ranked 5th in mortality and 7th in overall health burden in India. Household (indoor) air pollution from burning of solid fuels was

85    responsible for an additional one million premature deaths. A substantial increase was observed
86    in the cases of ischemic heart disease (which can lead to heart attacks), cerebrovascular disease
87    (which can lead to strokes), chronic obstructive pulmonary diseases, lower respiratory infections,
88    and cancers (in trachea, lungs, and bronchitis). Several other studies have estimated premature
89    mortality rates due to outdoor PM pollution for several Indian cities, using similar methodologies
90    and are summarized in **Table 2**.
91
92    While the field of air pollution and atmospheric science is gaining ground in India and
93    there has been a surge in the published research, much of the knowledge is widely scattered.
94    While reviews in the past have provided scientific recommendations (**Pant and Harrison, 2012;**
95    **Krishna, 2012**), there has been no concerted effort towards addressing the various aspects of the
96    air pollution (source to impacts), and providing a global summary as well as gaps in current
97    knowledge. Existing local (and international) knowledge can be leveraged in designing effective
98    interventions in India, where pollutant sources are often complex. In this paper, we aim to
99    present an overview of the emission sources and control options for air quality improvements in
100   Indian cities, with a particular focus on key sectors such as transportation, dust, power plants,
101   brick kilns, waste, industries, and residential. Also included is a broad discussion on key
102   institutional measures necessary for building an effective air quality management plan.
103
104   **2.0    AIR QUALITY IN INDIAN CITIES**
105
106   *2.1    Air Quality Data*
107
108   The national ambient monitoring program collects 24-hour averages of key air pollutants
109   2-3 times per week at 342 manual stations in 127 cities and is managed by CPCB. However, only
110   a limited number of cities operate continuous monitoring stations, measuring the full array of
111   criteria pollutants and as such, access to the monitoring data is limited. A summary of the
112   measurements for $PM_{10}$, $SO_2$, and $NO_2$ for 2009-10 is presented in **Table 1**. Delhi and Pune also
113   have citywide monitoring networks outside the national framework (**SAFAR, 2013**).
114
115   To supplement the data generated at on-ground monitoring stations, several studies have
116   utilized satellite data to derive global ground-level ambient $PM_{2.5}$ concentrations (**Van**
117   **Donkelaar et al., 2010**). These were utilized for the GBD assessments (**IHME, 2013**). An
118   extract of this data covering India is presented in **Figure 1**. Since the satellite extractions are
119   available at 0.1° resolution (~10 km), there is some uncertainty associated with these derivatives
120   and these retrieval methods are being improved every year, to complement the on-ground
121   measurements. For example, most of southern India in **Figure 1** seems to comply with the WHO
122   guideline of 15 $\mu g/m^3$. However, the urban pollution levels here are some of the highest in the
123   country including Chennai and Coimbatore (Tamil Nadu), Hyderabad and Vishakhapatnam
124   (Andhra Pradesh), Kochi (Kerala), and Bengaluru (Karnataka).
125
126   The Indo-Gangetic plain has the largest number of brick kilns, with old and inefficient
127   combustion technology, using a mix of biomass and coal for combustion needs (**Maithel et al.,**
128   **2012**). The states of Bihar, West Bengal, Jharkhand, Orissa, and Chhattisgarh harbor the largest
129   coal mines in the country, and a cluster of power plants around the mines (**Guttikunda and**
130   **Jawahar, 2014**). Several large power plants also exist in the states of Punjab, Haryana, Delhi,

and Uttar Pradesh, making the north and north-eastern belt the most polluted part of the country. The cities in the north are also landlocked, which are also affected by the prevalent meteorological conditions, unlike some of the Southern cities with the privilege of land-sea breezes (**Guttikunda and Gurjar, 2012**).

Besides $PM_{2.5}$ concentrations, the satellite observations can also help estimate the concentrations of $SO_2$, $NO_x$, and CO, and help analyze the severity of on-ground anthropogenic and natural emission sources (**Streets et al., 2013**).

## *2.2 Sources of Air Pollution*

For city administrators, regulating air pollution is the primary concern and accurate knowledge of the source contributions is vital to developing an effective air quality management program. The contribution of various sources to the ambient PM pollution is typically assessed via receptor modeling and this methodology has been applied in many Indian cities (**CPCB, 2010; Pant and Harrison, 2012**). However, between 2000 and 2013, 70% of the known studies were conducted in five big cities - Delhi, Mumbai, Chennai, Kolkata, and Hyderabad and very limited number in other cities, which are also listed as exceeding the ambient standards and WHO guidelines (**Table 1** and **WHO, 2014**). The number of studies in various cities is presented in **Table 3**, with limited number of studies on $PM_{2.5}$ size fraction.

The most commonly identified sources are vehicles, manufacturing and electricity generation industries, construction activities, road dust, waste burning, combustion of oil, coal, and biomass in the households, and marine/sea salt. A multi-city study was conducted by CPCB for six cities – Pune, Chennai, Delhi, Mumbai, Kanpur, and Bengaluru, at an approximate project cost of US$6 million (**CPCB, 2010**). A summary of this study is presented in **Figure 2**. Unlike the popular belief that road transport is the biggest cause of urban air pollution, the **CPCB (2010)** results showed that there are other sources which also need immediate attention and the road transport is only one of the major contributors to the growing air quality problems in the cities. In the six cities, the share of road transport ranged 7% in Pune to 43% in Chennai. Along with Mumbai, Chennai harbors one of the largest commercial ports in India, which means a large number of diesel fueled heavy duty trucks pass through the city, to and from the port, and thus increasing the share of road transport in ambient PM pollution.

However, a vital limitation of the receptor modeling approach is the spatial representation of the contributions, i.e., the results are representative of the sampling location and its close vicinity (~2-3km radius from the sampling location). Hence, in order to understand the source contributions in a city, it is important to conduct detailed analysis at multiple locations. The receptor modeling studies also require detailed chemical characterization of emission sources (either as an input or for validation). While several source profiles have been created in India, there is scope for further addition and improvement (**Pant and Harrison, 2012**).

## *2.3 Emissions Inventory & Dispersion Modeling*

While the receptor modeling approach is ideal to ascertain the source contributions, it is an expensive method and has limited spatial coverage. This limitation can be overcome by

177 complementary source modeling. This relies on availability of data such as vehicle activity on
178 the roads, fuel consumption in the domestic, industrial, and electricity generation sectors, waste
179 collection and waste burning, silt loading on the roads for resuspension, and geography,
180 population, and meteorology of the city. Since the analysis includes spatial dispersion modeling,
181 there is a need for computational facilities to input, analyze, and output geo-referenced emissions
182 inventories and concentration fields. Several studies have been carried out in India since 2000
183 and are summarized together with known emission factor databases and key requirements to
184 conduct dispersion modeling in the **Supplementary Material**. An example of gridded vehicle
185 exhaust emissions from Pune, Chennai, and Ahmedabad at 1 km grid resolution is also presented
186 in the **Supplementary Material**. Most of the studies have focused on PM pollution and a very
187 few studies on ozone pollution.

188
189 The source modeling results are driven by user inputs and rely on measurements to test
190 their validity, before they can be used for any policy dialogue. It is also important to note that the
191 dispersion and receptor models should not be used as substitutes for each other and they provide
192 best results when used complementarily.

193
194 **3.0    POTENTAL for AIR POLLUTION CONTROL**

195
196 In most Indian cities, $SO_2$ is the only pollutant that complies with NAAQS. Interventions
197 such as introduction of Bharat-4 diesel (with 50 ppm sulfur) in the cities and Bharat-3 diesel
198 (with 350 ppm sulfur) for the rest of the country and relocation or refurbishing of industries
199 consuming coal and diesel with better efficiency norms have led to this compliance. However,
200 the same is not true for $PM_{10}$, CO, and $NO_2$ concentrations, as their emissions from combustion
201 processes have significantly increased, regardless of the improvements in fuel quality and
202 technology. While most of the industrial equipment and the on-road vehicles individually adhere
203 to their respective emission norms; collectively, they emit enough to register ambient
204 concentrations beyond the standards (**Table 1**).

205
206 There is a vast potential for pollution control in the cities, which can be achieved through
207 the twin approach of stringent regulations technological interventions.  The following sections
208 provide an overview of the potential measures, some under implementation and some which
209 need urgent attention.

210
211 *3.1    Vehicle Fuel Standards and Alternative Fuels*

212
213 Road transport plays a vital role in India's growing economy and the contribution of
214 vehicular emissions is only expected to increase (**Ghate and Sundar, 2013**). Fuel emission
215 standards in India lag behind the global emission standards (**Table 4**). It is essential to implement
216 and enforce Bharat-5 (equivalent of Euro-5) or higher standards nationwide by 2015 or sooner,
217 in order to maintain a balance between the energy demand and the growing emissions
218 (**Guttikunda and Mohan, 2014**). Any delay in implementation or staggered implementation (as
219 is the case currently), will result in a delayed response for improving air quality in Indian cities.

220
221 While the staggered introduction of the fuel standards is beneficial for the cities in the
222 short run, the overall benefits are lost in transition. For example, the heavy duty vehicles

223 operating on diesel contribute significantly to PM emissions and often run on lower grade fuel,
224 which can lead to failure of catalytic converters.  It is therefore imperative that "*one nation, one*
225 *fuel standard*" norm is mandated for better air quality in the cities.
226
227 There is an increasing focus on shifting the public transport and para-transit vehicles to
228 run on compressed natural gas (CNG). In Delhi, buses, three-wheeler rickshaws, and taxis were
229 converted to operate on CNG and a steady supply of fuel coupled with lower prices is
230 encouraging private car owners also to switch. The number of CNG outlets in Delhi increased
231 from 30 in year 2000 to 300 in 2013, according to the Ministry of Petroleum & Natural Gas of
232 India, there will be 200 cities with CNG network by 2015 (**PIB, 2013**).
233
234 *3.3    Urban Travel Demand Management*
235
236 As the cities are growing in geography and inhabitants, there is also a push to promote
237 safe and clean public transport systems. In bigger cities like Delhi, Mumbai, Hyderabad,
238 Kolkata, Chennai, Ahmedabad, and Bangalore, there is an established formal public
239 transportation system and they also benefitted from Jawaharlal Nehru National Urban Renewal
240 Mission (JNNURM) programs to better and increase the fleet (**MoUD, 2012**). Since 2009, more
241 than 14,000 new buses were delivered under this program. However, most of these cities need to
242 at least triple or quadruple the current fleets, in order to for the 4-wheeler and 2-wheeler
243 passengers to shift public transport systems.
244
245 In urban India, implementation of dedicated bus corridors, known as "bus rapid transport
246 (BRT) system" is among the priorities. International examples from Bogota (Colombia) and
247 Curitiba (Brazil) serve as models with bus modal share of 62% and 45% respectively (**LTA
248 Academy, 2011**). The cities of Delhi, Ahmedabad, Jaipur, Pune, and Indore have implemented
249 BRT projects with varying corridor lengths and the cities of Rajkot, Surat, Bhopal, Vijayawada,
250 and Visakhapatnam have approved BRT projects (**Mahadevia et al., 2013**). Since the projects
251 are not fully integrated into the public transport systems, the results and the public response has
252 been mixed.
253
254 For smaller cities, the definition of the public transport is changing. Most of these cities
255 do not have an organized public transportation system; rather, they are supported by informal
256 para-transit systems, mostly plying on the dominant corridors of the city. Among the para-transit
257 systems, most common are the traditional three-wheeler auto-rickshaws (to seat up to 4 people),
258 a larger version of the auto-rickshaws (to seat up to 10 people), and mini-buses. With their ability
259 to negotiate the tiny by-lanes and weave through mixed traffic, these vehicles form an integral
260 part of passenger and freight movement and in most cities is also a popular mode of mass
261 transport for school children. An example is the city of Alwar (Rajasthan) where para-transit
262 system "Alwar Vahini" was successfully formalized with regulations, as well as dedicated routes
263 reaching various parts of the city. The para-transit systems have also benefited from the use of
264 alternative fuels like CNG and LPG. In response to a Supreme Court mandate, the Delhi
265 Government converted the entire three-wheeler fleet to CNG between 1998 and 2002, followed
266 by similar initiatives in other cities.
267

Most Indian cities have a majority share of trips by walk and cycle (**Mohan, 2013**). This is because of low vehicle ownership (compared to the cities of the United States and the European Union) as well as traditional mixed-use design of the cities, which leads to shorter access to work, school, and other activities. In big cities with higher population density, in the absence of dedicated NMT infrastructure, motorized vehicles also pose serious risk of injury, because of which, people owning two-wheelers and cars are encouraged to use their vehicles, even for walkable distances. In the context of growing cities, the measures to improve air quality should include NMT policies as an integral part.

Some economic measures are also designed to force the use of public transport. One such measure is the congestion pricing – where the motorists are charged to use a network of roads during periods of the heaviest use. Its purpose is to reduce automobile (mostly car) use during peak congestion periods, thereby easing traffic and encouraging commuters to walk, bike, or take mass transit rail/bus as an alternative. Congestion pricing programs were successfully implemented in Singapore, London, and Stockholm (**Eliasson, 2009; Menon and Guttikunda, 2010; Litman, 2011**). On average, in London, congestion pricing is estimated to have reduced 20-30% of the downtown passenger car traffic and promote the non-motorized transport, whereas Stockholm experienced an immediate reduction of at least 20% in the daily car use. In Singapore, the average traffic speeds increased by at least 15 km/h. In all three cities, 10-20% reduction in $eCO_2$ emissions was estimated, along with health benefits of reducing air pollution.

A major reason for its success in Singapore, London, and Stockholm was the availability of widely accessible public transport system (road and rail) which can support the shift to a car-free environment. If implemented, there will be immediate benefits in big cities like Delhi, Mumbai, and Chennai. However, the public transport system is still not at par with those in Singapore, London, and Stockholm for effective implementation of this option.

While congestion pricing policies are difficult to replicate in the Indian context, at least for the foreseeable future, there is an important lesson. With increasing costs for private vehicles linked with their usage (fuel and other operational expenses), it is possible to achieve a shift to public transport, if combined with the provision of an adequate, reliable, and safe public transportation. One such measure is the increased parking cost. Currently, parking in most cities is either free or priced very low. Increased parking cost, if coupled with the parking locations so that they are as far as the bus and the rail stops, will make public transportation an attractive option (**Barter, 2012; CSE, 2012**).

While the congestion pricing and parking policies target reduced vehicle usage, some countries have used regulatory measures to reduce the growth of private vehicles. For instance, a Chinese national regulation enacted in September, 2008, raised taxes on big cars and reduced on smaller ones. Car owners with engines above 4-liters capacity have to pay a 40% tax; 15% to 25% for cars with engines above 3-liters capacity; and 1% to 3% for cars with engines below 1-liter capacity (**Murad, 2008**). China also introduced a policy to limit the number of licenses issued every year, where the license plates are auctioned in the cities of Beijing, Shanghai, and Guangzhou. Similar to congestion pricing, for the time being, such measures are difficult to implement under democratic political context of India.

### *3.4    Regulations for Coal-fired Power Plants*

In 2011-12, there were 111 coal-fired power plants in India with a combined generation capacity of 121GW (**CEA, 2012**). The emissions and pollution analysis for these plants, resulted in an estimated 80,000 to 115,000 premature deaths and more than 20.0 million asthma cases from exposure to total $PM_{2.5}$ pollution annually (**Guttikunda and Jawahar, 2014**). While Indian coal has a low sulfur content in comparison with other coals, ash levels are reported to be quite high and can contribute to coarse PM emissions (**Pant and Harrison, 2012**).

Despite the volume of coal used in the power generation sector, there are very few regulations in place to address these environmental and health costs. To date, for PM emissions, the emission standard in India lags to those implemented in China, Australia, the United States, and the European Union (**Table 5**). For other key pollutants, there are no prescribed emission standards despite the fact that India is a relatively dense country and several power plants are in close proximity to residential areas. Aggressive pollution control regulations such as mandating flue gas desulfurization, introduction of tighter emission standards for all criteria pollutants, and updating procedures for environment impact assessments are imperative for regional clean air and to reduce health impacts. For example, a mandate for installation of flue gas desulfurization systems could reduce the $PM_{2.5}$ concentrations by 30-40% by eliminating the formation of the secondary sulfates and nitrates (**Guttikunda and Jawahar, 2014**).

Besides flue gas PM emissions, fugitive dust from coal-handling plants and ash ponds (after the disposal from the plants) is also a problem. According to Central Electrical Authority, after the combustion and application of control equipment, ash collection at the power plants range 70-80% of the total ash in the coal. In 2003, an amendment notification from MoEF mandated 25% bottom ash in all brick kilns within 100km radius of the power plant and all building construction within 100km to use 100% ash based bricks, blocks, and tiles. To date, percentage of ash utilized in the construction industry is low.

### *3.5    Power Shortages and Diesel Generators*

In 2011, the peak electricity demand was approximately 122 GW and the peak electricity supply was approximately 110 GW (**CEA, 2012**). The gap between the supply and the demand is crucial to understand India's power generation sector. In India, a third of the population in rural areas do not have access to electricity and those areas on the grid are not assured of uninterrupted supply. The blackout in July, 2012, that paralyzed 600 million people in 22 states in the Northern, Eastern, and North-eastern India, is testament to how tenuous power situation in the country.

In the urban areas, power cuts are severe in the winter and the summer months, when heaters and air conditioners are in full service, respectively. These needs are usually supplemented by in-situ large, medium, and small diesel generator (DG) sets at hotels, hospitals, malls, markets, large institutions, apartment complexes, cinemas, and farm houses and form an additional source of air pollution to an already deteriorating air quality in the cities. Telecommunication towers stand out, which with more than 500 million mobile phones in the country, are heavily dependent on DG sets. According to the Telecom Regulatory Authority of

8

India (TRAI), 310,000 towers consumed over 2 billion liters of diesel in 2010 (**TRAI, 2011**). The mobile subscriber base is expected to reach 800 million by the end of 2013 with an additional 100,000 telecom towers in service.

For Chennai, Pune, Indore, Ahmedabad, Surat, and Rajkot, up to 10% of the modeled $PM_{10}$ concentrations were found to originate from diesel generator sets (**Guttikunda and Jawahar, 2012**). In case of Delhi, the contribution went up to 15% (**Guttikunda and Calori, 2013; Guttikunda and Goel, 2013**). The use of generator sets is even higher in the rural areas, where they are mostly utilized for the pumping water in the agricultural lands.

An alternative to DG sets is not simple. One option is to increase the number of power plants to meet the electricity demand and reduce the transmission losses or provide alternatives like renewable energy. On the other hand, tightening of the emission standards for DG sets, at par with the heavy and light duty vehicles can help control some emissions.

### *3.6 Domestic Fuels*

The issue of indoor air pollution is also critical because of the high magnitude of population getting exposed to such pollution every day (**Venkatraman et al., 2010; Grieshop et al., 2011; Smith et al., 2014**). According to GBD 2010 assessments, household air pollution has been a persistent health hazard in India and has retained its position as the $2^{nd}$ highest risk factor for disability life years lost and resulting in 1.0 million premature deaths annually (**IHME, 2013**). Several studies have characterized the impacts of household air pollution and health risks due to indoor solid fuel use in India (**Balakrishnan et al., 2011**).

In 2011, Non-LPG fuels are used in 35% of urban and 89% of rural households in India, compared to 52% and 94% respectively in 2001 (**Census-India, 2012**), with little improvement for the rural households. Keeping in view the magnitude of the health risks, the Ministry of Petroleum & Natural Gas of India aims to provide LPG connections to up to 75% of households in India by year 2015 (**PIB, 2013**). For the rural areas, the program is also proposing to set up community kitchens with LPG connections where users can pay as per usage. Alternatives like electric (induction) stoves are cleaner (with pollution generated somewhere else), but their usage is dependent on power supply in the rural communities. The use of electric stoves, in the urban centers, is increasing and currently limited by the cost of stoves.

### *3.7 Emerging Technologies for the Brick Kilns*

The traditional building construction in India believes in the fired clay bricks. The construction is one of the fastest growing sectors, contributing approximately 10% of the national GDP and has a growth rate of 9%. Overall, there are more 100,000 brick kilns in India, producing 150-200 billion bricks annually, employing 10 million workers, and consuming 25 million tons of coal (**Isebelle et al., 2007; Maithel et al., 2012**). Within a radius of 20-30km, one can spot 500-1000 brick manufacturing kilns in the big cities of Delhi, Chennai, Kolkata, Pune, Ahmedabad, Hyderabad, Kanpur, and Patna (**Guttikunda and Jawahar, 2012; Guttikunda and Calori, 2013**).

406  Brick manufacturing includes land clearing for sand and clay, combustion of fuel for
407 burning, operation of diesel engines on site, and transport of the end product to various parts of
408 the city. Traditionally, the rectangle shaped clay bricks are sun dried and readied for firing in
409 "clamps" - a pile of bricks with intermittent layers of sealing mud, and fuel. A significant amount
410 of energy is lost during the cooling with no possibility of recycling. These are mostly located in
411 the Central and Northeast India. In the Indo-Gangetic plains, some advanced manufacturing
412 technologies with a 50m fixed chimney (FCK) are in practice. The chimney supports further
413 dispersion of the emissions and is noted for its low cost of construction. A major disadvantage of
414 these kilns is associated with weather – an open cast kiln means they can be operated only in the
415 non-monsoonal season.
416
417  The emerging technologies and their operational features are summarized in **Table 6**.
418 Between the available technologies, the newer technologies such as vertical shaft brick kilns
419 (VSBK), zigzag, and Hoffmann, could result in at least 40% reduction in the PM emission rates
420 compared to the currently in use FCK technology. VSBK design and construction details are
421 presented as a manual in **World Bank (2010)** with some pilots in India, Bangladesh, and Nepal.
422
423 *3.8    Construction*
424
425  Construction activities emit particles during various activities including block cutting,
426 excavation, demolition, mixing, road building, drilling, loading and unloading of debris etc. In
427 addition, movement of vehicles (especially trucks) in and around construction sites increases the
428 amount of particles by crushing and pulverizing the particles on the road surface. Several studies
429 have highlighted the importance of construction as a PM source, though in receptor modeling
430 studies, the source is combined with sources such as road dust (**Pant and Harrison, 2012**). For
431 six cities, construction accounted for up to 10% of the annual emissions (**Guttikunda and
432 Jawahar, 2012**; **CPCB, 2010**). There is a window of opportunity for the establishment of best
433 practices in the construction industry as there are no nation-wide norms and regulations.
434
435 *3.9    Resuspended/Road Dust*
436
437  Dust is a major concern for many cities in India (**Figure 2**) and comprises of particles
438 emitted due to wear and tear of tyres and brakes and materials from the roads, pavements, and
439 street furniture. Dust loadings increase even further in case the roads are not paved (**CPCB,
440 2010**).
441
442  Traditionally, all the streets, sidewalks and public areas are swept manually and
443 depending on the resources, poor or marginal areas receive reduced or inadequate service, or no
444 service at all, while wealthier, commercial, or tourist areas receive extensive service. However,
445 often in manual street sweeping, most of the dust swept is left on the side of the roads, which
446 gets re-entrained when the vehicle movement resumes during the day. A better alternative is
447 heavy-duty or light-duty trucks with vacuum cleaners to suck up dust from the roads and/or
448 water sprinklers, so that the resuspension of any leftover dust is suppressed. The operational
449 costs of mechanized sweeping could be similar to manual sweeping - given the latter is a labor
450 intensive exercise. Since the road dust accounts for up to 30-40% of the $PM_{10}$ pollution in most

451 cities (**CPCB, 2010; Guttikunda and Jawahar, 2012**), an immediate intervention for this
452 source is considered to be the lowest hanging fruit.
453
454 *3.10 Open Waste Burning*
455
456 There is no reliable national-level data on the technical or financial aspects of solid waste
457 management, and figures are therefore approximations. The country's annual generation of
458 municipal solid waste is in the range of 35 to 45 million tons; likely to quadruple by 2030 at
459 which time, the waste generation will be over 150 million tons a year (**World-Bank, 2006;**
460 **Annepu, 2012**). The scale is perhaps more comprehensible at the city level - the national capital
461 region of Delhi generates 10,000 tons/day and Mumbai 7000 tons/day. The waste collection
462 efficiency in the cities is 50-90%, depending on the commercial and residential activities in
463 various parts of the city. The waste not collected is eventually burnt. The best option for reducing
464 the waste burning is to implement an efficient solid waste management program across the
465 country. Currently, only a few cities operate landfills and manage waste collections. The waste
466 management falls under the jurisdiction of the municipal corporation and according to Toxics
467 Link (New Delhi, India), the municipalities spend an estimated INR 1500-2000 per ton of solid
468 waste for collection (60-70%), transportation (20-30%), and treatment and disposal (5-10%).
469
470 The open waste burning problems are particularly worse in the medium and small scale
471 cities, with very limited or no waste collection and no landfill facilities. Emissions of criteria
472 pollutants from garbage burning are hard to quantify and are accompanied by large uncertainty.
473 The toxic chemicals released during burning of paper, plastic, and biomass includes $NO_x$, $SO_2$,
474 volatile organic chemicals (VOCs), and dioxins.
475
476 **4.0 POLICY IMPLICATIONS**
477
478 According to the 2011 census, 2774 rural settlements are now reclassified as urban
479 settlements, pushing the total to 3894, primarily based on the definition of an urban settlement -
480 population exceeds 5000, population density is above 400 per $km^2$, and more than 75% of the
481 male workforce is employed outside of agriculture (**Census-India, 2012**). The population in
482 urban areas is expected to grow from 30% to 50% by 2030 (**MoUD, 2011**). By 2030, the
483 expected growth in industrial, transportation, domestic, and power generation sectors will
484 consequently result in an increase in emissions and air pollution for almost all the cities listed in
485 **Table 1** and many more cities which are medium and small today. There are growing concerns
486 about the impact of air pollution on human health and general well-being, which requires a
487 multi-pronged approach for better air quality. Some key institutional measures which can led the
488 way are the following
489
490 *4.1 Monitoring and Data Dissemination*
491
492 Before the GBD 2010 assessments (**IHME, 2013**), the 2008 Olympic Games in Beijing
493 resulted in raising significant awareness on the urban air pollution problems. In Beijing, stringent
494 measures were introduced to achieve blue skies rating for the Games and this included shutting
495 down 50% of the on-road vehicles (based on their registration numbers) and shutting major coal-
496 fired industrial estates in the vicinity of the city. These measures not only raised the awareness

497 on the air pollution and benefits of pollution control measures, but also showed the level of
498 commitment necessary from the public and the government to achieve such a result.
499
500       The city of Delhi hosted the 2010 Commonwealth Games, which raised some awareness
501 on air pollution in the city. The number of official monitoring stations tripled during the Games.
502 The national bodies established variable messaging systems and also disseminated the
503 monitoring data on web (**Beig et al., 2013**). However, the emission control programs did not
504 involve any stringent measures like those practiced during the Beijing Olympics (**Streets et al.,**
505 **2007; Wang et al., 2010**) and the implemented measures were found to be ineffective during the
506 Games (**Beig et al., 2013**). While such mega events help raise awareness intermittently, more
507 efforts are necessary to prioritize air pollution and health into long term policy planning.
508
509       There is an acute need to not only increase the monitoring programs across all cities, but
510 also to publicly disseminate the information. While the monitoring stations can be established,
511 legislations amended, and standards improved, these efforts will be a waste, if the regular
512 dissemination of the information is not practiced to raise the awareness for pollution control
513
514 *4.2    Scientific Studies*
515
516       The array of air quality studies in India (listed in **Supplementary Material**) points to
517 significant need for information on spatial and temporal resolution of emissions inventories and
518 pollution dispersion characteristics in the cities. It is important to build the necessary capacity of
519 the state pollution control boards (SPCBs) to undertake focused analysis as well as scrutiny of
520 intervention programs to improve the air quality.
521
522       Much of the past and current work focuses on $PM_{10}$ and there is a growing trend towards
523 analysis of $PM_{2.5}$ (**Table 3**). Due to the negative health impacts, there is a growing need for
524 assessment of particles in the small size ranges ($PM_1$ and less). Very little is known in terms of
525 spatial and temporal distribution of air pollutants and parameters such as particle size distribution
526 (mass/number/volume). Semi-volatile and volatile organic species have also not been analyzed in
527 much detail (**Krishna, 2012; Ram et al., 2014**). Some recent work focused on unique sources
528 such as funeral pyres (**Chakrobarty et al., 2013**) and festive biomass burning (**Deka and**
529 **Hoque, 2014**) and specific chemical components of PM such as brown carbon (**Srinivas and**
530 **Sarin, 2014**).
531
532       One of the key missing pieces is the personal exposure and toxicological analysis which
533 is an important input for the assessment of health impacts of outdoor and household air pollution
534 (**Clark et al., 2013**). This includes assessment of indoor and outdoor concentrations of various
535 pollutants and integrated physio-chemical characterization (**Wong et al., 2008; Massey et al.,**
536 **2012; Balakrishnan et al., 2013; Chithra and Shiva Nagendra, 2013; Habil et al., 2013**).
537
538 *4.3    Conceptualizing Combined-Benefits*
539
540       All the combustion sectors are interlinked, which leads to the concept of co-benefits for
541 better air quality in the cities. There are many definitions for co-benefits and one of them is "a
542 single activity or policy that can generate multiple benefits across varying sectors or fields". For

example (a) a program in the solid waste management where the wet waste is collected and used to generate biogas, can support the domestic energy needs and thus reduce the load at the local power plant (b) a program designed to increase the energy efficiency of industries can lead to the supply of the excess power to areas plagued with frequent outages, and thus resulting in lesser usage of DG sets.

The definition of co-benefits can also be extended to pollutants. For example, programs to control pollutants like PM, $SO_2$, $NO_x$, and CO, can also reduce greenhouse gas emissions, and vice versa. For example (a) a program to improve the fuel economy of the vehicles by increasing vehicle speeds by reducing the number of cars and motorcycles on the roads, will result in a systematic reduction of all pollutant emissions (b) a program to encourage LPG and electricity usage for domestic cooking and heating, will result in lesser usage of the conventional fuels like coal, biomass, and kerosene, and can result in reduction of all pollutant emissions.

**5.0     CONCLUSIONS**

Ground measurements, computational studies, and satellite measurements, are all pointing towards changing pollution trends in India. Today, India has the unique opportunity to further the air pollution abatement measures at the urban and the regional scale, but these depend on effective inter-sector and inter-ministerial collaboration. This is primarily due to the fact that all the sources contributing to the air pollution are interlinked. Among the sectors, transportation is the most critical and most connected.

Following the review, two challenges have emerged for better air quality in the Indian cities (a) the need to secure greater public awareness of the problems and commitment to action at civic, commercial, and political levels (b) to ensure that action to tackle air pollution is seen in the context of wider social and economic development policies. For example, how much can these interventions help reduce the local challenges, like providing safer and reliable public transportation systems; cleaner and efficient waste management; dust free roads; and pollution free industries and power plants.

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733

1 **Table 1: Cities at a glance**

2

| City | AR | Pop | A | B | C | D | E | F | PM10 (μg/m³) | SO2 (μg/m³) | NO2 (μg/m³) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Hyderabad | 500 | 7,749,334 | 155 | 50% | 14% | 32% | 70.82 (40) | No | 81.2 ± 34.0 | 5.0 ± 2.4 | 22. ± 7.0 |
| Vijayawada | 79 | 1,491,202 | 189 | 26% | 4% | 21% | | No | 79. ± 14.9 | 4.6 ± 0.5 | 13.5 ± 3.1 |
| Vishakhapatnam | 159 | 1,730,320 | 109 | 36% | 8% | 21% | | Yes | 91.2 ± 34.8 | 11.9 ± 12.7 | 29.1 ± 13.8 |
| Guwahati | 145 | 968,549 | 67 | 10% | 3% | 80% | | No | 132.6 ± 89.9 | 8.1 ± 3.3 | 16.6 ± 5.3 |
| Patna | 86 | 2,046,652 | 238 | 32% | 10% | 29% | | No | 138.8 ± 84.4 | 5.3 ± 2.8 | 32.9 ± 18.8 |
| Korba | 39 | 365,073 | 94 | 43% | 8% | 56% | | No | 116.9 ± 17. | 13.3 ± 0.7 | 21.3 ± 0.8 |
| Raipur | 95 | 1,122,555 | 118 | 38% | 9% | 48% | 65.85 (63) | No | 272.2 ± 43.3 | 17.8 ± 3.7 | 45.9 ± 2.7 |
| Delhi | 669 | 16,314,838 | 244 | 39% | 21% | 9% | | No | 260.1 ± 117.1 | 6.5 ± 4.2 | 51.1 ± 17.2 |
| Ahmedabad | 275 | 6,352,254 | 231 | 51% | 13% | 24% | 75.28 (22) | No | 94.3 ± 21.8 | 15.9 ± 3.5 | 20.9 ± 4.0 |
| Rajkot | 86 | 1,390,933 | 162 | 60% | 10% | 33% | 66.76 (59) | No | 105.6 ± 27. | 11.3 ± 2.1 | 15.4 ± 2.6 |
| Surat | 155 | 4,585,367 | 296 | 44% | 9% | 28% | 57.9 (79) | No | 89.1 ± 13.1 | 18.6 ± 3.9 | 26.3 ± 3.2 |
| Vadodhara | 145 | 1,817,191 | 125 | 60% | 14% | 20% | 66.91 (57) | No | 86. ± 34.6 | 16.2 ± 5.8 | 30.2 ± 13.1 |
| Vapi | 37 | 163,605 | 44 | 44% | 11% | 32% | 88.09 (2) | No | 78.3 ± 8.1 | 16.4 ± 1.9 | 23.9 ± 1.7 |
| Yamuna Nagar | 41 | 383,318 | 93 | 42% | 13% | 24% | | No | 281.5 ± 132.3 | 12.7 ± 2.7 | 27.1 ± 3.3 |
| Dhanbad | 45 | 1,195,298 | 266 | 31% | 5% | 72% | 78.63 (13) | No | 164. ± 95.5 | 16.6 ± 3.5 | 41. ± 8.9 |
| Jamshedpur | 119 | 1,337,131 | 112 | 49% | 12% | 38% | 66.06 (61) | No | 171.7 ± 13.4 | 36.4 ± 2.2 | 49.3 ± 3.9 |
| Ranchi | 106 | 1,126,741 | 106 | 43% | 13% | 36% | | No | 178.9 ± 67.9 | 18.1 ± 2.2 | 31.6 ± 3.0 |
| Bangalore | 556 | 8,499,399 | 153 | 46% | 18% | 20% | | No | 109.4 ± 92.6 | 15. ± 3.1 | 37.5 ± 6.0 |
| Jammu | 123 | 651,826 | 53 | 48% | 25% | 13% | | No | 118.2 ± 37.4 | 8.2 ± 4.4 | 12.7 ± 3.4 |
| Trivandrum | 108 | 1,687,406 | 156 | 34% | 17% | 43% | | Yes | 62.9 ± 17.8 | 9.7 ± 5.2 | 26.1 ± 5.2 |
| Bhopal | 178 | 1,883,381 | 106 | 48% | 15% | 30% | | No | 118.5 ± 73.2 | 7.1 ± 2.4 | 17.5 ± 5.9 |
| Gwalior | 78 | 1,101,981 | 141 | 45% | 8% | 29% | 54.63 (83) | No | 227.7 ± 84.6 | 8.6 ± 1.9 | 16.8 ± 4.1 |
| Indore | 102 | 2,167,447 | 212 | 50% | 13% | 17% | 71.68 (38) | No | 160.6 ± 73.4 | 9.4 ± 4.3 | 16.4 ± 6.5 |
| Jabalpur | 104 | 1,267,564 | 122 | 46% | 8% | 34% | | No | 135.7 ± 13.0 | | 24.3 ± 2.1 |
| Ujjain | 33 | 515,215 | 156 | 40% | 6% | 26% | | No | 78.4 ± 42.0 | 10.9 ± 3.4 | 11.9 ± 3.1 |
| Shillong | 46 | 354,325 | 77 | 9% | 16% | 42% | | No | 78.8 ± 31.0 | 19.4 ± 19.0 | 12.5 ± 5.4 |
| Amritsar | 90 | 1,183,705 | 132 | 50% | 15% | 21% | | No | 188.7 ± 24.2 | 14.8 ± 2.2 | 35.1 ± 3.1 |
| Chandigarh | 115 | 1,025,682 | 89 | 47% | 26% | 27% | | No | 79.9 ± 32.6 | 5.8 ± 0.5 | 15.4 ± 7.8 |
| Ludhiana | 167 | 1,613,878 | 97 | 50% | 19% | 19% | 81.66 (10) | No | 251.2 ± 21.9 | 8.4 ± 2.3 | 36.2 ± 7.0 |
| Chennai | 426 | 8,917,749 | 210 | 47% | 13% | 17% | | Yes | 121.5 ± 45.5 | 12.1 ± 3.5 | 20.8 ± 7.0 |
| Agra | 129 | 1,746,467 | 135 | 48% | 12% | 27% | 76.48 (19) | No | 184.1 ± 95.9 | 6.6 ± 3.5 | 20.8 ± 12.1 |
| Allahabad | 71 | 1,216,719 | 171 | 54% | 11% | 26% | | No | 165.3 ± 70.7 | 3.6 ± 1.0 | 23.7 ± 15.9 |
| Firozabad | 21 | 603,797 | 288 | 25% | 4% | 40% | 60.51 (75) | No | 195.6 ± 78.2 | 21.6 ± 4.8 | 32.1 ± 4.9 |
| Kanpur | 150 | 2,920,067 | 195 | 11% | 3% | 42% | 78.09 (15) | No | 211.5 ± 25.3 | 7.5 ± 1.2 | 31.3 ± 4.9 |
| Lucknow | 240 | 2,901,474 | 121 | 52% | 15% | 20% | | No | 200.4 ± 28.4 | 8.4 ± 1.0 | 36.1 ± 2.6 |
| Varanasi | 102 | 1,435,113 | 141 | 40% | 7% | 29% | 73.79 (29) | No | 125.3 ± 8.4 | 17.2 ± 0.7 | 19.6 ± 0.7 |
| Asansol | 49 | 1,243,008 | 254 | 27% | 4% | 61% | 70.2 (42) | No | 162.7 ± 98.7 | 9.4 ± 3.1 | 61.8 ± 18.5 |
| Durgapur | 56 | 581,409 | 104 | 27% | 4% | 61% | 68.26 (52) | No | 172.5 ± 107.1 | 9.8 ± 3.2 | 63.9 ± 18.6 |
| Kolkota | 727 | 14,112,536 | 194 | 12% | 9% | 34% | | No | 160.8 ± 109.3 | 17.3 ± 15.4 | 59.7 ± 27.8 |

Notes:

AR = build-up area (in km²) is estimated from Google Earth maps.; A = population density (per hectare); B = % households with a motorized two wheelers; C = % households with a four wheeler; D = % households with a non-gas cookstove; E = CEPI rating (rank); F = is the city coastal;

3

4

**Table 2: Estimated premature mortality due to outdoor air pollution in India**

| City/Region | Study year | Pollutant | Premature mortality | Reference |
|---|---|---|---|---|
| All India | 1990 | $PM_{10}$ | 438,000 | **IHME (2013** |
| Delhi | 1990 | Total PM | 5070 | **Cropper et al. (1997)** |
| Mumbai | 1991 | $PM_{10}$ | 2800 | **Shah and Nagpal (1997)** |
| Delhi | 1993 | $PM_{10}$ | 3800-6200 | **Kandlikar and Ramachandran (2000)** |
| Mumbai | 1993 | $PM_{10}$ | 5000-8000 | **Kandlikar and Ramachandran (2000)** |
| Delhi | 2001 | $PM_{10}$ | 5000 | **Nema and Goyal (2010)** |
| Kolkata | 2001 | $PM_{10}$ | 4300 | **Nema and Goyal (2010)** |
| Mumbai | 2001 | $PM_{10}$ | 2000 | **Nema and Goyal (2010)** |
| Chennai | 2001 | $PM_{10}$ | 1300 | **Nema and Goyal (2010)** |
| Ahmedabad | 2001 | $PM_{10}$ | 4300 | **Nema and Goyal (2010)** |
| Kanpur | 2001 | $PM_{10}$ | 3200 | **Nema and Goyal (2010)** |
| Surat | 2001 | $PM_{10}$ | 1900 | **Nema and Goyal (2010)** |
| Pune | 2001 | $PM_{10}$ | 1400 | **Nema and Goyal (2010)** |
| Bhopal | 2001 | $PM_{10}$ | 1800 | **Nema and Goyal (2010)** |
| Pune | 2010 | $PM_{10}$ | 3600 | **Guttikunda and Jawahar (2012)** |
| Chennai | 2010 | $PM_{10}$ | 3950 | **Guttikunda and Jawahar (2012)** |
| Indore | 2010 | $PM_{10}$ | 1800 | **Guttikunda and Jawahar (2012)** |
| Ahmedabad | 2010 | $PM_{10}$ | 4950 | **Guttikunda and Jawahar (2012)** |
| Surat | 2010 | $PM_{10}$ | 1250 | **Guttikunda and Jawahar (2012)** |
| Rajkot | 2010 | $PM_{10}$ | 300 | **Guttikunda and Jawahar (2012)** |
| All India | 2010 | $PM_{2.5}$ + ozone | 695,000 | **IHME (2013)** |
| Delhi | 2010 | $PM_{2.5}$ | 7350 to 16,200 | **Guttikunda and Goel (2013)** |
| Delhi | 2030 | $PM_{2.5}$ | 22,000 | **Dholakia et al. (2013)** |

**Table 3: Number of receptor modeling studies conducted between 2000 and 2013 in India**

| City | A | B | C | A&B | D | Total |
|---|---|---|---|---|---|---|
| Delhi | 4 | 1 | | 1 | 5 | 11 |
| Mumbai | 3 | 1 | | 1 | 2 | 7 |
| Kolkata | 2 | 1 | | | 1 | 4 |
| Chennai | 1 | 1 | | 2 | | 4 |
| Hyderabad | | 1 | | 1 | | 2 |
| Agra | | | | 1 | 1 | 2 |
| Kanpur | | | 1 | | | 1 |
| Ahmedabad | | | | 1 | | 1 |
| Chandigarh | | | | | 1 | 1 |
| Tirupati | 1 | | | | | 1 |
| Talcher | 1 | | | | | 1 |
| Dhanbad | 1 | | | | | 1 |
| Jorhat | | 1 | | | | 1 |
| Virudhanagar | | | | 1 | | 1 |
| Mithapur | | | | | 1 | 1 |
| Bhubaneshwar | | | | | 1 | 1 |
| Multi-city | | 1 | | 1 | | 2 |
| Raipur | 1 | | | | 5 | 1 |
| Notes: A = $PM_{10}$; B = $PM_{2.5}$; C = $PM_1$; D = mixed size fractions; | | | | | | |

11 **Table 4: Chronology of Bharat emission standards**

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| Standard | Date | Region |
|---|---|---|
| India 2000 | 2000 | Nationwide |
| Bharat-2 (Ref: Euro-2) | 2001 | NCR, Mumbai, Kolkata, and Chennai |
| | 2003.04 | NCR + 13 cities |
| | 2005.04 | Nationwide |
| Bharat-3 (Ref: Euro-3) | 2005.04 | NCR + 13 cities |
| | 2010.04 | Nationwide |
| Bharat-4 (Ref: Euro-4) | 2010.04 | NCR + 13 cities |
| | 2012.03 | NCR+ 13 cities + 7 cities |
| | 2015 | 50+ cities |
| * NCR is the national capital region of Delhi, including Delhi and its satellite cities<br>** 13 cities are Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, Lucknow, Sholapur, Jamshedpur and Agra<br>*** 7 cities are Puducherry, Mathura, Vapi, Jamnagar, Ankaleshwar, Hissar and Bharatpur | | |

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14 **Table 5: Summary of emission standards for coal-fired power plants**

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| Country [a] | PM | SO$_2$ | NO$_2$ | Mercury |
|---|---|---|---|---|
| India | 350mg/Nm$^3$ for <210MW<br>150mg/Nm$^3$ for >210MW | None | None | None |
| China | 30mg/Nm$^3$ (proposed all)<br>20mg/Nm$^3$ for key regions | 100mg/Nm$^3$ for new<br>200mg/Nm$^3$ for old<br>50mg/Nm$^3$ for key regions | 100mg/Nm$^3$ | None |
| Australia | 100mg/Nm$^3$ for 1997-2005<br>50mg/Nm$^3$ after 2005 | None | 800mg/Nm$^3$ for 1997-2005<br>500mg/Nm$^3$ after 2005 | In discussion based on USA standards |
| European Union | Pre-2003<br>100mg/Nm$^3$ for <500MW<br>50mg/Nm$^3$ for >500MW<br>Post 2003<br>50mg/Nm$^3$ for <100MW<br>30mg/Nm$^3$ for >100MW | Pre-2003<br>Scaled for <500MW<br>400mg/Nm$^3$ for >500MW<br>Post 2003<br>850mg/Nm$^3$ for <100MW<br>200mg/Nm$^3$ for >100MW | Pre-2003<br>600mg/Nm$^3$ for <500MW<br>500mg/Nm$^3$ for >500MW<br>Post 2003<br>400mg/Nm$^3$ for <100MW<br>200mg/Nm$^3$ for >100MW | In discussion |
| USA [b] | 6.4 gm/GJ | 640 gm/MWh | 720 gm/MWh for old<br>450 gm/MWh for new | 0.08 gm/MWh for lignite<br>0.01 gm/MWh for IGCC |
| a – Source: **Guttikunda and Jawahar (2014)**; b – in official units; mercury as 12 month rolling average | | | | |

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19 **Table 6: Comparison of technical and operational benefits and constraints of current**
20 **and alternative brick manufacturing technologies**
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| Technology | Fuel consumed per 100,000 bricks | Investment and operational costs (million USD) [f] | Brick production capacity (million/kiln) | Number of kilns required to produce 3.5 billion bricks | Average tons of $CO_2$ produced per 100,000 bricks | Average reduction in PM emissions compared to FCK |
|---|---|---|---|---|---|---|
| FCK | 20-22 tons coal | 1.7 | 4.0 | 1000 | 50 | |
| Zigzag [b] | 16-20 tons coal | 1.6 | 4.0 | 1000 | 40 | 40% |
| Hoffmann [c] | 15,000-17,000 $m^3$ NG | 5.7 | 15.0 | 270 | 30 | 90% |
| Hoffmann [d] | 12-14 tons coal | 5.7 | 15.0 | 270 | 30 | 60% |
| VSBK [e] | 10-12 tons coal | 1.6 | 5.0 | 800 | 25 | 60% |

a. FCK = fixed chimney bull trench kiln; NG = natural gas; VSBK = vertical shaft brick kiln
b. Some zigzag pilot kilns are in operation, listed as medium performance. Any improvement in the efficiency of operations can lead to further reductions in coal consumption
c. Manufacturing period for Hoffmann kilns is round the year, compared to the current non-monsoonal month operations for the other kilns; thus increasing the land and raw material requirements; Link to natural gas grid and continuous fuel supply is a major constraint
d. Initial investments are higher for Hoffmann kilns
e. Operational models are available in India and Kathmandu
f. Costs include initial investment, land, building, operational, and taxes estimates (**World-Bank, 2010**)
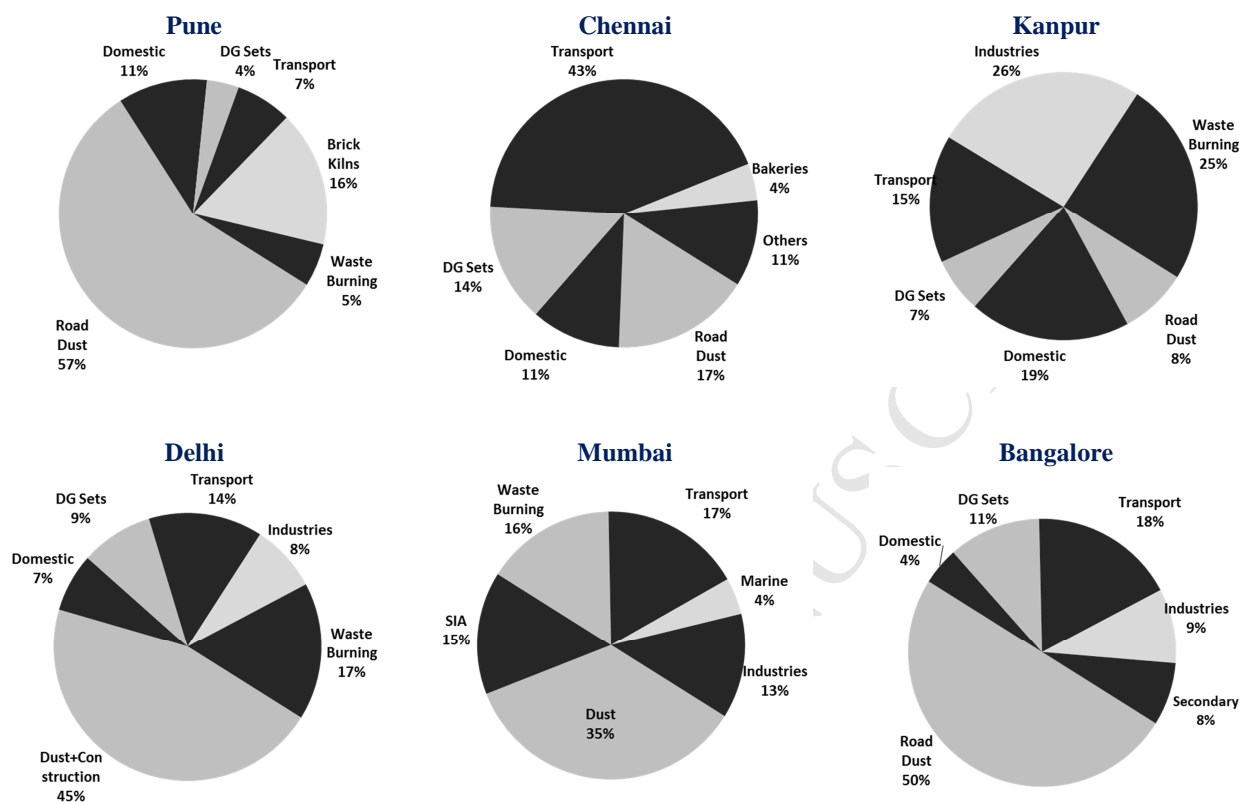
22
23

24 **Figure 1: Ambient PM$_{2.5}$ concentrations derived from the satellite observations**
25
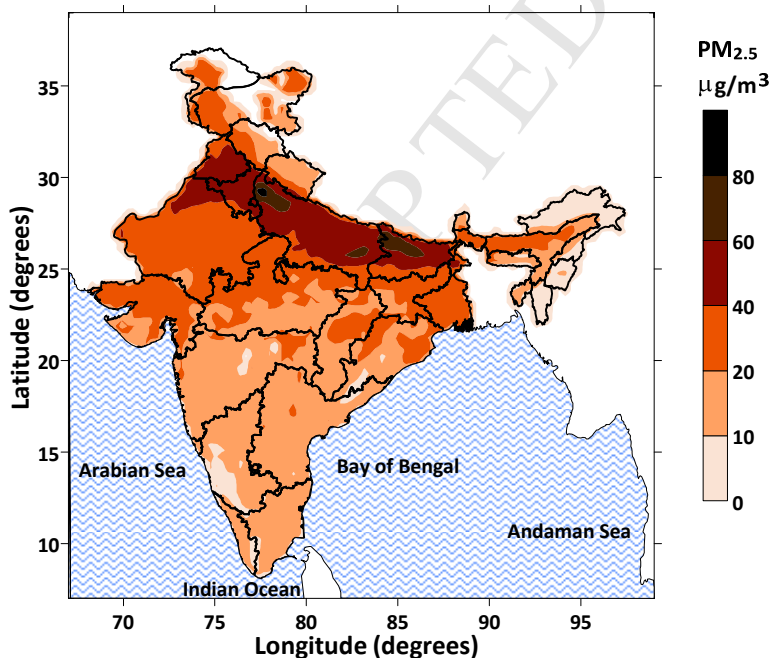


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29  **Figure 2: Average percent contributions of major sources to PM$_{10}$ pollution (CPCB, 2010)**
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# Nature of Air Pollution, Emission Sources, and Management in the Indian Cities

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**HIGHLIGHTS**
- Air quality monitoring in the Indian cities
- Sources of air pollution in the Indian cities
- Health impacts of outdoor air pollution in India
- Review of air quality management options at the national and urban scale

1

# Nature of Air Pollution, Emission Sources, and Management in the Indian Cities

**SUPPLEMENTARY MATERIAL**

**Table 1: Summary of national ambient standards and the WHO guidelines for air quality**

| Pollutant | Averaging Time | India | China | EU | USA | USA ** | WHO |
|---|---|---|---|---|---|---|---|
| $PM_{10}$ | Annual | 60 | 40 | 40 | - | - | 20 |
| | 24-hour | 100 | 50 | 50 | 150 | 150 | 50 |
| $PM_{2.5}$ | Annual | 40 | 15 | 25 | 15 | 15 | 10 |
| | 24-hour | 60 | 35 | - | 35 | 35 | 25 |
| $SO_2$ | Annual | 50 | 20 | - | - | - | - |
| | 24-hour | 80 | 50 | 125 | - | - | 20 |
| | 1-hour | - | 150 | 350 | 75 (ppb) | 196 | - |
| $NO_2$ | Annual | 40 | 40 | 40 | 53 (ppb) | 107 | 40 |
| | 24-hour | 80 | 80 | - | - | - | - |
| | 1-hour | - | 200 | 200 | 100 (ppb) | 203 | 200 |
| CO | 24-hour | - | 4000 | - | - | - | - |
| | 8-hour | 2000 | - | 10000 | 9 (ppb) | 11,100 | - |
| | 1-hour | 4000 | 10000 | - | 35 (ppb) | 43,170 | 30,000 |
| Ozone | 8-hour | 100 | 100 | 120 | 0.075 (ppm) | 159 | 100 |
| | 1-hour | 180 | 160 | - | - | - | - |
| All the values are in $\mu g/m^3$, except for those with units listed in brackets | | | | | | | |
| ** Numbers converted to $\mu g/m^3$ for comparison | | | | | | | |

12 **Table 2: An inventory of emissions and dispersion modeling studies in India**

13

| City/Region | Study year | Emissions | | | | | | | Dispersion | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PM | SO$_2$ | NO$_x$ | CO | VOC | BC/OC | GHGs | | |
| India | 1985-2005 | * | * | * | * | | | * | | **Garg et al (2006)** |
| Delhi | 1987-88 | * | * | * | | | | | * | **Singh et al (1990)** |
| Delhi | 1990-2000 | * | * | * | | | | * | * | **Mohan et al (2007)** |
| Delhi | 1990-2000 | * | * | * | * | * | | * | | **Gurjar et al (2004)** |
| Delhi, Calcutta | 1990-2015 | * | | * | | * | * | | | **Sharma et al (2002)** |
| Delhi | 1990 | * | * | * | * | * | | * | | **Bose and Anandalingam (1996)** |
| India | 1990, 1995 | | * | * | | | | | | **Garg et al (2001)** |
| Mumbai | 1992-93 | * | * | * | | | | | * | **Shah and Nagpal (1997)** |
| Jamshedpur | 1993 | | * | * | | | | | * | **Bhanarkar et al (2005)** |
| India | 1996-97 | * | * | | | | | | | **Reddy and Venkataraman (2002)** |
| India | 2000-2008 | * | * | * | * | * | * | * | | **Kurokawa et al (2013)** |
| Pune | 2003 | * | * | * | * | * | | | | **Barth et al (2007)** |
| Delhi, Mumbai, Chennai, Kolkata | 2003-04 | | | | | * | | | | **Srivastava and Majumdar (2010)** |
| India | 2003-04 | * | * | * | * | * | | * | | **Ramachandra and Shwetmala (2009)** |
| Nagpur | 2004 | | * | | | | | * | | **Majumdar and Gajghate (2011)** |
| Delhi | 2004 | * | | | | | | | | **Mohan et al (2011)** |
| Kanpur | 2004 | | * | | | | * | | | **Mehta et al (2009)** |
| Pune | 2005 | * | | | | | | | * | **Kesarkar et al (2007)** |
| Kanpur | 2006 | * | | | | | | | * | **Behera et al (2011)** |
| Hyderabad | 2006-07 | * | * | * | | | | | * | **IES (2008)** |
| Delhi | 2010 | * | | | | | | | | **Sahu et al (2011)** |
| Delhi | 2010 | * | * | * | * | * | | | * | **Guttikunda and Calori (2013)** |
| Pune, Chennai, Ahmedabad, Indore, Surat, Rajkot | 2010 | * | * | * | * | * | | | * | **Guttikunda and Jawahar (2012)** |

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When developing emissions inventories, emission factor is a very important input, in addition to data on consumption patterns and spatial information of sources. An emission factor can be defined as the mass of pollutant emitted up on combustion of various fuels in various sectors, under varying technical and operational conditions. It is assumed that a series of tests are conducted in the cities for as many sectors as possible and a database of emission factors is available for use. However, this is also a very expensive exercise and a very limited number of studies are conducted in India to ascertain these values. **CPCB (2010)** provides one such database for transport, industrial, domestic, and electricity generation, based on the tests conducted during the project period (2006-08). Other useful regional and global databases include **DIESEL (2008)**, **GAINS (2012)**, **SEI (2012)**, and **EEA (2013)**.

The best available regional and global emissions inventories commonly utilized for the bottom-up source modeling are REAS (Regional Emission inventory in ASia); GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies); EDGAR (Emission Database for Global Atmospheric Research) and GEIA (Global Emissions InitiAtive).

The atmospheric dispersion models utilize physics from the meteorology and chemistry from the emissions inventories to predict concentrations of various air pollutants. Using such models, the contributions of different sources to PM, $SO_2$, $NO_x$, CO, and ozone pollution can be estimated. A wide range of dispersion models has been published in scientific papers and even a larger number of unpublished models and special model versions exist depending on end-use such as regulatory purposes, policy support, public information, and scientific research. A subjective assessment of the level of requirements, ease of operations, and possible detail of results for various model types is presented in **Table 3**. Most of these models have established forums where users can connect with others and discuss operational and data analysis queries.

**Table 3: What to expect from different types of atmospheric dispersion models?**

|  | Box | Gaussian/Plume | Eulerian |
|---|---|---|---|
| Example |  | ISC3 ATMoS AERMOD | WRF-Chem CMAQ CAMx |
| Model formulation and complexity | * | ** | **** |
| Data requirements | * | ** | **** |
| Advection of pollutants | - | ** | **** |
| Pollution chemistry | *** | * | **** |
| Ease of operations | **** | ** | * |
| Computational requirements | * | ** | **** |
| Computational times | * | ** | **** |
| Results – level of detail | * | ** | **** |
| Source apportionment | **** | **** | ** |
| * = input requirements/quality of results is less **** = input requirements/quality of results is the highest | | | |

47 **Figure 1: Estimated on-road vehicle exhaust PM$_{10}$ emissions (Units: tons/km$^2$) in 2010**
48 **(Guttikunda and Jawahar, 2012)**

49
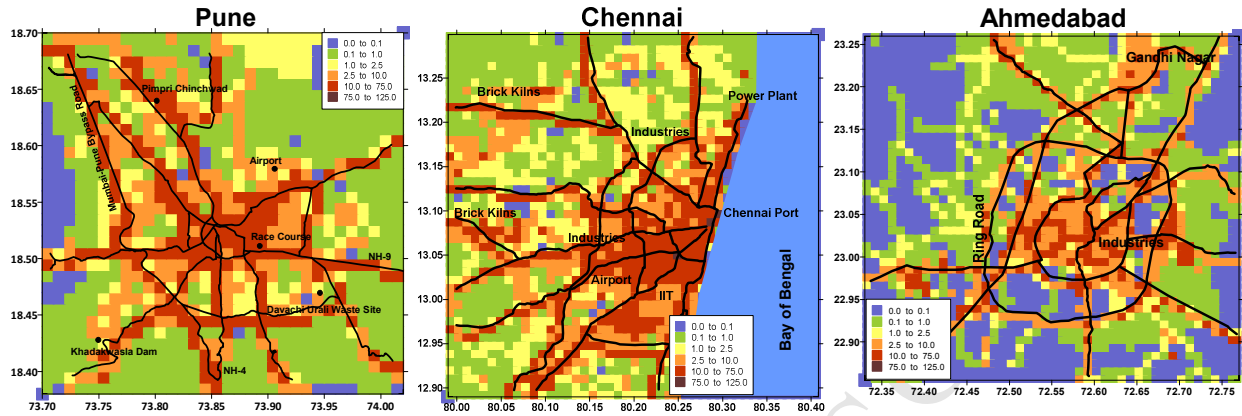


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51 **Figure 2: Modeled PM$_{10}$ concentrations (Units: μg/m$^3$) in 2010**
52 **(Guttikunda and Jawahar, 2012)**

53
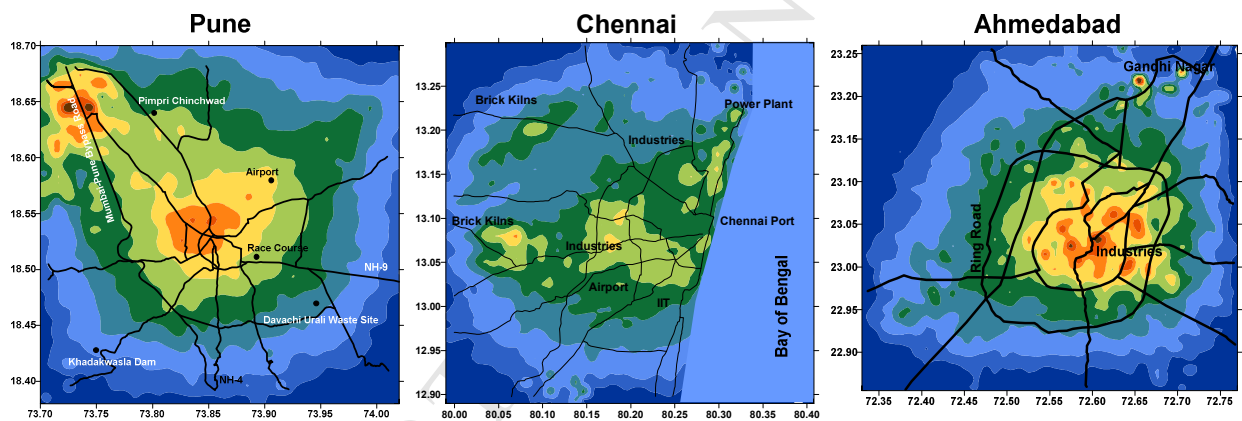


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56 **EMISSION INVENTORIES and DISPERSION MODELS**
57 Website last accessed on April 25<sup>th</sup>, 2014
58
59 **REAS**
60 @ http://www.jamstec.go.jp/frsgc/research/d4/emission.htm
61
62 **GAINS**
63 @ http://gains.iiasa.ac.at/models/
64
65 **EDGAR**
66 @ http://edgar.jrc.ec.europa.eu/
67
68 **GEIA**
69 @ http://www.geiacenter.org/
70
71 **ISC3**
72 @ http://www.epa.gov/ttn/scram/dispersion_alt.htm#isc3
73
74 **AERMOD**
75 @ http://www.epa.gov/ttn/scram/dispersion_prefrec.htm#aermod
76
77 **ATMoS**
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79
80 **WRF-Chem**
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82
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