Characterizing Patna's Ambient Air Quality & Assessing Opportunities for Policy Intervention

July 2014

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SHAKTI SUSTAINABLE ENERGY FOUNDATION

New Delhi, India

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&
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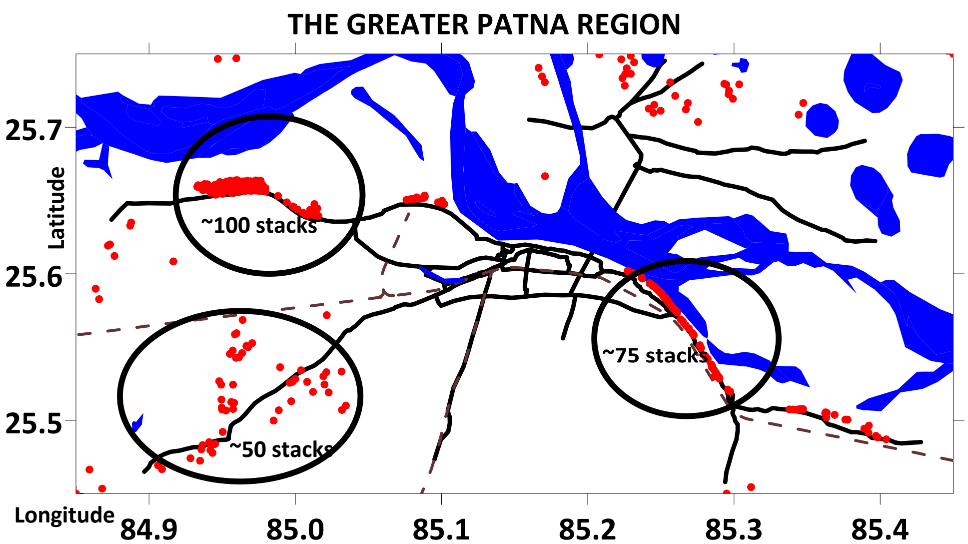

The black lines indicate the major roads in the city and the major highways passing through the city. The red dots are the known brick kiln stacks, mapped from the Google Earth open source files for 2013. The shaded blue area is the river Ganges

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Acronyms and Abbreviations

AQ	Air Quality
ATMoS	Atmospheric Transport Modeling System
BAU	Business As Usual
BRT	Bus Rapid Transport
BSPCB	Bihar State Pollution Control Board
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
DG sets	Diesel Generator Sets
EF	Emission Factors
FCKs	Fixed Chimney Kilns
FE	Fuel Efficiency
GDP	Gross Domestic Product
GIS	Global Information Systems
HDV	Heavy Duty Vehicles
INR	Indian Rupees
JNNURM	Jawaharlal Nehru National Urban Renewable Mission
Km	Kilometer
LDV	Light Duty Vehicles
LPG	Liquefied Petroleum Gas
MC	2-wheeler Motor Cycles
MoRTH	Ministry of Road Transport and Highways
MW	Megawatt
NCEP	National Centers for Environmental Prediction
NMVOC	Non-methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NTPC	National Thermal Power Corporation
PJ	Peta Joules
PM	Particulate Matter
PM_{10}	Particulate Matter (with aerodynamic diameter less than 10 μm)
$PM_{2.5}$	Particulate Matter (with aerodynamic diameter less than 2.5 μm)
SIAM	Society of Indian Automobile Manufacturers
SO_2	Sulfur Dioxide
SSEF	Shakti Sustainable Energy Foundation
USD	United States Dollar
USEPA	United States Environmental Protection Authority
VKT	Vehicle Kilometers Travelled
VOC	Volatile Organic Compounds
VSBK	Vertical Shaft Brick Kilns
WHO	World Health Organization
$\mu g/m^3$	Micrograms Per Cubic Meter
µm	Micron-meter

ACKNOWLEDGEMENTS

The "Characterizing Patna's Ambient Air Quality & Assessing Opportunities for Policy Intervention" project was conducted to assist the Bihar State Pollution Control Board (BSPCB) in addressing the air pollution issues in Patna, with the support of Shakti Sustainable Energy Foundation (SSEF, New Delhi, India).

Special thanks are due to Mr. Rakesh Kumar, the Member Secretary of BSPCB, for supporting the analysis and providing the logistical help in obtaining data from other government departments in the state.

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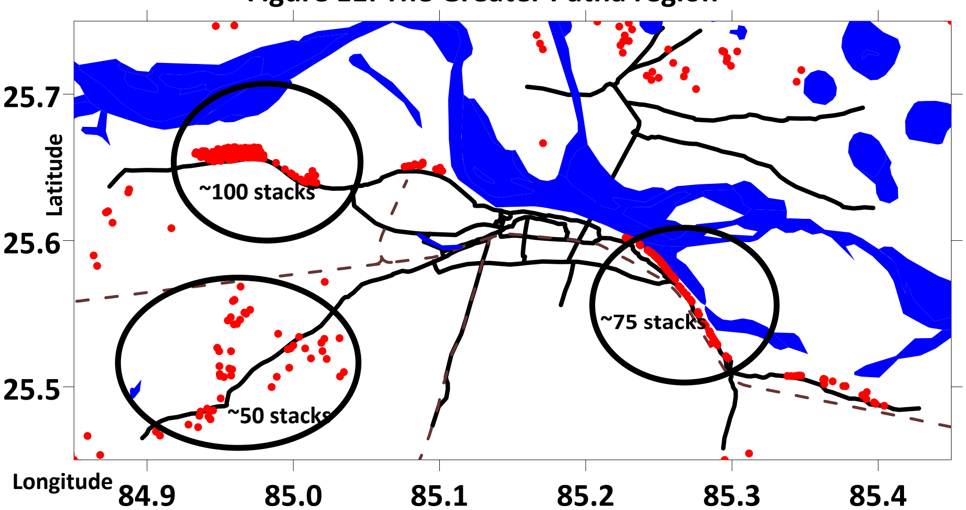
We would like to acknowledge the inputs from Mr. Sameer Maithel (Green Knowledge Solutions, New Delhi, India), whose expertise (and his staff) on the clay and alternative brick manufacturing technologies, shaped the brick kiln scenario for emissions control.

We would like to highlight the fruitful participation of all senior staff from BSPCB and the other public sector officials, present at the project inception meeting in Patna, which helped shaping the background notes on the emissions and pollution characteristics of the city.

EXECUTIVE SUMMARY

As the capital of the state of Bihar, Patna is the largest city in the state with 2.1 million inhabitants. The municipality of Patna (Patna Nagar Nigam) consists of 72 wards and administers the city. According to the 2011 Census of India, 32% of the households own a 2-wheeler motorcycle, 10% own a 4-wheeler car or jeep, and 29% of the households still use a non-gas stove for cooking and heating purposes in Patna.

Figure E1: The Greater Patna region



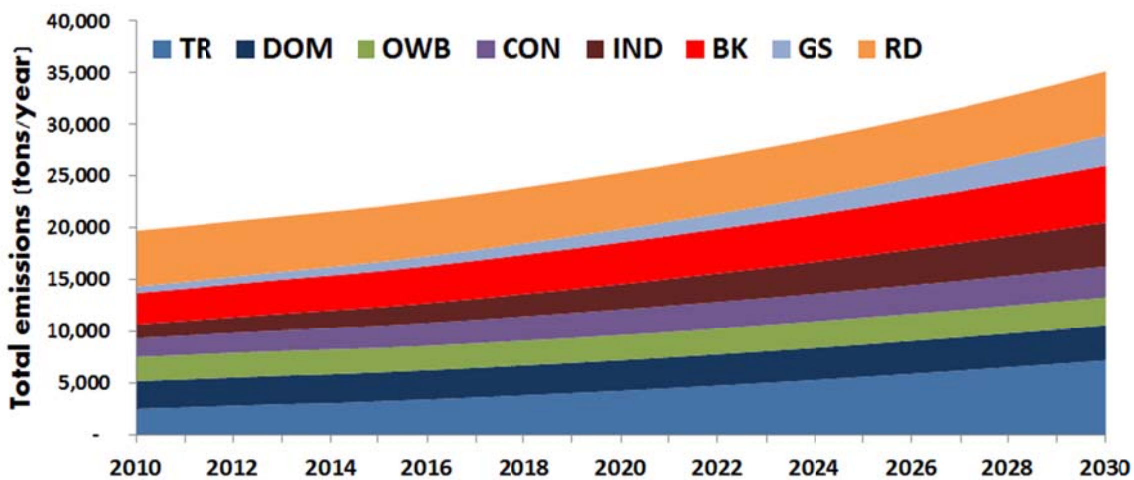
The black lines indicate the major roads in the city and the major highways passing through the city. The red dots are the known brick kiln stacks, mapped from the Google Earth open source files for 2013. The shaded blue area is the river Ganges

The Greater Patna region has more than 30,600 operational industrial units. The industrial types range from metal processing to textiles, paper, agricultural processing, and pharmaceuticals, to paint manufacturing. The sand and brick earth industry are the most lucrative in the region, which is also supported by the growing construction industry. In 2010-11, the official production of sand was 3,153,600 tons and brick earth 150,000 tons. The Bihar State Power Holding Company is the main supplier of electricity, with the demand for electricity supplemented by diesel generator sets. A 3,300 MW coal-fired power plant, commissioned in two stages with 1,980 MW in Barh I and 1,320 MW in Barh II, is under construction. This facility has been named as a 'mega power' project for Bihar, and is owned by Indian energy company National Thermal Power Corporation. This power plant is located approximately 140 km east of Patna and is expected to fully support the electricity demand from residential and industrial sectors in the city by 2015-16.

Air pollution from these known sources, such as road transport, aviation, industries (including brick kilns), diesel generator sets, domestic cooking and heating, open waste burning, and dust (including resuspension on roads and construction activities) is increasing in the city. According to the World Health Organization (2014), air quality in the city of Patna is among the Top 100 cities with the worst PM_{10} pollution globally. The "Characterizing Patna's Ambient Air Quality & Assessing Opportunities for Policy Intervention" project was conducted to assist the Bihar State Pollution Control Board, in addressing the air pollution issues in Patna, with the support of Shakti Sustainable Energy Foundation (New Delhi, India).

The emissions inventory for the Greater Patna region was developed for total PM in two size fractions (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO_2). All the databases, calculations, and interfaces are available as spreadsheets for easy access and model transparency. To assess air quality, a 60km x 30km area was selected, which includes most of the industrial estates and brick kiln clusters in and around Patna. This domain is further segregated into 1km grids, to study the spatial variations in the emission and pollution loads. The total emissions are further projected to 2030 for emission reduction scenario analysis.

Figure E2: Total PM_{10} emissions for the Greater Patna region 2010-2030 business as usual



Notes: TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

For 2012, base year for emissions and dispersion calculations, the PM_{10} concentrations averaged 140 $\mu g/m^3$ over the urban Patna region (national ambient standard is 60 $\mu g/m^3$). The transport sector and the on-road resuspension are the primary contributors. This is due to (a) growing number of vehicles on the road and (b) growing congestion rates, compounding the total emissions and exposure rates. While the clusters of the brick kilns were more than 10km away from the main city center, contributions of up to 11% are observed in the city center. With the majority of the wind fields originating from the southeast, we believe that the contribution of the southeast cluster is the highest to the urban parts. Among the diffused sources, domestic cooking and heating, open waste burning, construction activities, and diesel generator sets, dominate the reminder of the sources

The PM pollution in the greater Patna region is often above the national standards and the WHO guidelines; which is estimated to result in 2,600 premature deaths, 200,000 asthma attacks, and 1,100 cardiac admissions in 2012 and could reach 4,900 premature deaths, 507,000 asthma attacks, and 2,850 cardiac admissions in 2030, if no control measures are introduced and enforced. We benchmarked the emission sources and following emission reduction strategies were considered (1) Emission control options for the brick kiln manufacturing – technology changes, landuse changes (relocation) and operational changes (raw material) (2) Introduction of cleaner fuel for the in-use vehicle fleet, which currently has access to only Bharat-3 type fuel (3) Improvements in the public- and para- transit systems and introduction of alternative fuel (CNG) for these modes (4) Targeting the diesel generator sets, with thermal power plant in Barh coming online to support the electricity demand in the city (5) Controlling dust resuspension on the roads and (6) Combination all the above five scenarios.

Table E1: Evaluation of emission reductions and health benefits under various scenarios

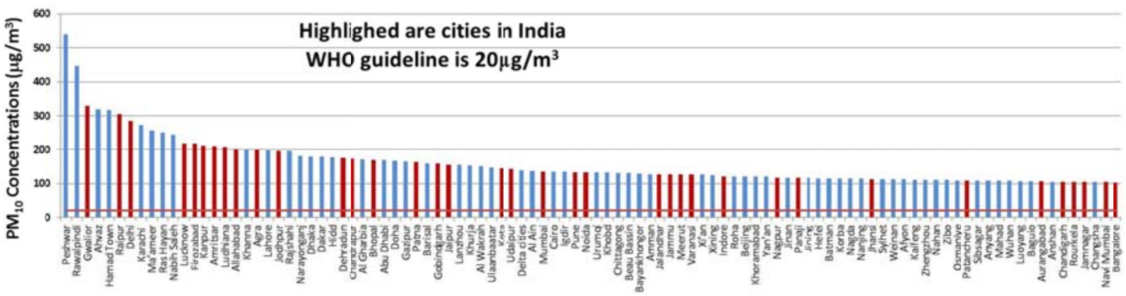
	PM_{10} concentrations in ($\mu g/m^3$)			**Premature mortality**		
	2012	**2020**	**2030**	**2012**	**2020**	**2030**
Business as usual	124.6	152.6	217.1	2,600	3,450	4,900
Reduction Scenarios	**Scenario average (% reduction from BAU)**			**Premature mortality reduced**		
Brick Kilns		139.0 (8.9%)	197.6 (9.0%)		360	440
Fuel Standards		132.2 (13.4%)	175.7 (19.1%)		420	700
Public & Para Transit		142.0 (7.0%)	202.8 (6.6%)		280	360
DG sets		146.0 (4.3%)	201.9 (6.6%)		180	300
Road Dust		138.5 (9.3%)	190.7 (12.2%)		280	400
All Combined		115.2 (24.5%)	139.2 (35.9%)		880 (25.5%)	1,540 (31.5%)

Overall, the brick kilns and the road transport are the major contributors to the air pollution problems and the interventions discussed here can lead up to 35% reduction in the PM pollution and likely more reduction in the health impacts. However, it is important to note that these are speculative scenarios and often overlapping when they are implemented, and these estimated benefits can be verified only after the interventions are studied for their technical and financial feasibility to the fullest extent. Other sectors and interventions, which are equally important are (a) shift from the conventional fuels like coal and biomass in the domestic sector to a cleaner fuel like liquefied petroleum gas (LPG) and electricity (b) banning garbage burning in the residential and industrial sectors and improvement in the municipal waste management systems in the city and (c) an overall improvement in the efficiency of industries in the greater Patna region.

1.0 BACKGROUND

In 2014, the World Health Organization (WHO), listed the top 100 cities with the worst air quality globally (based on the ambient monitoring data). Patna is one of the 37 Indian cities in the top 100[1]. In **Figure 1**, the horizontal line indicates the WHO guideline for particulate matter (PM) with diameter ≤10µm (PM_{10}) at 20µg/m^3. The Indian annual ambient average standard for PM_{10} is 60µg/m^3.

Figure 1: Ambient PM_{10} concentrations in the top 100 cities with the worst air quality (WHO)



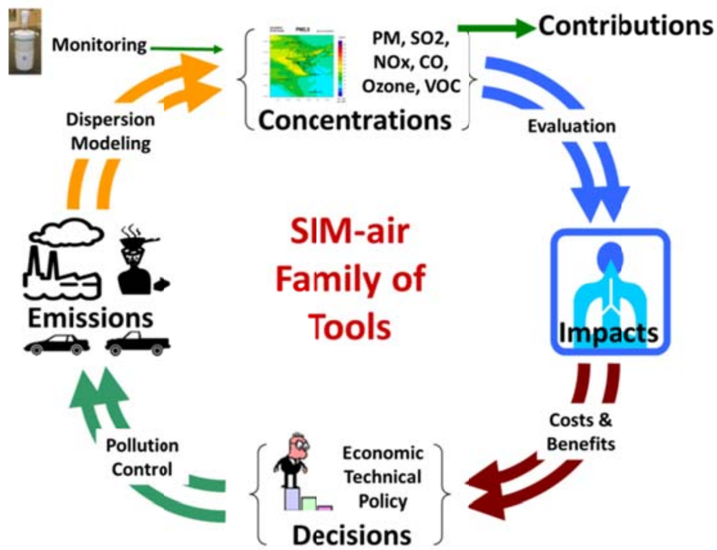
This research study was commissioned to characterize Patna's air quality, to support the Bihar State Pollution Control Board (BSPCB) in its endeavor to improve Patna's air quality. The main objectives of this research study, using the local air pollution as the primary indicator are

- To establish a baseline emissions inventory for the criteria pollutants – particulate matter (PM), sulfur dioxide (SO_2), and nitrogen oxides (NO_x), and the greenhouse gas (CO_2) - from all the known emission sources in the city
- To analyze ambient PM_{10} pollution and associated health impacts; based on dispersion modeling for the Greater Patna region
- To analyze select interventions for health benefits of reducing PM pollution in the city. These interventions are designed for the primary sources in the city, such as transport, industries (including brick kilns), power consumption (diesel generator sets), and road dust
- To identify information gaps while building the emission inventories and conducting the scenario analysis.

[1] Database of outdoor air pollution in the cities, by the World Health Organization @ http://www.who.int/phe/health_topics/outdoorair/databases/en

The methodology employed to assess the total emissions in and around the Greater Patna region is similar to the methodology employed by the Central Pollution Control Board (CPCB) for their comprehensive six city particulate pollution source apportionment study[2]. The emissions inventory, dispersion modeling, health impact assessment, and analysis of policy interventions follow the schematics presented in **Figure 2**. Since 2012, the SIM-air tools have been applied for similar air quality assessments in 8 other cities in India[3].

Figure 2: Schematics of the air quality management tools



The air pollution analysis for the Greater Patna region was conducted with the guidance of BSPCB. The sources of information, methodologies applied, and study results are detailed in the following chapters. **Chapter 2** presents an overview of the city, along with a summary of the monitoring data from the stations operated by BSPCB, as part of the national ambient monitoring program[4] and the local meteorology, which plays a vital role in the dispersion of emissions in the region. **Chapter 3** presents the emissions inventory for the base year 2012 and projections up to 2030 for all the criteria pollutants – PM, SO_2, NO_x, carbon monoxide (CO), volatile organic compounds (VOCs) and carbon dioxide (CO_2). The inventory includes emissions from road transport, aviation, industries (including brick kilns), diesel generator sets, domestic cooking and heating, and dust (including resuspension on roads and construction activities). **Chapter 4** presents the PM pollution concentrations, based on dispersion model simulations, under the business as usual scenario for the base year 2012 and for two future years 2020 and 2030, followed by the health impacts assessments, under the business as usual scenario, in **Chapter 5**. The health impacts are assessed as premature mortality, asthma attacks, and cardiac

[2] Particulate pollution source apportionment study for Delhi, Pune, Chennai, Kanpur, Bengaluru, and Mumbai, by the Central Pollution Control Board @ http://cpcb.nic.in/Source_Apportionment_Studies.php
[3] For Pune, Chennai, Indore, Ahmedabad, Surat and Rajkot with support from SSEF; For Hyderabad and Delhi from external funding and academic collaborations. Reports for each of these cities are available @ http://www.urbanemissions.info
[4] National ambient monitoring program (NAMP) @ http://cpcb.nic.in/RealTimeAirQualityData.php

hospital admission linked to air pollution exposure. **Chapter 6** presents scenario analysis for 2020 and 2030, along with the description of the scenarios and possible benefits of these interventions up on implementation. We conclude with summary and recommendations for the future research works and feasibility studies in **Chapter 7**.

2.0 PATNA: CITY AT A GLANCE

As the capital of the state of Bihar, Patna is the largest city in the state with 2.1 million inhabitants. The municipality of Patna (Patna Nagar Nigam) consisting of 72 wards, administers the city. The state of Bihar is part of the rich Indo-Gangetic plain, largely supported by agricultural activities and is among the states with the highest population density.

Table 1: General characteristics of Patna, data based on 2011 Census	
Built-up area in the city (km^2)	86
per capita GDP (state) (INR)	38,000
Urban population	2,100,000
Population density (per hectare)	238
% households with a two wheeler	32%
% households with a four wheeler	10%
% households with a non-gas cookstove	29%
CEPI rating (rank)	-
Registered industrial units	12,230
Total industrial units	30,600
Registered medium-large industrial units	21
No. of industrial estates	4
Registered total vehicles (March 31st, 2011)	660,000
National ambient monitoring stations	2
PM_{10} in 2009-10 ($\mu g/m^3$)	138.8 ± 84.4
SO_2 in 2009-10 ($\mu g/m^3$)	5.3 ± 2.8
NO_2 in 2009-10 ($\mu g/m^3$)	32.9 ± 18.8

The ambient $PM_{2.5}$ concentrations (**Figure 3a**) in the Indo-Gangetic plain are high and this overlaps with the highest population density (**Figure 3b**) in the country. This region also has the largest number of brick kilns with old and inefficient combustion technology, using a mix of biomass and coal for combustion. The states of Bihar, West Bengal, Jharkhand, Orissa, and Chhattisgarh harbor the largest coal mines in the country, and a cluster of power plants around the mines[5]. 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. The cities in the

[5] An assessment of the air pollution impacts from the coal-fired power plants in India is available @ http://www.urbanemissions.info/india-power-plants

north are also landlocked, which are also affected by the prevalent meteorological conditions. The mixing heights during the winter months are very low compared to those observed in the summer months, hindering the dispersion of emissions[6].

Figure 3: (a) Ambient $PM_{2.5}$ concentrations derived from the satellite observations [7] (b) Gridded population in India for 2011 [8]

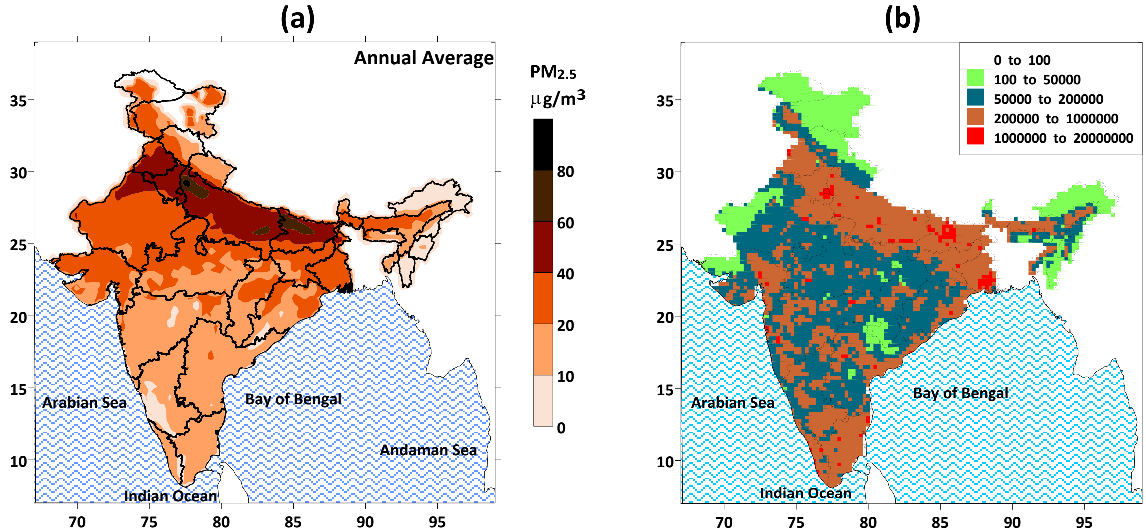
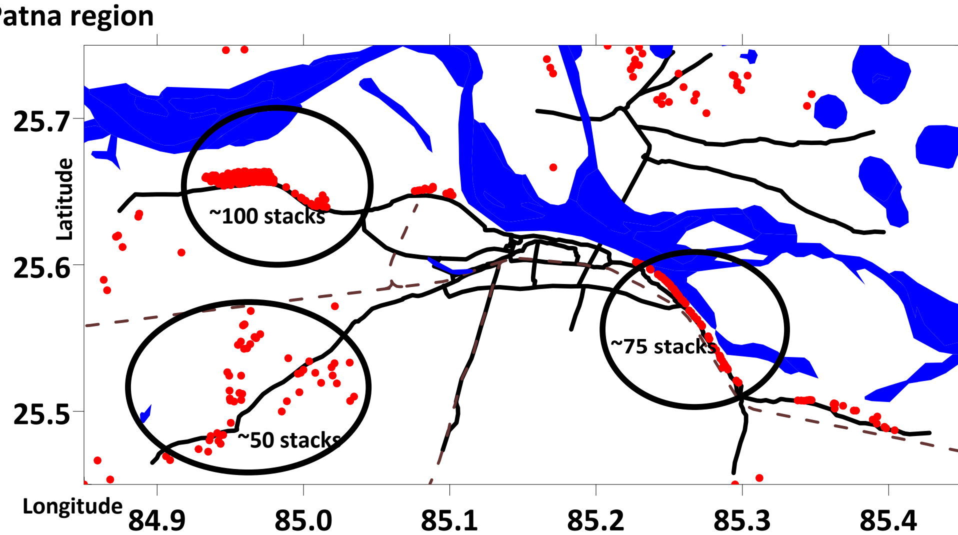


Figure 4: The study domain, the road network, and the brick kiln clusters in and around the Greater Patna region



The black lines indicate the major roads in the city and the major highways passing through the city. The red dots are the known brick kiln stacks, mapped from the Google Earth open source files for 2013. The shaded blue area is the river Ganges

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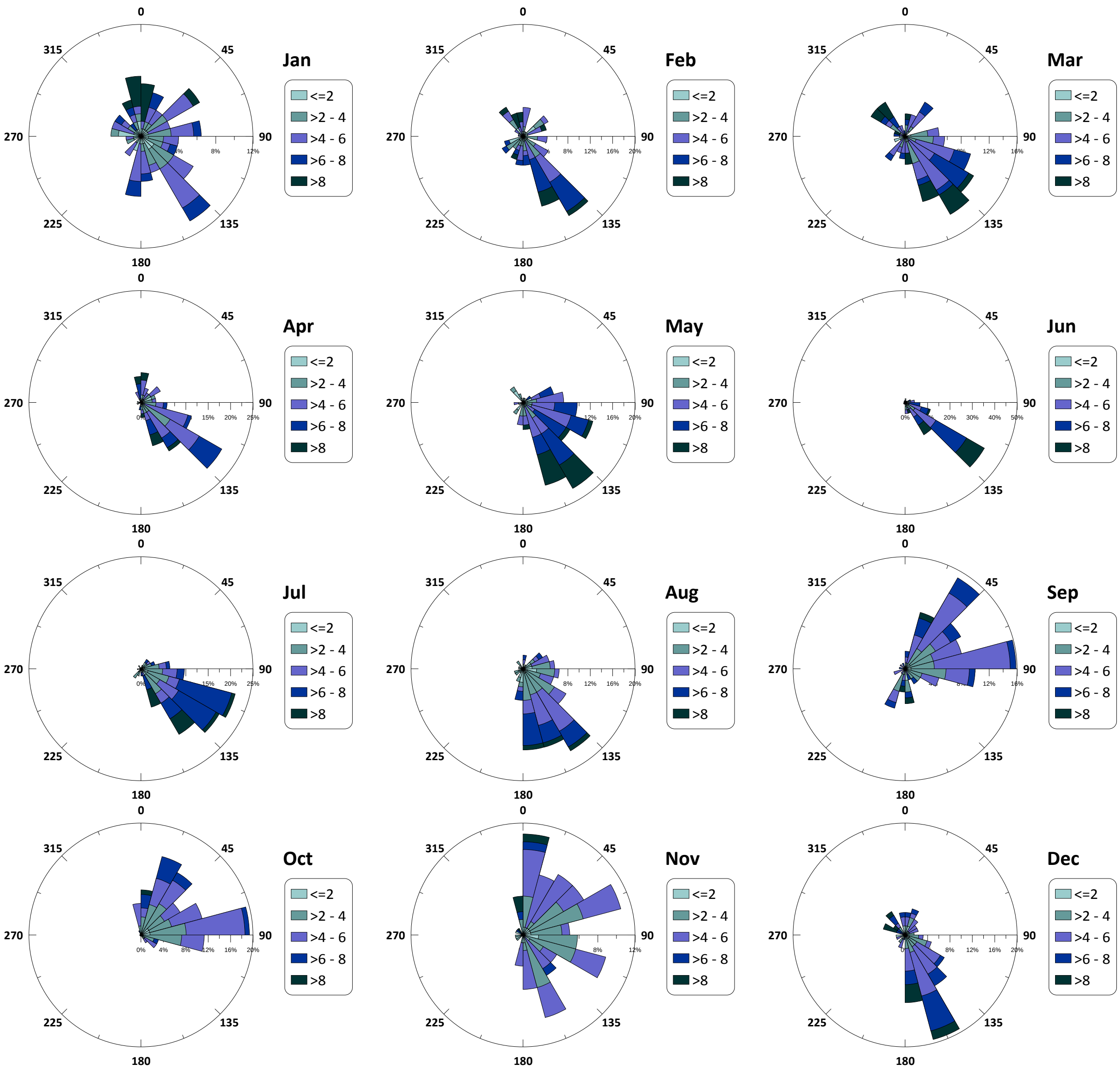
[6] Guttikunda and Gurjar (2012). "Role of meteorology in seasonality of air pollution in megacity Delhi, India" @ http://rd.springer.com/article/10.1007/s10661-011-2182-8

[7] Methodology on the satellite data retrievals and uncertainties is explained by van Donkelaar et al (2010). The report and data is available @ http://fizz.phys.dal.ca/~atmos/martin/?page_id=140

[8] Grid resolution is 0.25° and gridded data is obtained from GRUMP @ http://sedac.ciesin.columbia.edu and adjusted to the 2011 state totals from Census @ http://censusindia.gov.in

To assess air quality, we selected 60km x 30km domain (**Figure 4**), which includes most of the industrial estates and brick kiln clusters in and around Patna. This domain is further segregated into 1km grids, to study the spatial variations in the emission and pollution loads. There is one coal-fired power plant, located farther from the city, which is not included in this study domain.

Figure 5: Typical wind speeds and wind directions prevalent over the Patna city[9]



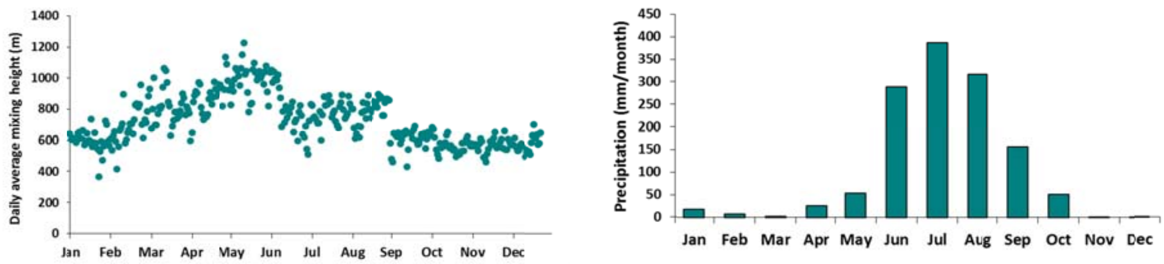
Patna city lies on the southern banks of the river Ganges, and uniqueness is that it also sits on the banks of the smaller rivers of Sone, Gandak and Punpun. This is particularly important in shaping the economy and culture of the city, via rich aluvial soil deposits contributing to the dominant agricultural sector. It continues to be an important center for growth in Bihar and

[9] All the meteorological fields are obtained from National Centers for Environmental Prediction (NCEP), which archives data from 1948 @ http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html

India - with the rise of the educational sector and agriculture processing. In 2010, the per capita income of Patna was approximately INR 38,000 – the 5th fastest growing city in India.

The climate in Patna is sub-tropical in nature, with extremely hot summers from late March to early June, the monsoon season from late June to late September, and a mild winter from November to February. A summary of the monthly winds (mostly southeast), monthly total precipitation, and daily average mixing layer heights are presented in **Figure 5** and **Figure 6**.

Figure 6: Typical mixing layer heights and precipitation fields



Patna is a major city on the eastern railway network of India and is served by 6 stations within the city limits. With the National Highways 19, 30, 31, and 83 running through the city, this forms one the busiest junctions of the Indo-Gangetic plan.

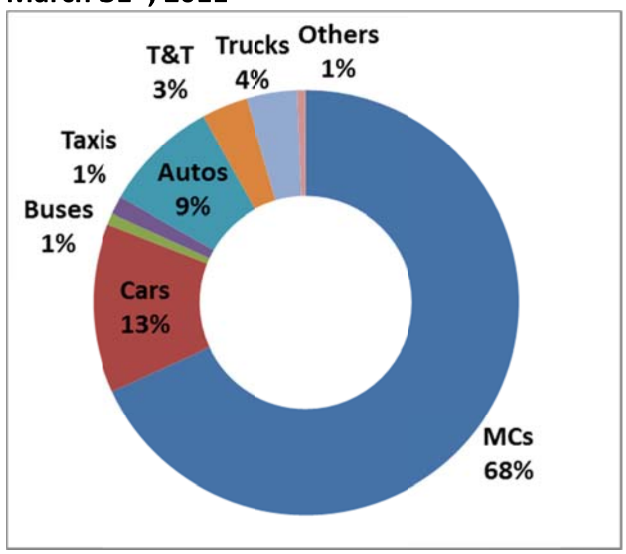
The industrial types range from metal processing to textiles, paper, agricultural processing, and pharmaceuticals, to paint manufacturing. The sand and brick earth industry are the most lucrative in the region, which is also supported by the growing construction industry. In 2010-11, the official production of sand was 3,153,600 tons and brick earth 150,000 tons. The Bihar State Power Holding Company is the main supplier of electricity to the city of Patna. Eight grids run by the company supply approximately 500MW of power to the city.

3.0 EMISSIONS INVENTORY

The emissions inventory for the Greater Patna region was developed for total PM in two size fractions (PM_{10} and $PM_{2.5}$), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOCs), and carbon dioxide (CO_2). All the databases, calculations, and interfaces are available as spreadsheets for easy access and model transparency.

A large share of increase in air pollution was attributed to the growing vehicle population in the city. According to the Ministry of Road Transport and Highways (MoRTH), the in-use vehicular population grew was 660,000 as of March 31st, 2011. Of the total registered fleet, two-wheelers (including mopeds, scooters, and motorcycles) and passenger four-wheelers are the dominant, followed by heavy duty (HDV) and light duty (LDV). Besides cars, motorcycles, and trucks, the registered fleet information includes the public, contract, school, and private sector buses and para-transit vehicles that can carry three to seven passengers per trip. Detailed break-up of the registered vehicles in the city is presented in **Figure 7**.

Figure 7: Registered vehicle fleet in Patna as of March 31st, 2011



For the transport sector, the ASIF principles[10] were utilized to calculate the exhaust emissions – using the total travel activity (A), modal shares (S) in vehicle-km traveled per day, modal energy intensity (I) representing energy use per kilometer, and an emission factor (F) defined as the mass emitted per vehicle-km travelled. The average vehicle kilometers traveled (VKT) per day are assigned at 150 km for public transport buses (operational for 8-10 hours at an average speed of 15 kmph during the day), 40 km for passenger cars and multi-utility vehicles, 80 km for taxis and light commercial vehicles, 150 km for three-wheelers and other para-transit vehicles, and 100 km for heavy duty vehicles (most of them operating on the highways and in the

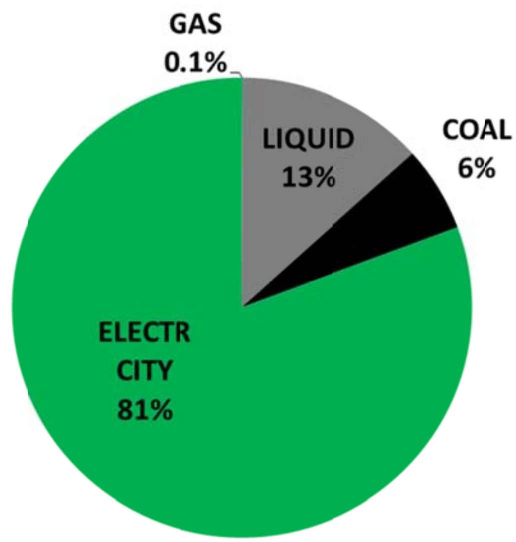
[10] Schipper L, Marie-Lilliu, C., Gorham, R. (2000) Flexing the link between transport and greenhouse gas emissions: A path for the World Bank. Vol. 3. International Energy Agency, Paris, France

industrial areas or passing through the city). The emission factors were developed for the Indian fleet[11]. A summary of the emission factors is attached in the emissions calculator. The total vehicle exhaust emissions were adjusted for the congestion levels in the city. The transport emissions inventory also includes landing and take-off emissions at the airport.

Many studies have developed empirical functions that estimate re-suspension rates. We estimated the dust re-suspension on roads using the USEPA AP-42 methodology[12], which suggests its application for average road speeds less than 55mph. The average speeds in urban Patna are less than 20kmph and ±10kmph on the sections of highways passing through the city. The total gridded road dust emissions are estimated based on the vehicle density data from MoRTH and fractions assigned for each vehicle type to two road categories (main and arterial). Silt loading was assigned to the road types ranging between 30 and 100 grams/m^2 depending the paved or unpaved conditions.

The industrial emissions inventory is based on fuel consumption information obtained from the Ministry of Statistics[13]. The industrial types ranged from metal processing to textiles, paper, agricultural processing, and pharmaceuticals, to paint manufacturing. The shares of fuels and electricity consumed, in terms of the total bills paid (INR 107 crores) by the industries in the city is presented in **Figure 8**. While most of the industries rely on the grid electricity for their energy needs, there are frequent power outages, which force them to use in-situ diesel generators.

Figure 8: Share of various energy sources utilized in the Patna district, based on the total bills for 2009-10



Besides the traditional manufacturing industries, there are kiln clusters around the metropolitan city, supporting the growing demand for traditional red and fired clay bricks for construction. The location of the brick kiln clusters is marked in **Figure 4**. More clusters were identified further south of the modeling domain, which are not included in this analysis. The brick manufacturing includes land clearing for sand and clay, combustion of fuel for baking bricks, operation of diesel engines on site, and transport of the end product to various parts of the city. Traditionally, the rectangle shaped clay bricks are sun dried and readied for firing in the kilns with a fixed chimney (FCKs), as a pile of bricks with intermittent layers of sealing mud and fuel. This fuel would vary from agricultural waste to biofuels like cow

11 The emission factor database was developed as part of the PM pollution source apportionment study by CPCB @ http://cpcb.nic.in/Source_Apportionment_Studies.php

12 Clearing House for Inventories and Emission Factors (CHIEF) by USEPA @ http://www.epa.gov/ttn/chief

13 Ministry of Statistics and Programme Implementation, the Government of India @ http://mospi.nic.in/Mospi_New/site/India_Statistics.aspx?status=1&menu_id=43

dung and wood to fossil fuels like coal and heavy fuel oil. These FCKs are known for its low cost of construction, lower energy consumption, and a production capacity of 20,000 to 40,000 per day. In this, the firing is continuous where sun dried bricks are loaded from one end and finished bricks are drawn from the other end. The fuel saving is achieved by reusing part of the energy that is otherwise lost in clamp kilns. For firing, fuel is stuffed intermittently from the top through the layers of bricks and the kiln is designed such that after combustion, the hot air on its way to the chimney passes through the yet unfired bricks.

Figure 9: Google Earth images from two major brick kiln clusters outside the Patna city

Cluster of brick kilns stacks from northwest region of **Figure 3** | Cluster of brick kiln stacks from southeast region of **Figure 3**

A major disadvantage of these kilns is associated with weather – an open cast kiln means they can be operated only in the non-monsoonal season. During the heavy monsoonal rains of June to September, all the kilns are shut down. The older FCK designs allowed for a moving chimney, which is discontinued because of higher local pollution from their low stacks[14].

The domestic sector emissions are based on fuel consumption estimates for cooking and waste burning. Using census statistics, household total energy consumed in the form of solid (coal and wood), liquid (kerosene), and gaseous (LPG) fuels was estimated at the grid level[15]. According to

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[14] A summary of the various brick manufacturing technologies, their technical characteristics, and benefits of emerging technologies is presented in "Health benefits of adapting cleaner brick manufacturing technologies in Dhaka, Bangladesh" @ http://link.springer.com/article/10.1007%2Fs11869-013-0213-z and "Emissions from South Asian Brick Production" @ http://pubs.acs.org/doi/abs/10.1021/es500186g

[15] Household energy usage in India, Database maintained by the Institute for Financial Management and Research, Chennai, India @ http://www.householdenergy.in

2011 Census, there are at least 29% of the households using non-LPG stove for cooking and heating. In the city, the dominant fuel is LPG. In slum areas, construction sites, some restaurants, and areas outside the municipal boundary, however, use of coal, biomass, and agricultural waste is common. The gridded population at 30-second spatial resolution from GRUMP (2010)[16] was interpolated to the model grid, with the high density areas utilizing mostly LPG and the low density areas utilizing a mix of fuels.

Figure 10: Diffused sources in the Patna city using coal and biomass for cooking

Garbage burning in the residential areas emit substantial amount of pollutants and toxins. This is a source with the most uncertainty in the inventory. Because of the smoke, air pollution, and odor complaints, the local authorities have banned this activity, but it continues unabated at makeshift landfills. According to the city development plan submitted to the Jawaharlal Nehru National Urban Renewable Mission (JNNURM), Patna metropolitan produces an estimated 1,200 tons of solid waste per day, which is transported to collection units, and then to a landfill facility. The facility has a capacity to handle 600 to 1000 tons of waste per day. It is assumed that at least once a week, the garbage is put to fire at an estimated 500 makeshift sites in the city. The solid waste management site is located at Ram Chak Mauja, adjacent to State Highway 78, approximately 10 km from main city[17].

There are no power plants in the immediate vicinity of the modeling domain. The nearest power plant is 60km east of the city. While most of the electricity needs are met by the coal and gas fired power plants situated to the south of the city (closer to the coal mines), a large proportion of mobile phone towers, hotels, hospitals, malls, markets, large institutions, apartment complexes, and cinemas, supplement their electricity needs with in-situ diesel

[16] GRUMP (2010) - Gridded Population of the World and Global Rural and Urban Mapping Project. Center for International Earth Science Information Network (CIESIN) of the Earth Institute, Columbia University, New York, USA @ http://sedac.ciesin.columbia.edu

[17] More information on the formulated door-to-door waste collection and transportation of the municipal waste is detailed @ http://biharurban.in. Link to the document @ http://tinyurl.com/oketm6y

generator sets. The total diesel consumption in the in-situ generator sets is estimated at 7 PJ, approximately 10-15% of the total energy consumption in the transportation sector.

In the following figures, we present total emissions for the study domain for the period of 2012 to 2030. All the emissions are projected from the base year 2012. For 2012, the emissions inventory results are summarized in **Table 2**. For reference, the estimated PM_{10} inventory for other cities in India in tons/year for the year 2010 was 38,400 in Pune, 50,200 in Chennai, 18,600 in Indore, 31,900 in Ahmedabad, 20,000 in Surat, and 14,000 in Rajkot. The cities of Pune, Chennai, and Ahmedabad are comparable with Patna in geography, demography, and industrial activity.

Table 2: Total emissions for the Greater Patna region for the base year 2012

	$PM_{2.5}$	**PM_{10}**	**SO_2**	**NO_x**	**CO**	**VOC**	**CO_2**
	tons	tons	tons	tons	tons	Tons	mil tons
Transport	2,400	2,800	600	26,350	49,650	24,650	3.3
Domestic	2,450	2,750	1,250	1,100	109,600	5,050	0.7
Open Waste Burning	1,700	2,400	150	650	9,700	850	0.1
Construction	400	1,950	50	550	650	50	0.1
Manufacturing Industries	1,050	1,500	950	1,800	20,750	1,600	0.2
Brick Kilns	2,350	3,250	1,200	2,400	40,600	4,300	0.3
Generator Sets	650	750	200	13,700	14,300	5,350	0.8
Road Dust	850	5,400					
Total	**11,850**	**20,800**	**4,400**	**46,550**	**245,250**	**41,850**	**5.5**

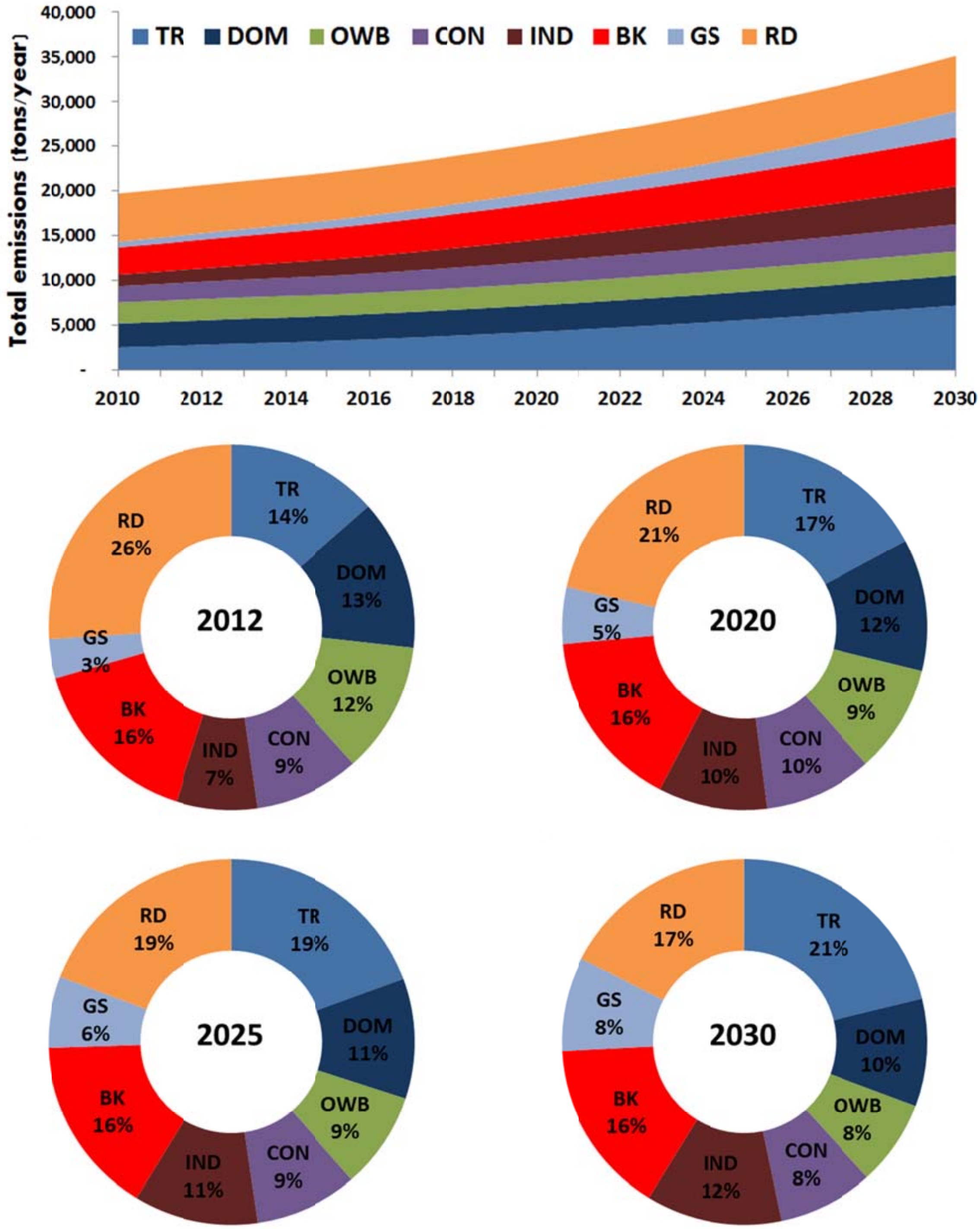
For the projections to 2030, the growth rates are assumed as the following

- The vehicle growth rate is assumed from the national road transport emissions study, based on the sales projection numbers from SIAM, New Delhi, India[18]
- The industrial growth is projected according to the gross domestic product of the state
- The domestic sector, construction activities, brick demand, diesel usage in the generator sets, and open waste burning are linked to the population growth rates according to the 2011 census

Since, there are many factors which influence the changes in a city's economic, landuse, and industrial layout, the growth rates assumed should be considered as an estimate only. We used these estimates to evaluate the likely trend in the total emissions in the city, their likely impact on the ambient PM_{10} and $PM_{2.5}$ concentrations, and health impacts through 2030. Also presented in **Figure 11-14** are the estimated changing contributions of various sectors to the total emissions in the city for PM_{10}, $PM_{2.5}$, SO_2, and CO, in 2012, 2020, 2025, and 2030. For PM emissions, the vehicle exhaust, brick manufacturing, diesel generator sets, open waste burning, road dust, and industries are the major contributors.

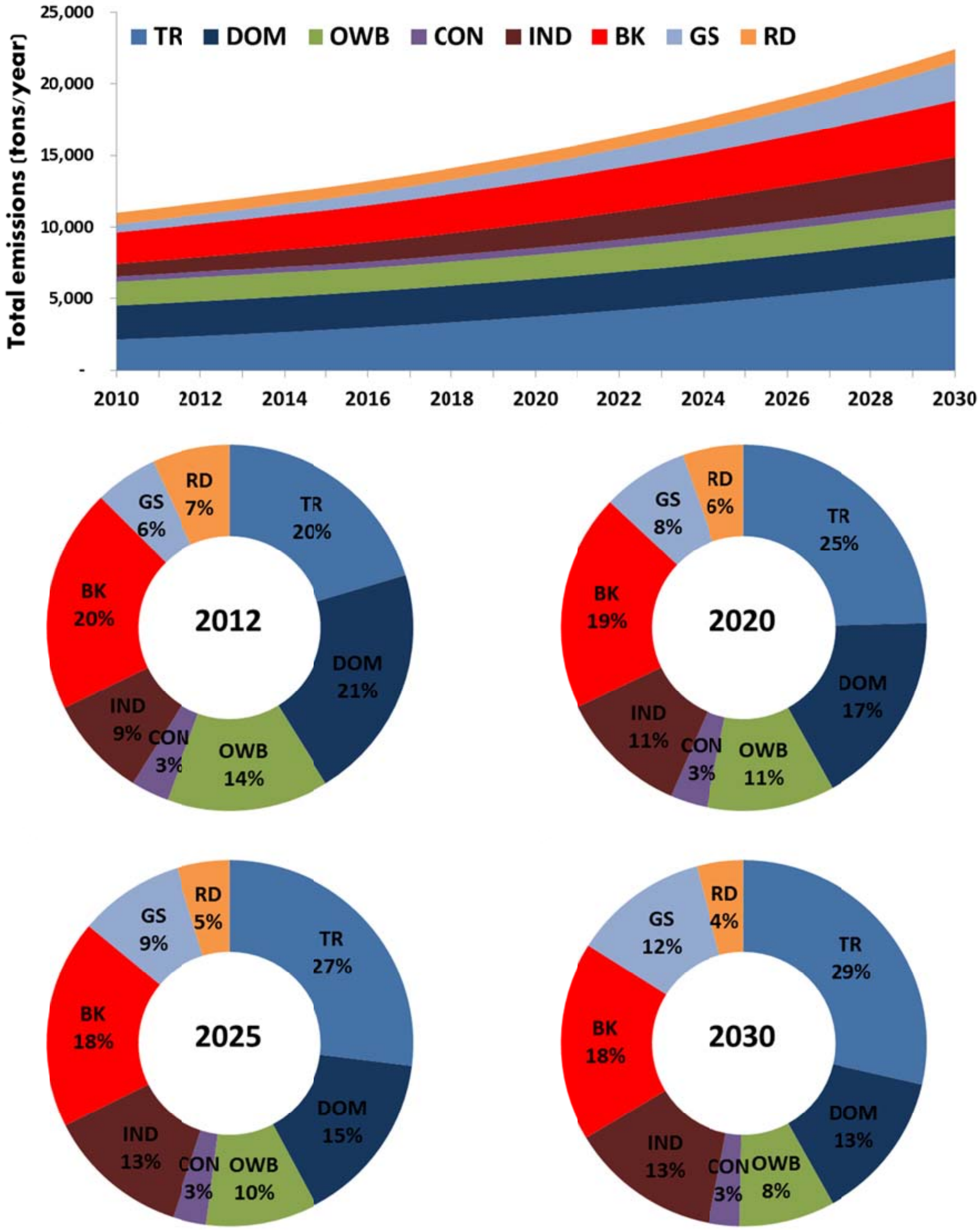
[18] The national road transport emissions study report is available @ http://www.urbanemissions.info/india-road-transport

Figure 11: PM_{10} total emissions and percentage shares for the Greater Patna region



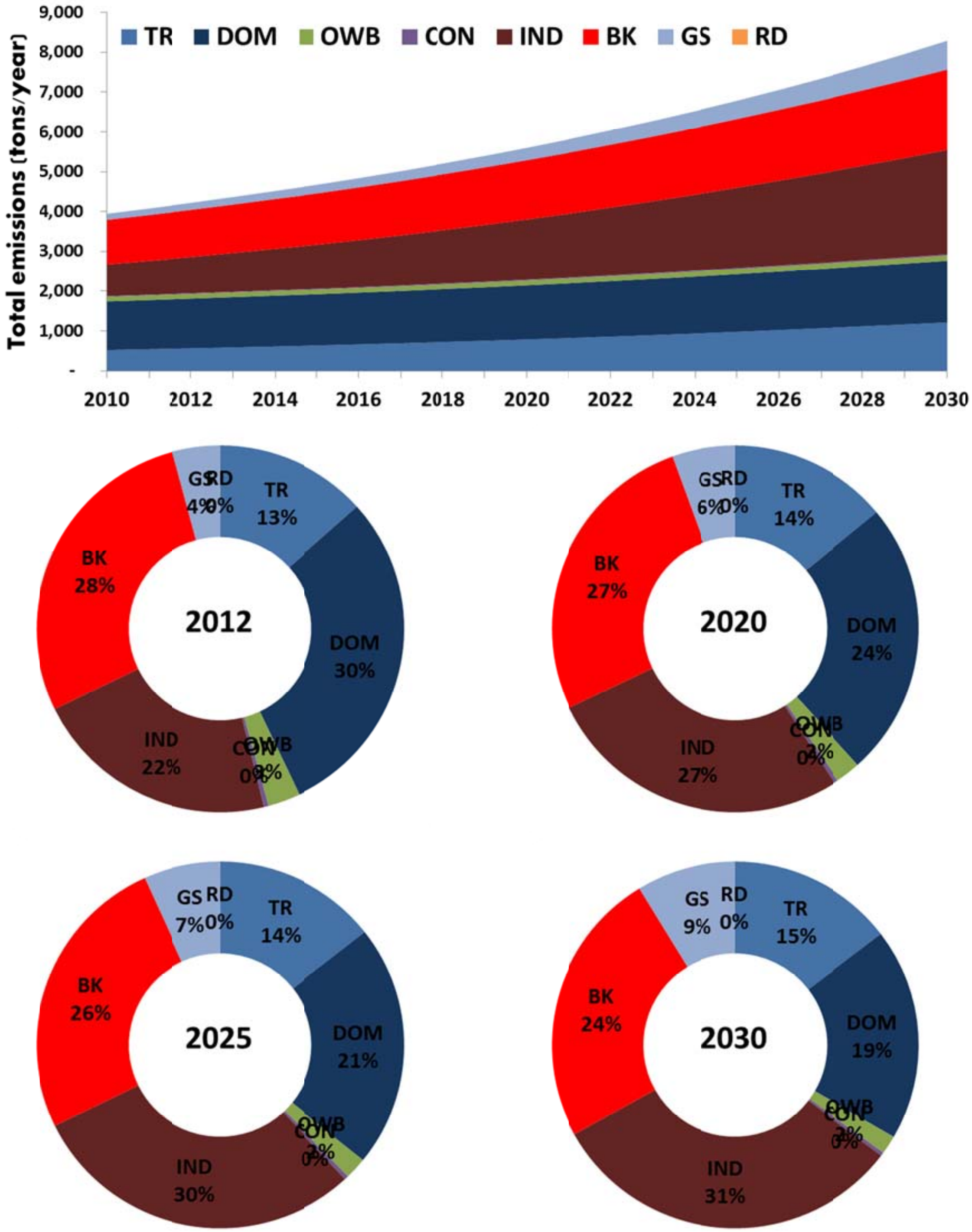
Notes: Base year for all the emission calculations is 2012. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

Figure 12: $PM_{2.5}$ total emissions and percentage shares for the Greater Patna region



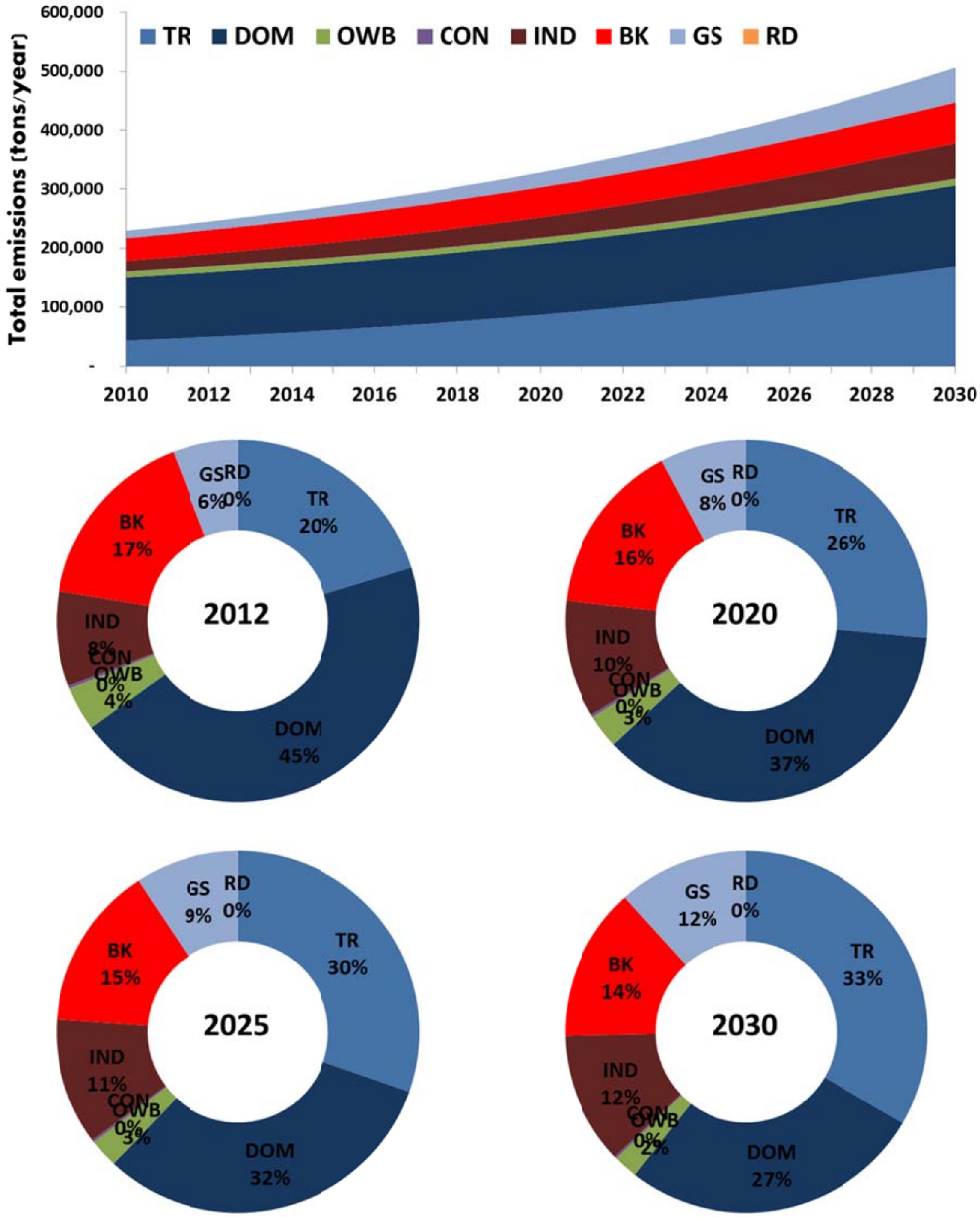
Notes: Base year for all the emission calculations is 2012. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

Figure 13: SO_2 total emissions and percentage shares for the Greater Patna region



Notes: Base year for all the emission calculations is 2012. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

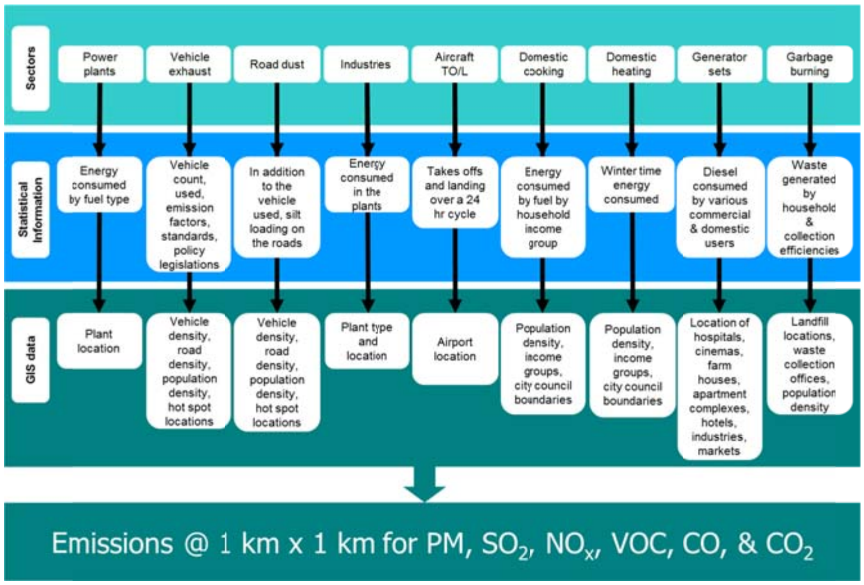
Figure 14: CO total emissions and percentage shares for the Greater Patna region



Notes: Base year for all the emission calculations is 2012. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

The emissions inventory is also maintained on a GIS platform and spatially segregated at a finer resolution of 0.01° in longitudes and latitudes (equivalent of 1km) and for further use in atmospheric modeling. We used spatial proxies to allocate the emissions for each sector to the grid, similar to the methodology utilized for six other cities in India[19]. The schematics of the gridding procedure are presented in **Figure 15**.

Figure 15: Schematics for gridding the emissions to ~1km resolution

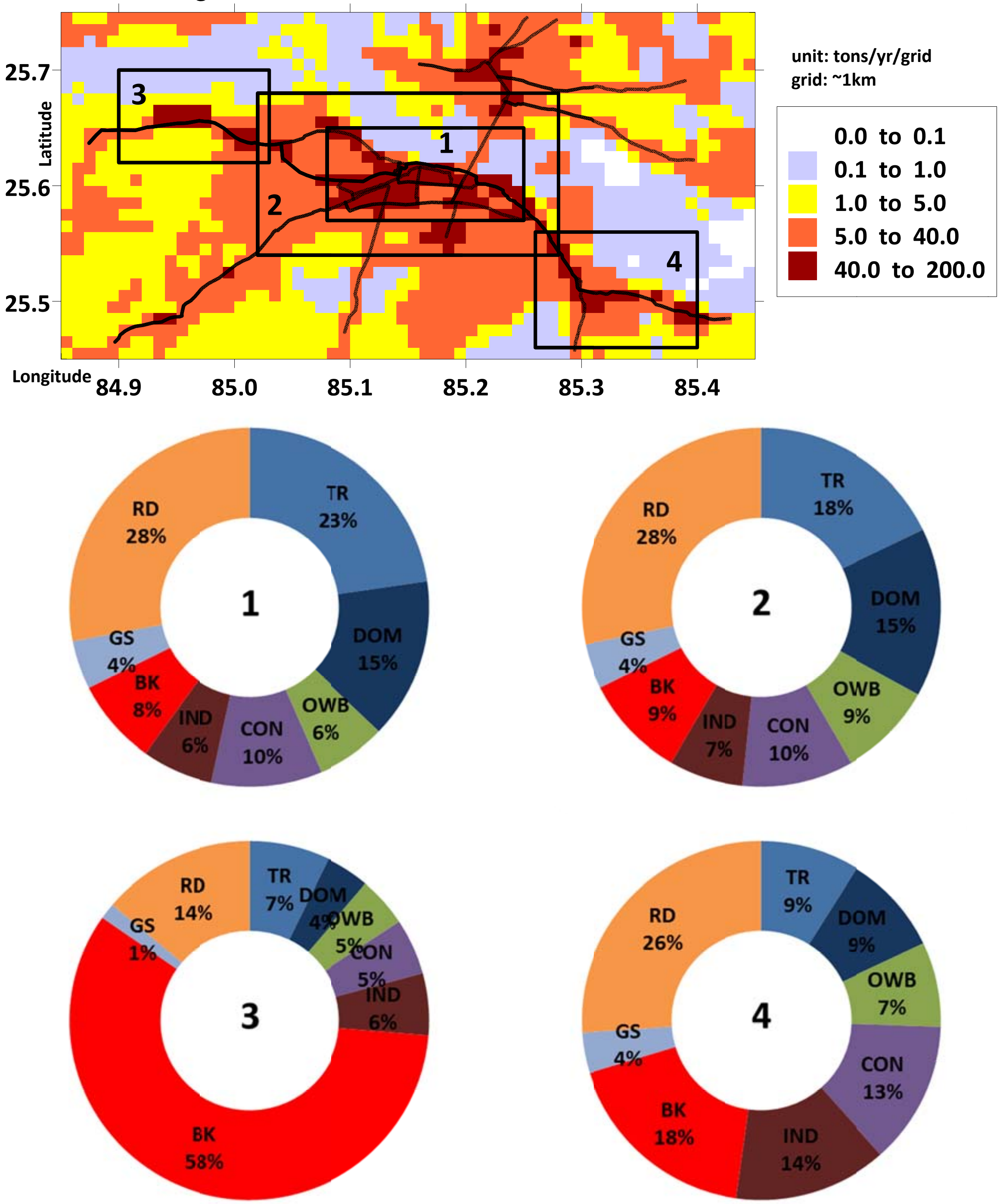


The gridded total PM_{10} emissions are presented in **Figure 16**. In case of the transport sector, we used grid based population density, road density (defined as number of km per grid), and commercial activity like industries, brick kilns, hotels, hospitals, apartment complexes, and markets to distribute emissions on feeder, arterial, and main roads. Emissions from industries were allocated to the respective industrial estates and brick kiln emissions were directly assigned to their respective clusters. The domestic sector and garbage burning emissions are distributed based on the population density. For PM_{10}, the highest density of emissions is in the city due to vehicle exhaust and around the city along the industrial estates, including brick kiln clusters. For convenience, only the gridded emissions for the PM_{10} are presented in the following **Figure 16**. The same are available for other pollutants – $PM_{2.5}$, SO_2, NO_x, CO and VOCs.

While the total emissions in **Table 2** provide the overall emission load for the city, the spatial gridding of the emissions provides information on the emission hotspots in the city, which is distinguished by specific sources. In **Figure 16**, extracts for four regions are also presented. This information is vital in apportioning the contributions of various sectors, especially sources like brick kilns, whose emissions can travel longer distances to affect ambient air quality.

[19] "Air Quality Management - Pune, Chennai, Indore, Ahmedabad, Surat, and Rajkot" - The study report is available @ http://urbanemissions.info/study-air-pollution-six-indian-cities.html

Figure 16: Gridded PM_{10} emissions and percentage shares in select regions in the Greater Patna region in 2012



Notes: The pie graphs are shares based on the emission totals for the select region. Region 1 = the urban Patna region; Region 2 = the larger Patna region; Region 3 = brick kiln (~100 stacks) cluster in the northwest; Region 4 = brick kiln (~75 stacks) cluster in the southeast. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

As expected the main share of emissions in the urban parts of the city (Region 1 and Region 2) are dominated by vehicle exhaust and resuspended road dust due to the movement of vehicles on the road, followed by domestic and industries. Note that the boxes represented in **Figure 16** are not administrative city boundaries, but cover the designated zones. For example, the city passed an ordinance for no brick kilns within the city boundary limits and those which were in the city limits have relocated. However, for the urban box (Region 1), we do see some emissions from the brick kilns, which is the result of modeling domain. While the brick kilns have relocated, their emissions and their contributions are still relevant for the observed air quality in the city.

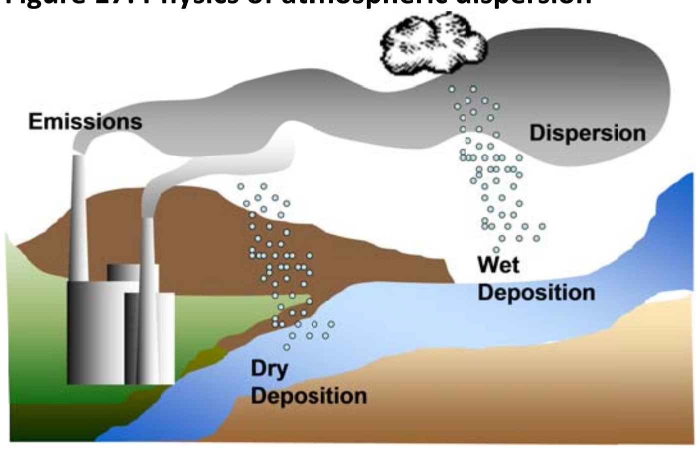
Overall, the emissions inventory estimation has an uncertainty of ±20-30%. Since, the inventory is based on bottom-up activity data in the city and secondary information on emission factors in India, there is some uncertainty associated with our estimates. In the transport sector, the largest margin is in vehicle km traveled and vehicle age distribution with an uncertainty of ±20% for passenger, public, and freight transport vehicles. The silt loading, responsible for road dust resuspension, has an uncertainty of ±25%, owing to continuing domestic construction and road maintenance works. In the brick manufacturing sector, the production rates which we assumed constant per kiln, has an uncertainty of ±20%. The data on fuel for cooking and heating in the domestic sector is based on national census surveys with an uncertainty of ±25%. Though lower in total emissions, open waste burning along the roads and at the landfills has the largest uncertainty of ±50%. The fuel consumption data for the in-situ generator sets is based on random telephone surveys conducted in other cities, to hotels, hospitals, large institutions, and apartment complexes, with an uncertainty of ±30%.

Overall, based on the data available from various state departments for various activities in the city, this is considered as a representative emissions inventory. All the calculations and databases presented in this Chapter are also maintained in MS Excel workbooks, which will be updated as and when new data is available for various sectors. A copy of the calculators and tools will be available for distribution @ UrbanEmissions.info.

4.0 PARTICULATE POLLUTION – business as usual

Typically, the emissions are released from an individual point or an area source, which after entering the atmosphere, depending on the local canopy and meteorological conditions, such as wind speed, wind direction, pressure, temperature, and moisture content, interacts with other pollutants, either deposits on to a surface (dry or wet) or lingers in the air in the form of pollution, which we breathe [20].

Figure 17: 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. The dispersion modeling exercise requires both computational and data assimilation techniques and there are a number of modeling systems available, with varying capacity and complexity to address the physical and chemical aspects of atmospheric transport of pollutant.

For Patna's air quality analysis, the Atmospheric Transport Modeling System (ATMoS) dispersion model was utilized, using local specific meteorological data[21]. The dispersion model schematics are summarized in the equation below for changes in concentrations (δC) and emissions (δE) by grid

$$\delta C_{grid} = \int_{i=1}^{\#sources} \int_{j=1}^{\#grids} \int_{met=1}^{\#hours} \delta E_{advection} - \delta C_{deposition} \pm \delta C_{reactions}$$

[20] "Atmospheric Chemistry and Physics" by Seinfied and Pandis, and "Fundamentals of Atmospheric Modeling" by Mark Jacobson, provide detailed discussion on air pollution modeling

[21] This model was previously utilized for urban air pollution modeling studies in Delhi, Hyderabad, Pune, Chennai, Ahmedabad, Surat, Rajkot, Udaipur, Vizag, and Indore. The ATMoS model formulation, manual, and application reports are available @ http://www.urbanemissions.info.

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 for total PM pollution over the city. This includes chemic conversion of SO_2 to sulfates and NO_x to nitrates[22]. The total PM_{10} concentration comprises of all the sub-fractions (PM_{coarse}+PM_{fine}+SO_4+NO_3) while the total $PM_{2.5}$ concentration comprises of the finer sub-fractions only (PM_{fine}+SO_4+NO_3), thus providing a multi-pollutant aspect to the PM pollution. The meteorological data utilized for the dispersion modeling is presented in **Figure 5 & 6**.

For the Greater Patna region, the ambient concentrations were modeled for the base year 2012, along with the estimated contributions of various sources is presented in **Figure 18** for PM_{10} and **Figure 19** for $PM_{2.5}$, and for the projected years 2020 and 2030 in **Figure 21**.

Conclusions from the dispersion modeling exercise, for the base year 2012 are

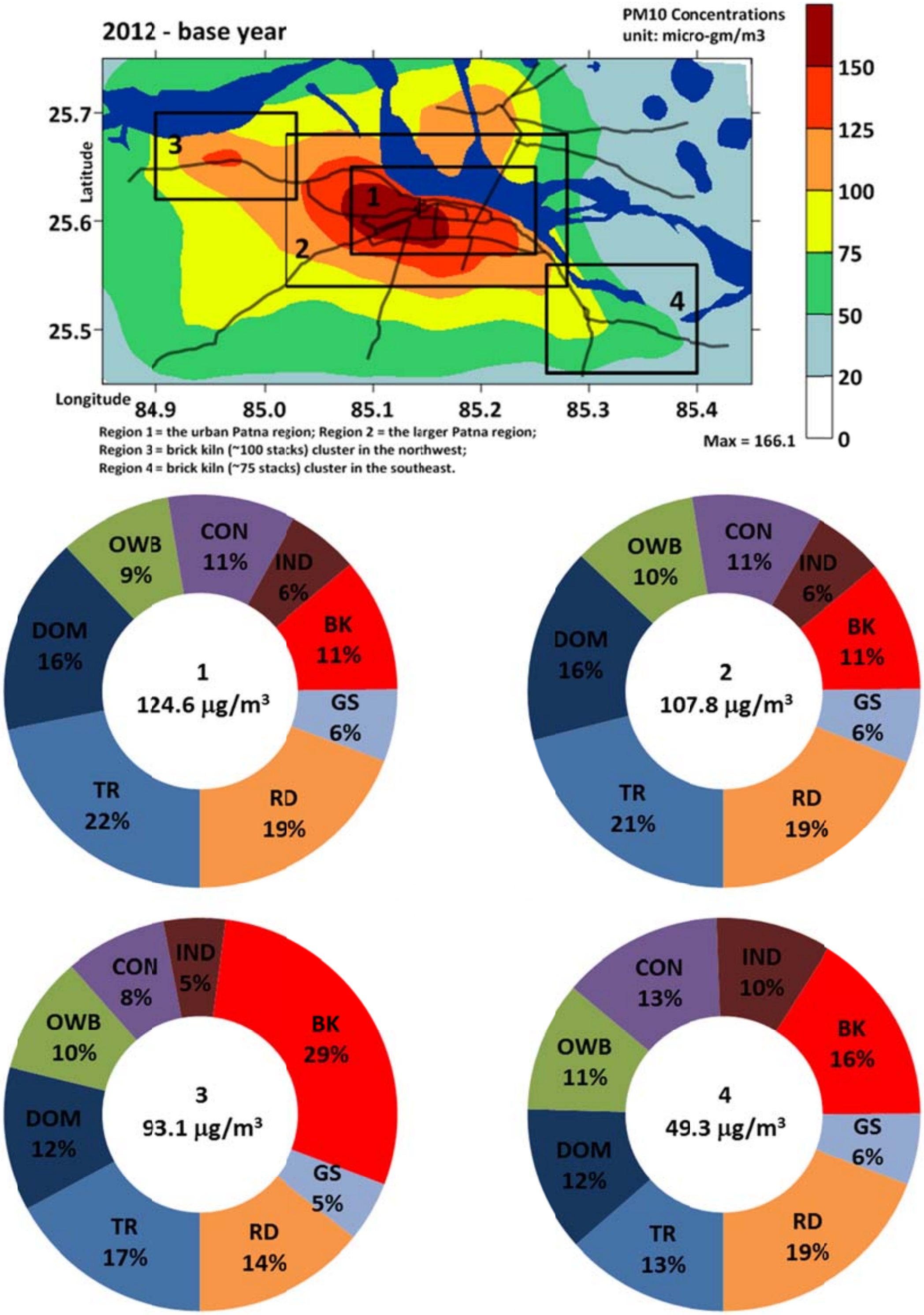
- The PM_{10} concentrations averaged 140μg/m^3 over the urban Patna region. The transport sector and the on-road resuspension are the primary contributors. This is due to (a) growing number of vehicles on the road and (b) growing congestion rates, compounding the total emissions and exposure rates
- While the clusters of the brick kilns were more than 10km away from the main city center, contributions of up to 11% are observed in the city center
- With the majority of the wind fields originating from the southeast, we believe that the contribution of the southeast cluster is the highest to the urban parts
- Among the diffused sources, domestic cooking and heating, open waste burning, construction activities, and diesel generator sets, dominate the reminder of the sources

The measured annual average PM_{10} concentrations at a monitoring station near BSPCB averaged 140μg/m^3 and a station near the Gandhi Maidan averaged 180μg/m^3. The area surrounding the Gandhi Maidan experiences dense traffic during the day, and being a playground, there is also a lot of elevated dust in the neighborhood, which explains the highs measured in the vicinity. The modeled grid-average PM_{10} concentrations in **Figure 18** and $PM_{2.5}$ concentrations in **Figure 19** show a high of 166μg/m^3 and 112μg/m^3, respectively.

The WHO guideline for annual average PM_{10} is 20 μg/m^3 and annual average $PM_{2.5}$ is 10μg/m^3.

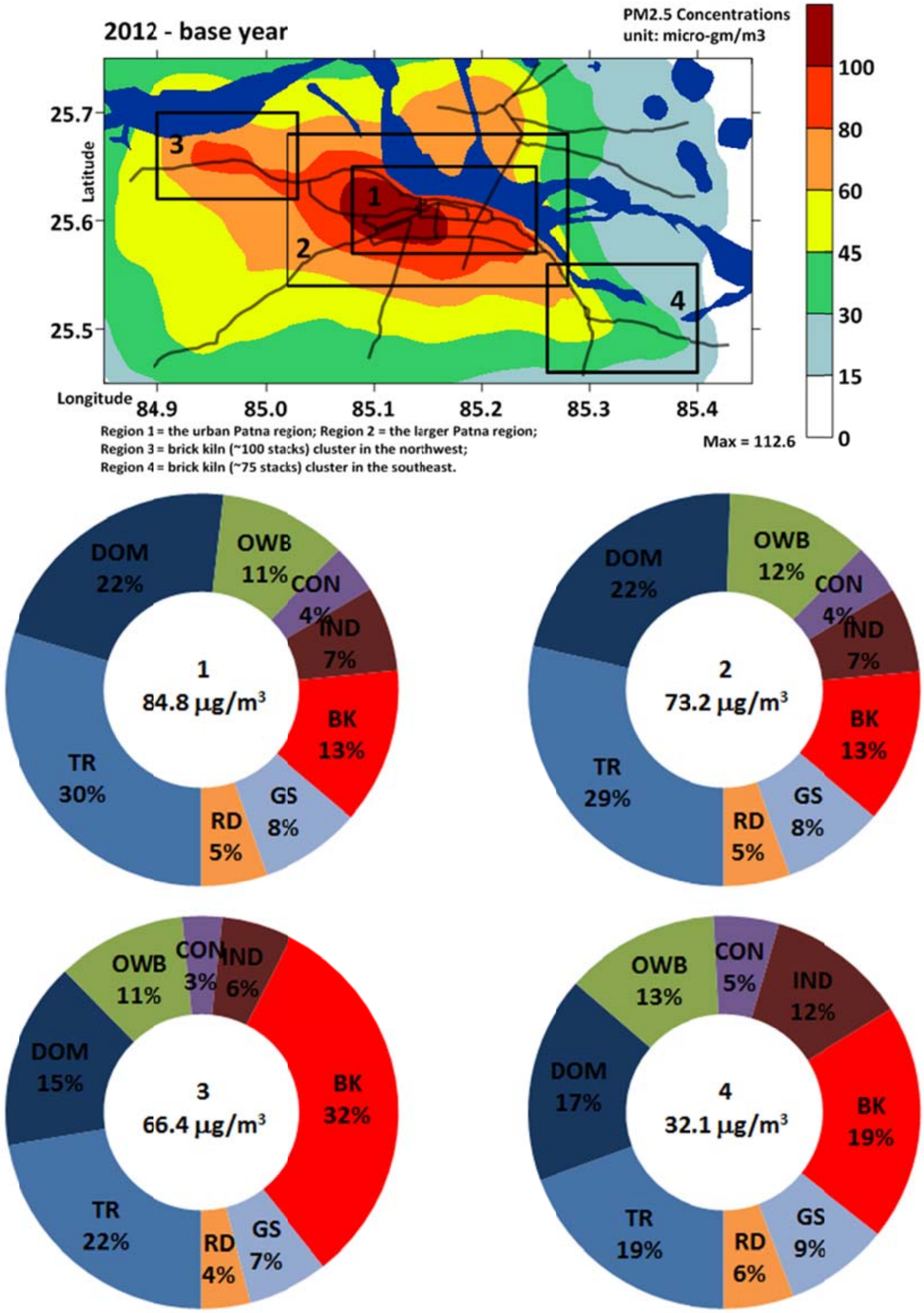
[22] These rates are specified in the model input file and user has an option to either use the default value or change it accordingly. No chemical transformation is applied to direct PM emissions.

Figure 18: Modeled annual average PM_{10} concentrations and percentage shares and average concentration in select regions in the Greater Patna region in 2012



Notes: The pie graphs are shares based on the emission totals for the select region. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

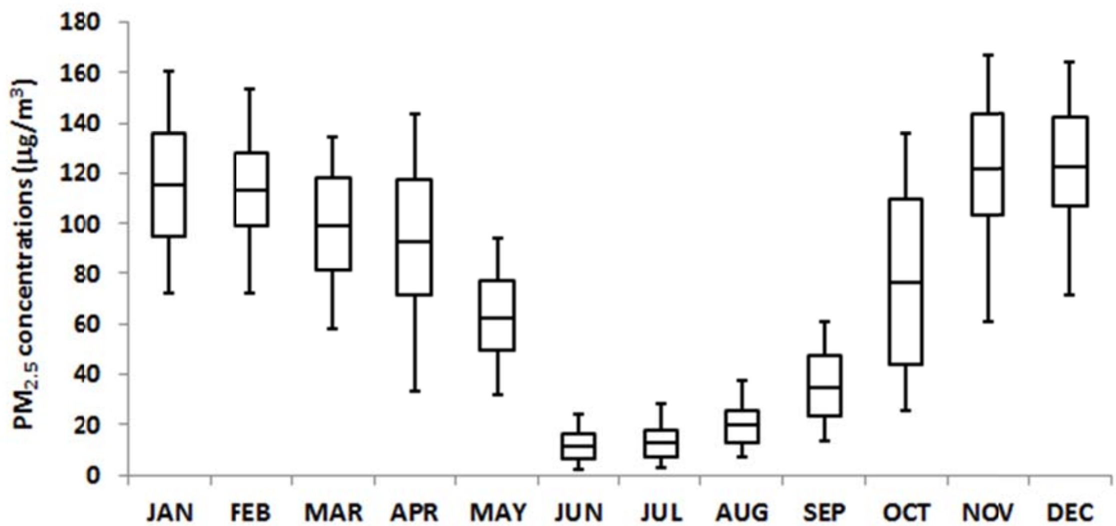
Figure 19: Modeled annual average $PM_{2.5}$ concentrations and percentage shares and average concentration in select regions in the Greater Patna region in 2012



Notes: The pie graphs are shares based on the emission totals for the select region. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

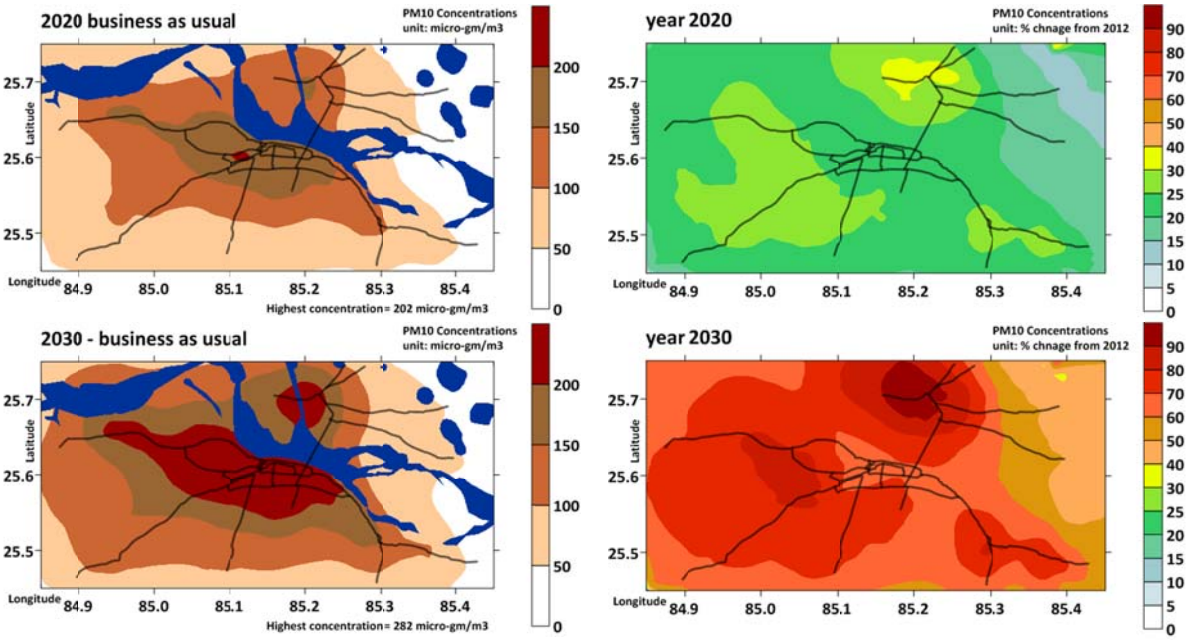
Besides the annual average concentrations presented in **Figure 18** and **Figure 19**, the ATMoS dispersion model also releases monthly average concentrations, which is affected by the monsoons for a large part of the year and the seasonality associated with the sources like brick manufacturing. The monthly variation in the concentrations over the urban Patna (Region 1 in **Figure 19**) is presented in **Figure 20**. The box plot is 25th and 75th percentile concentrations and the error bars are one standard deviation among the $PM_{2.5}$ concentrations estimated for all grids in Region 1.

Figure 20: Variation of monthly average grid concentrations for the urban Patna region (designated as Region 1 in this study)



Due to strong monsoons over the Indo-Gangetic plains, most of the pollutants get scavenged during the heavy rains in the summer months (**Figure 6**). The mixing layer heights during the winter months are also lower than the summer months, which tend to hinder full dispersion of the emissions from the diffused and the point sources, which pushes the average concentrations to at least 5-10 times worse than those observed in the summer months.

Figure 21: (a) Modeled annual average PM_{10} concentrations under the business as usual scenario for 2020 and 2030; (b) Percentage increase in the concentrations compared to levels of 2012



Conclusions from the dispersion modeling exercise, for the years 2020 and 2030, under the business as usual scenario are

- With no additional controls assigned to the current trends in total emissions (**Figure 11 to 14**) from all the known sectors, the ambient PM_{10} concentrations expected to get worse - the modeled annual average PM_{10} concentrations in 2020 and 2030 will be at least 25% and 70% higher than those in 2012 (**Figure 18**)
- The transport sector remains the dominant source of emissions, along with the on-road resuspension as the primary contributor, followed by the industries (including the brick kilns)
- For the business as usual scenario, we assumed a growth rate parallel to population for the construction and the brick manufacturing sectors, which is an underestimate and their shares could double, and further worsen the ambient pollution levels in the city
- While the urban parts of the city see changes, the highest percentage changes are expected in the peri-urban areas, outside the Patna municipal boundaries, where the urban expansion plans are already underway (Southwest and North of the city boundaries – **Figure 4**)

5.0 HEALTH IMPACTS

In India, the morbidity and mortality burden of outdoor air pollution is particularly costly in terms of work days lost, lost productivity, and loss in terms of gross domestic product (GDP), which was approximately USD 23.4 billion and 1.7% of national GDP in 2009[23]. Since, most of the pollution related deaths occur within a year or two of exposure, reducing PM pollution from sources like transport, brick kilns, and industries has immediate benefits for health and national economy. The direct link between emissions, outdoor air pollution, and human health has been extensively documented - most notable for chronic obstructive pulmonary disease, lower respiratory infections, cerebrovascular disease, ischemic heart disease, and cancers of trachea, bronchitis, and lung, all of which result in premature mortality[24]. The global burden of disease (GBD) study for 2010, estimated a total of 695,000 premature deaths due to outdoor PM and ozone pollution and ranked the outdoor air pollution among the top 10 health risks in India.

Of all the pollutants, the public health concerns are focused on PM, which contributes to a host of respiratory and cardiopulmonary ailments. Epidemiological studies conducted in India (Delhi and Chennai) under the public health and air pollution in Asia (PAPA) program also highlighted the linkages between outdoor air pollution and premature mortality, hospital admissions, and asthma cases[25]. Other studies in India have consistently demonstrated higher rates of respiratory and cardiovascular diseases in populations exposed to PM, NO_x, and ozone pollution[26]. Using these established dose-response functions, health impacts were estimated for the Greater Patna region, along with the modeled $PM_{2.5}$ concentrations and gridded

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23 "An Analysis of Physical and Monetary Losses of Environmental Health and Natural Resources in India", Policy Research Working Papers, WPS-6219, The World Bank, Washington DC, USA.

24 The Global Burden of Disease 2010: Generating Evidence and Guiding Policy. Institute for Health Metrics and Evaluation, Seattle, USA @ http://www.healthmetricsandevaluation.org/gbd
Outdoor Air Pollution and Health in the Developing Countries of Asia: A Comprehensive Review, Special Report 18 (2010), Health Effects Institute (HEI), Boston, USA @ http://www.healtheffects.org

25 PAPA program implemented by HEI @ http://cleanairinitiative.org/portal/whatwedo/projects/PAPA

26 More references to the case studies and established dose-response functions for outdoor air pollution are available up on request

population for the city and summarized below for 2012 (the baseline year) and under the business as usual scenarios for 2020 and 2030.

Table 3: Additional health impacts due to ambient $PM_{2.5}$ concentrations in Patna			
	Premature mortality	**Asthma attacks**	**Cardiac admissions**
Year 2012 (base year)	2,600	200,000	1,100
Year 2020 (business as usual)	3,450	295,000	1,650
Year 2030 (business as usual)	4,900	507,000	2,850

For comparison[27], we estimated 7,350 to 16,200 premature deaths per year for the city of Delhi in 2010. For cities similar in size to Patna, the estimated premature mortality was 3,600 for Pune, 3,950 for Chennai, 3,700 for Hyderabad, and 4,950 for Ahmedabad. An international study, estimated 14,700 premature deaths for Dhaka, 14,100 for Cairo, 11,500 for Beijing, and 11,500 for Delhi for the year 2000.

[27] All the case study reports are available @ http://www.urbanemissions.info

6.0 2020-2030 Scenario Analysis

Following the sectoral analysis of the emissions and concentrations for the baseline year 2012 and the projected emissions through 2030 under the business as usual scenario (**Chapter 4** and **Chapter 5**), emission reduction scenarios were developed, based on discussions with the local experts. Details of the scenarios are discussed in this Chapter, along with a summary of changes in the ambient concentrations and the health impacts in 2020 and 2030[28].

The projected emissions in **Figure 11-14** and the modeled concentrations in **Figure 21** for 2020 and 2030 are here-on used as the baseline for the scenario analysis. The percentage change in between the business as usual and the control scenario, for the modeled PM_{10} and $PM_{2.5}$ concentrations is similar. Hence, all the scenario figures are presented for PM_{10} pollution only. However, results are also available for $PM_{2.5}$ pollution, which currently has limited measurement scope in Patna.

The 2020 and 2030 scenarios evaluated for the Greater Patna region are

1. Emission control options for the brick kiln manufacturing – technology changes, landuse changes (relocation) and operational changes (raw material)
2. Introduction of cleaner fuel for the in-use vehicle fleet, which currently has access to only Bharat-3 type fuel
3. Improvements in the public and para transit systems and introduction of alternative fuel (CNG) for these modes
4. Targeting the diesel generator sets, with thermal power plant in Barh coming online to support the electricity demand in the city
5. Controlling dust resuspension on the roads
6. Combination all the above five scenarios

[28] All the scenarios discussed in the study are hypothetical, with reasonable assumptions, based on available data. For the feasibility of any likely projects under these scenarios, we need further surveys and scrutiny of what is possible

Scenario 01 – Brick Kilns

Under this scenario three concepts were combined for the brick manufacturing sector.

Firstly, relocation of the southeast brick kiln cluster in **Figure 4**. This cluster was targeted as the case study, depending on the prevalent wind patterns in the region (**Figure 5**) and their influence on the air quality in the Patna's urban area (**Figure 18-19**). The decision on the new location of the kilns is not certain, but based on discussion with the experts[29], their new location could be father south or farther east of the current location and away from the river. This is expected to minimize their overall impact on city's air quality. It is assumed that the brick kilns in this cluster will seize operations from 2015 and others will continue to operate as is.

Table 4: Comparison of technical and operational benefits and constraints of current and alternative brick manufacturing technologies [30]

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	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	1.0-2.0	800	25	60%

a. FCK = fixed chimney bull trench kiln; NG = natural gas; VSBK = vertical shaft brick kiln
b. 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
c. Initial investments are higher for Hoffmann kilns
d. Operational models are available in India and Kathmandu
e. Costs include initial investment, land, building, operational, and taxes estimates; the production rates for these kilns is up to 5.0 million

Secondly, shift from the FCK technology to the zigzag technology. The emission factoring tests conducted in India and Vietnam have shown that the improvement between these technologies can be as high as 70%[31]. Zigzag kilns, like the FCKs, are continuous in nature with batch output, with the firing circuit bent into a zigzag form. These kilns are divided into 16 or more chambers. Each chamber is connected to the next by a damper carrying hot gases from the fire. During

[29] Green Knowledge Solutions (New Delhi, India), whose expertise on the clay and alternative brick manufacturing technologies, shaped the brick kiln scenario for the Greater Patna region
[30] Table extracted from "Health benefits of adapting cleaner brick manufacturing technologies in Dhaka, Bangladesh" @ http://link.springer.com/article/10.1007%2Fs11869-013-0213-z
[31] Maithel S, Uma R, Bond T, Baum E, Thao VTK (2012) Brick Kilns Performance Assessment, Emissions Measurements, & A Roadmap for Cleaner Brick Production in India. Study report prepared by Green Knowledge Solutions, New Delhi, India

firing, the hot air is directed into the chamber which passes into the adjacent chamber for preheating the bricks. As the hot air passes from chamber to chamber, it gradually cools, which is essentially a counter-current heat exchange process and a more efficient use of heat and fuel. In principal, they do not differ much from the traditional designs, but with a high rate of fire travel, assisted by a strong fan draught system and better insulation provides for more efficient heating. In this scenario, we applied a 60% reduction in the fuel consumption, consequently a 60% reduction in the overall emissions for all the kilns (in **Figure 4**). In the estimates, we expect the kilns to undergo necessary structural changes in 2015 and start production in 2016.

Thirdly, replacement of the kiln fired clay brick kilns with the bricks made of alternative materials like fly-ash. Based on the assessment carried out the Green Knowledge Solutions (New Delhi, India), it is likely that 20% of the projected brick demand in 2020 and up to 50% of the projected brick demand in 2030 can be met with alternative materials. With the coal-fired power plant in operation near the city of Barh, 140km from Patna, we estimate that this transition is feasible.

Essentially, the total emissions under this scenario are reduced due to (a) relocation of the southeast brick kiln cluster to outside the study domain (b) replacement of the FCKs with zigzag technology for the remaining brick kilns in the study domain and (c) reduction in the production rates due to the introduction of the alternative construction material.

Figure 22: % Reduction in ambient PM_{10} concentrations under the brick kiln scenario

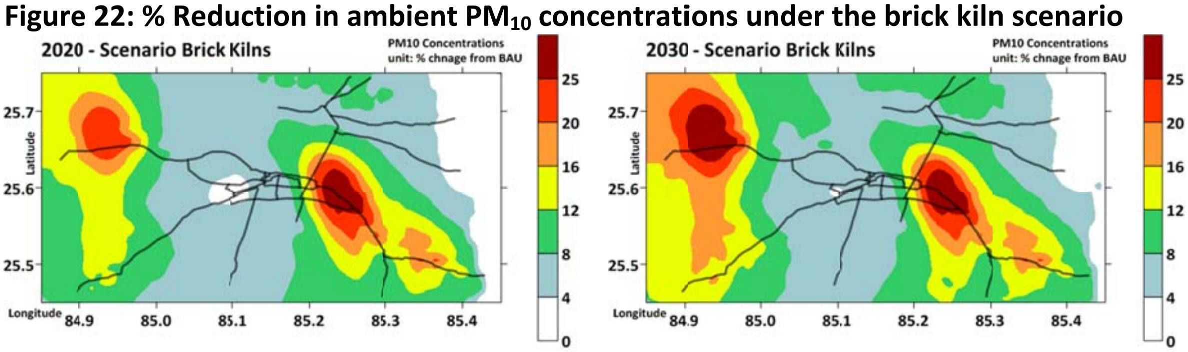


Table 5: Summary of particulate pollution reductions under the brick kiln scenario			
	2012	**2020**	**2030**
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		139.0 (8.9%)	197.6 (9.0%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		95.1 (10.2%)	141.9 (9.9%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		360	440

It is not necessary that all three actions will be implemented in the timeline anticipated in this analysis. However, the results are an estimate of, if these three scenarios are implemented through 2020 and 2030. The results presented in **Figure 22** and **Table 5** is due to the combination of all three control concepts for the brick kiln manufacturing sector. Of the three, the likeliness of action is anticipated in this (a) conversion of the kilns to zigzag technology (b) introduction of alternative building material in the city and (c) relocation of the kilns from the current location. The last option is the difficult one to implement, due to the involvement of the land acquisition at the new location, re-building of the kilns and re-arranging the access routes for raw material. This is also the one with substantial benefits due to the prevalent wind patterns (**Figure 5**) in the region. While the barriers exist for all these options, the positive news is that all these options have been implemented elsewhere, for example in Delhi, where clusters of brick kilns were relocated outside of Delhi city limits, along with improvements in then technology in-use.

Scenario 02 – Fuel and Vehicle Standards

In India, two types of fuels are consumed – one for the major urban centers (which is currently Bharat-4 with a maximum sulfur content of 150 ppm) and one for the rest of the country (which is currently Bharat-3 with a maximum sulfur content of 350 ppm). The chronology of the introduction of Bharat stage fuels is presented in **Table 6**. The fuel supplied in the Patna city is Bharat-3.

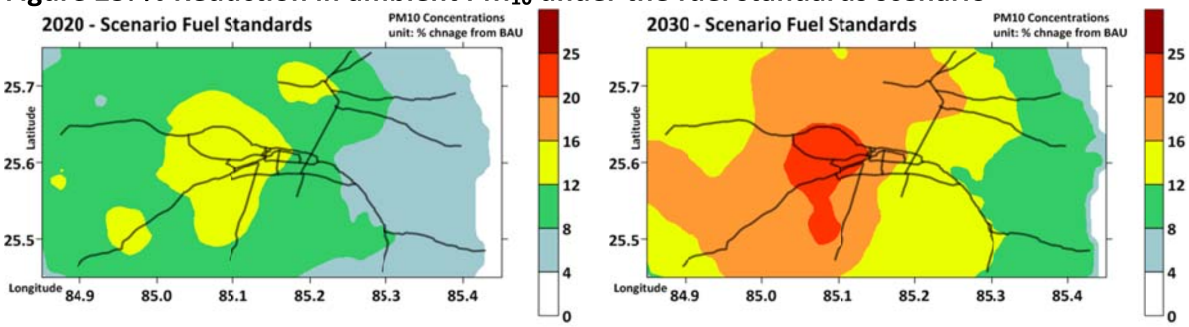
Table 6: Chronology of Bharat fuel and emission standards

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
** 13 cities are Mumbai, Kolkata, Chennai, Bengaluru, Hyderabad, Ahmedabad, Pune, Surat, Kanpur, Lucknow, Sholapur, Jamshedpur and Agra
*** 7 cities are Puducherry, Mathura, Vapi, Jamnagar, Ankaleshwar, Hissar and Bharatpur

While the staggered introduction of the fuel standards was beneficial for the major urban centers in the short run, the overall benefits are lost in transition. For example, the HDVs operating on diesel contribute significantly to PM emissions and often run on lower grade fuel, which can lead to failure of catalytic converters. It is therefore imperative that "*one nation, one fuel standard*" norm is mandated for better air quality in all the cities.

Figure 23: % Reduction in ambient PM_{10} under the fuel standards scenario



Under this scenario, the impact of the introduction of Bharat-4 fuel is analyzed, along with the introduction of the Bharat-4 compatible (new) vehicles in the city. It is assumed that Patna will have access to this fuel by end of 2015, with the program expanding the supply from the current 20 cities to 50 cities. The changes in the fleet average emission factors over the years are studied in the national study[32]. Along with the improvement in the fuel quality, this scenario included introduction of alternative fuel – compressed natural gas for the public- and para-transit systems in the city.

Table 7: Summary of particulate pollution reductions under the fuel standards scenario

	2012	2020	2030
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		132.2 (13.4%)	175.7 (19.1%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		87.5 (17.3%)	120.1 (23.7%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		420	700

Since the transport sector is one of the key contributors to the overall emissions and ambient concentrations, any changes to the fuel quality in the city, will impact the entire fleet, with immediate benefits to the local air quality.

[32] The full report detailing the methodologies and results on the "Road transport emissions in India 2010-30" is available @ http://www.urbanemissions.info

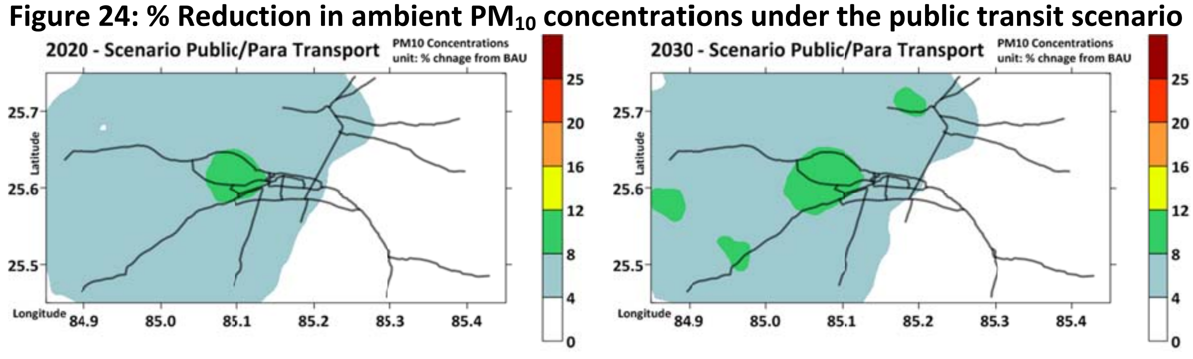
Scenario 03 – Public- and Para- Transit Systems

As city grows, there is a push to promote safe and clean public transport systems. In bigger cities like Delhi, Mumbai, Hyderabad, Kolkata, Chennai, Ahmedabad, and Bangalore, there is an established formal public transportation system that has benefitted from Jawaharlal Nehru National Urban Renewal Mission (JNNURM) programs. Since 2009, more than 14,000 new buses were delivered under this program.

Under this scenario, improvement in the public- and para- transit operations are assumed. In the face of rapidly growing economy and resulting increase in the vehicle ownership of individuals, in order to achieve a reduction in the emissions on a sustained basis, measures to increase share of non-motorized modes as well as public transportation need to be implemented. While short-trips are more likely to be catered to by walking and cycling, public- and para- transportation is most suitable for longer trips. The estimated modal shares in the city are 12.9 ± 4.2% for 2-wheeler motor cycles; 13.4 ± 3.5% for 3-wheelers auto rickshaws; 14.1 ± 6.7% for 4-wheeler cars and jeeps; 5.2 ± 1.8% for buses; 54.1 ± 9.3% for walking and cycling. The variation in the modal shares is due to the variation in the number passenger trips made by different age groups and working groups, vehicle carrying capacities, and on-road vehicle percentages.

Like most small and medium cities in India, Patna does not have an established and fully organized public transportation system; rather, it is supported by informal para-transit systems, mostly plying on the dominant corridors of the city. Among the para-transit systems, most common are the traditional three-wheeler auto-rickshaws (to seat up to 4 people), a larger version of the auto-rickshaws (to seat up to 10 people), and mini-buses. With their ability to negotiate the tiny by-lanes and weave through mixed traffic, these vehicles form an integral part of passenger and freight movement and in most cities is also a popular mode of mass transport for school children.

Figure 24: % Reduction in ambient PM_{10} concentrations under the public transit scenario



Under this scenario, we assume a tripling of the number of passenger trips by public- and para-transit, which accordingly will reduce the passenger trips from 4-wheeler and 2-wheeler motor vehicles in the city. We estimated changes from this scenario to reflect by 2017-18. Along with the improvement in the operations, this scenario included introduction of alternative fuel –

compressed natural gas for the public- and para- transit systems in the city. The expected changes in the emissions and pollution loads are concentrated to the Patna's urban area (**Figure 24**), where we expect the largest number of commuters for public- and para- transit modes.

Table 8: Summary of particulate pollution reductions under the public transit scenario			
	2012	**2020**	**2030**
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		142.0 (7.0%)	202.8 (6.6%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		94.3 (11.0%)	137.7 (12.6%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		280	360

The implementation of dedicated bus corridors, known as "bus rapid transport (BRT) system" is also among the priorities. The cities of Delhi, Ahmedabad, Jaipur, Pune, and Indore have implemented BRT projects with varying corridor lengths and the cities of Rajkot, Surat, Bhopal, Vijayawada, and Visakhapatnam have approved BRT projects. The para-transit systems have also benefited from the use of alternative fuels like CNG and LPG. In response to a Supreme Court mandate, the Delhi Government converted the entire three-wheeler fleet to CNG between 1998 and 2002, followed by similar initiatives in other cities like Patna.

Scenario 04 – Diesel Generator Sets

For the baseline emissions estimates (**Figure 11-14**), the share of emissions from the diesel generator (DG) sets is significant for all the pollutants, mostly from the industries, large hotels, large hospitals, institutions, and mobile towers. This is primarily fueled by frequent power shortages in the northern grid. The state of Bihar experiences a shortage of up to 15% in the peak demand.

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 duty vehicles can help control some emissions.

With a new power plant commissioned in the vicinity of the Greater Patna region, we assumed under this scenario a reduction of 50% of the emissions from the DG sets, starting 2016. Under ideal conditions, with full support from the electricity grid, these emissions can be cut 100%. In 2020, the expected reductions are concentrated in the Patna's urban area and by 2030, when we are also expecting a change in the urban landuse, the reductions, under this scenario are also expected in the peri-urban areas.

Figure 25: % Reduction in ambient PM_{10} concentrations under the DG set scenario

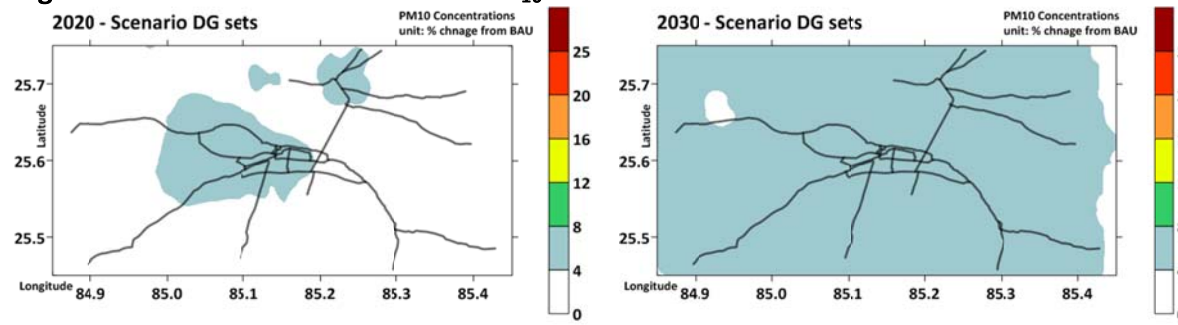
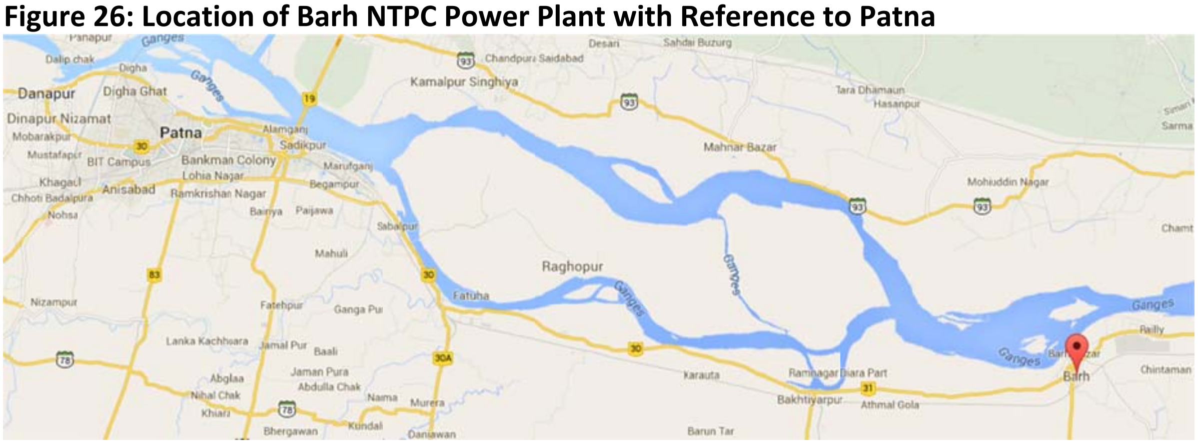


Table 9: Summary of particulate pollution reductions under the DG set scenario			
	2012	**2020**	**2030**
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		146.0 (4.3%)	201.9 (6.6%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		99.6 (5.9%)	143.1 (9.1%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		180	300

A 3,300 MW coal-fired power plant is listed as under construction with national and international funding, and will be commissioned in two stages with 1,980 MW in Barh I and 1,320 MW in Barh II. This facility has been named as a 'mega power' project for Bihar, and is owned by Indian energy company National Thermal Power Corporation (NTPC)[33]. The power plant is located approximately 140km east of Patna.

Figure 26: Location of Barh NTPC Power Plant with Reference to Patna



33 More details on the plant @ http://en.wikipedia.org/wiki/Barh_Super_Thermal_Power_Station, with the installation and operations listed as pending (2014/05/22)

Scenario 05 – Road Dust

This scenario is an extension of the Scenario-03, improving the public and para transit systems, which tends limit the improvements in the PM pollution on the roads, because the buses re-suspend more dust on the roads than the 4-wheeler and 2-wheeler motor vehicles. By introducing more buses on the road, without any improvements in the management on dust of the roads, limits the scope of benefits for the city. In this scenario, in addition to the steps introduced in Scenario-03, we assumed an increased awareness to control dust on the road, in order to reduce the silt loading and re-suspended road dust. This scenario has no impact on the pollutants other than the particulates.

Figure 27: % Reduction in ambient PM_{10} concentrations under the road dust scenario

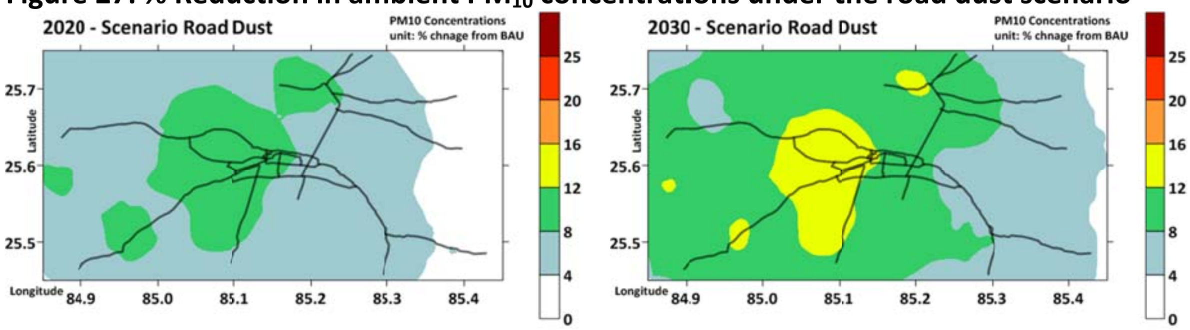


Table 10: Summary of particulate pollution reductions under the road dust scenario			
	2012	**2020**	**2030**
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		138.5 (9.3%)	190.7 (12.2%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		93.6 (11.6%)	135.4 (14.0%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		280	400

Traditionally, all the streets, sidewalks and public areas are swept manually and depending on the resources, poor or marginal areas receive reduced or inadequate service or no service at all. Often in manual street sweeping, most of the swept dust is left on the side of the roads, which gets re-entrained when the vehicle movement resumes during the day. The problem also lies with the uncoordinated road work by different departments (water, cable, electrical, and telecommunications) which often leave the roads dug and unmaintained, lead to more entrainment of dust on the roads for further resuspension and air pollution.

A better alternative is heavy-duty or light-duty trucks with vacuum cleaners to suck up dust from the roads or water sprinklers, so that the resuspension of any leftover dust is suppressed. The operational costs of mechanized sweeping could be similar to manual sweeping - given the latter is a labor intensive exercise. Not only a technocratic solution as above, but various departments need to work together to complete the projects and maintain the roads to reduce the silt loadings. Since the road dust accounts for up to 30% of the PM_{10} emissions (**Figure 11**), an immediate relief from dusty road is considered to be the lowest hanging fruit.

Scenario 06 – Above Five Scenarios Combined

By 2030, the expected growth in industrial, transportation, domestic, and power sectors will consequently result in an increase in emissions and air pollution in Patna. These anticipated changes are a growing concern for human health and general well-being in the city, which requires a multi-pronged approach for better air quality. In the previous sections, results for individual interventions were presented and in this section, results are presented for a combination of all them. This includes introduction of zigzag kiln technology and alternative building materials, relocation of a brick kiln cluster, introduction of Bharat-4 fuel standards, introduction of CNG for public- and para- transit vehicles, improvement of organized public- and para- transport system, reduction of the road dust loadings, and reduction of DG set usage.

Figure 28: % Reduction in ambient PM_{10} concentrations under the combined scenario

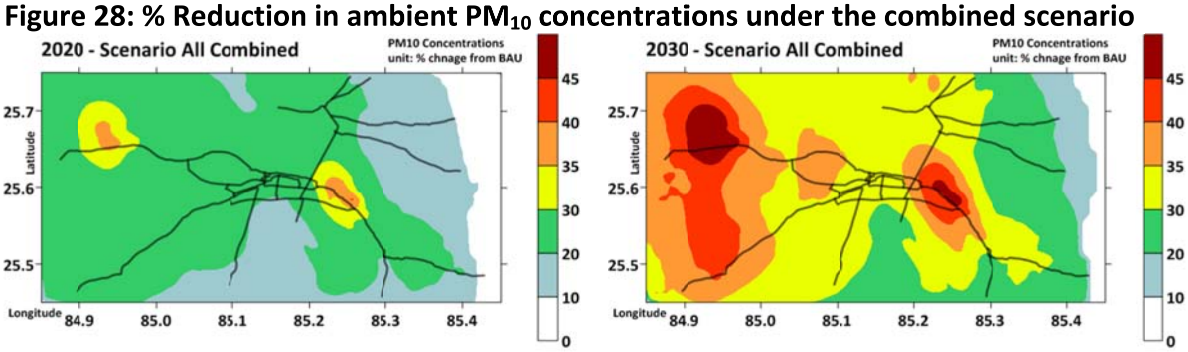


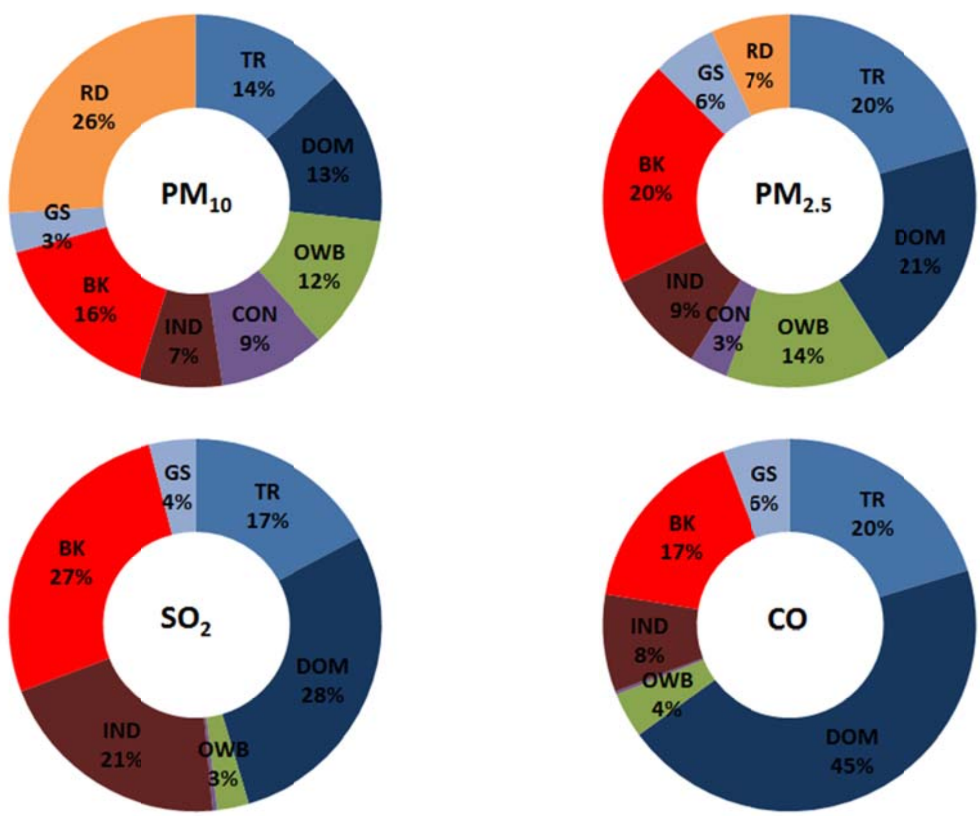
Table 11: Summary of particulate pollution reductions under the combined scenario			
	2012	**2020**	**2030**
Modeled annual average PM_{10} concentrations ($\mu g/m^3$)			
Business as usual	124.6	152.6	217.1
Scenario average (% reduction from BAU)		115.2 (24.5%)	139.2 (35.9%)
Modeled annual average $PM_{2.5}$ concentrations ($\mu g/m^3$)			
Business as usual	84.8	105.9	157.5
Scenario average (% reduction from BAU)		73.4 (30.7%)	89.4 (43.2%)
Estimated premature mortality cases			
Business as usual	2,600	3,450	4,900
lives saved under the scenario from BAU, annually		880 (25.5%)	1,540 (31.5%)

When all the interventions are implemented for all these sectors, the benefits to air quality will be substantial. However, it is important to note that these are speculative scenarios and estimated benefits, which can be verified only after the interventions are studied for their operational and financial feasibility and performance in the city.

7.0 Summary & Recommendations

The particulate pollution in the greater Patna region is often above the national standards and the WHO guidelines; which is estimated to result in 2,600 premature deaths in 2012 and could reach 4,900 premature deaths in 2030, if no control measures are introduced and enforced. As part of this study, to characterize Patna's air emissions and assess the opportunities for policy and technical interventions for better air quality, we benchmarked the sources of air pollution in the greater Patna region and projected the emissions through 2030, using the information available from BSPCB and the relevant government departments in the state of Bihar.

Figure 29: Total emissions and percentage shares for the Greater Patna region in 2012



Notes: Base year for all the emission calculations is 2012. TR = transport (including road, rail, and air); RD = road dust; DOM = domestic (including household and kiosks); GS = generator sets; OWB = open waste burning; IND = manufacturing industries (other than brick kilns); BK = brick kilns; CON = construction activities.

The sectors contributing the most to the PM pollution are the brick kilns surrounding the city, vehicle exhaust emissions, vehicle idling emissions, re-suspended road dust, industries, fuel burning for domestic cooking and heating, open waste burning, and construction activities. We also analyzed multiple scenarios for the brick kilns and the transport sector. A summary of the modeled PM concentrations under the business as usual scenario and a combination of all the possible scenarios for brick kilns and the transport sector and the health impacts under each of the scenarios is presented in **Table 12-14**.

Table 12: Reduction in PM_{10} pollution over Patna under various scenarios

PM_{10} concentrations in ($\mu g/m^3$)	**2012**	**2020**	**2030**
Business as usual	124.6	152.6	217.1
	Scenario average (% reduction from BAU)		
Scenario - Brick Kilns		139.0 (8.9%)	197.6 (9.0%)
Scenario – Fuel Standards		132.2 (13.4%)	175.7 (19.1%)
Scenario – Public & Para Transit		142.0 (7.0%)	202.8 (6.6%)
Scenario – DG sets		146.0 (4.3%)	201.9 (6.6%)
Scenario – Road Dust		138.5 (9.3%)	190.7 (12.2%)
Scenario – All Combined		115.2 (24.5%)	139.2 (35.9%)

Table 13: Reduction in $PM_{2.5}$ pollution over Patna under various scenarios

$PM_{2.5}$ concentrations in ($\mu g/m^3$)	**2012**	**2020**	**2030**
Business as usual	84.8	105.9	157.5
	Scenario average (% reduction from BAU)		
Scenario - Brick Kilns		95.1 (10.2%)	141.9 (9.9%)
Scenario – Fuel Standards		87.5 (17.3%)	120.1 (23.7%)
Scenario – Public & Para Transit		94.3 (11.0%)	137.7 (12.6%)
Scenario – DG sets		99.6 (5.9%)	143.1 (9.1%)
Scenario – Road Dust		93.6 (11.6%)	135.4 (14.0%)
Scenario – All Combined		73.4 (30.7%)	89.4 (43.2%)

Table 14: Summary of health benefits under various scenarios

	2012	**2020**	**2030**
Business as usual	2,600	3,450	4,900
	Premature mortality reduced		
Scenario - Brick Kilns		360	440
Scenario – Fuel Standards		420	700
Scenario – Public & Para Transit		280	360
Scenario – DG sets		180	300
Scenario – Road Dust		280	400
Scenario – All Combined		880 (25.5%)	1,540 (31.5%)

The two sectors (the brick kilns and the transport) are major contributors to the air pollution problems and the interventions discussed here can lead up to 35% reduction in the PM pollution and the likely health impacts in the city. However, it is important to note that these are speculative scenarios and often overlapping when they are implemented, and these estimated benefits can be verified only after the interventions are studied for their technical and financial feasibility and operational to the fullest extent.

Also, there are other sectors, which are equally important (and not studied in this report), which can further reduce the air pollution levels in the city are

- A 100% shift from the conventional fuels like coal and biomass in the domestic sector to a cleaner fuel like liquefied petroleum gas (LPG) and electricity
- A 100% shut down of the diesel generator sets in the city, which is feasible only by improving the power generation and transmission lines to the city
- A 100% control on the waste burning in the residential and industrial sectors and improvement in the municipal waste management systems in the city
- An overall improvement in the efficiency of industries in the greater Patna region.

Improving Information for Air Quality Analysis

Overall, the issue of air quality is a primary concern and needs immediate attention. During the analysis, the following activities are identified, which can further improve the overall confidence in the emissions and pollution load assessment

- An enhancement of the air quality monitoring network. Currently, there is a continuous monitoring system operational at the BSPCB premises. This network needs to be expanded to cover 4-5 more locations in the city, for better representation of the ambient air quality measurements, with the data available in the public domain for all the criteria pollutants
- The information utilized for emissions and pollution load assessments for Patna, is from the secondary sources such as reports from various ministries and academic literature. No primary surveys or measurements were conducted in the city. A series of surveys at the domestic and industrial sectors, will be beneficial in improving the confidence levels and to better understand the energy consumption pattern in the city
- Similarly, for the on-road characteristics, surveys to better understand the movement of vehicles (speeds and congestion times on road), vehicle usage, and vehicle mileage, will further enhance the vehicle exhaust emissions analysis, which is one of the key contributors in the city
- A source apportionment case study with sampling at least four mixed locations over an extended period of time, similar to the experiment carried out by CPCB in six other cities in India, will help scientifically ascertain the contribution of various sources to the PM pollution in the city
- The interventions discussed in this study are speculative in nature and often overlapping with other sectors. The estimated benefits can only be verified after the interventions are studied for their technical and financial feasibility, which should be carried out by appropriate authorities.

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