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Estimated Air Pollution and Health Benefits of Metro System in Delhi

Dr. Sarath Guttikunda
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Metro Layout in Delhi, India

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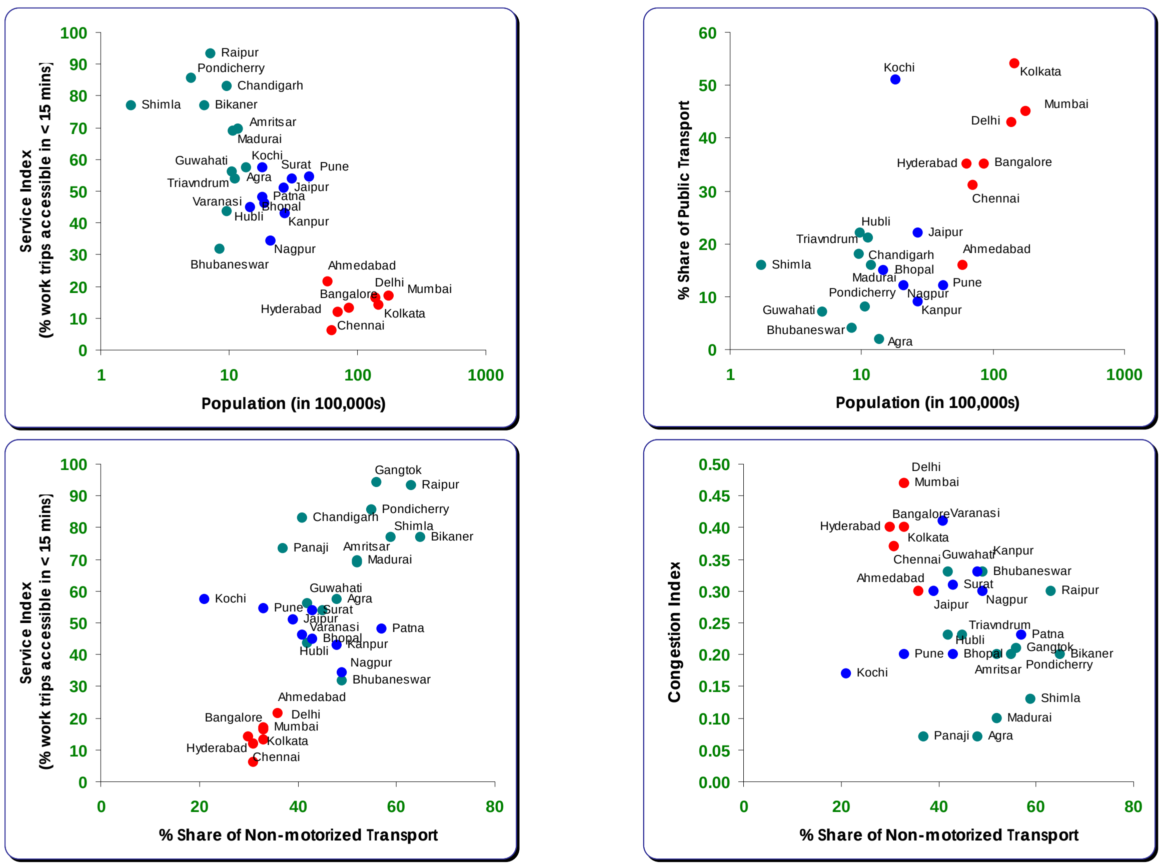
Dr. Sarath Guttikunda, New Delhi, India (Email: sguttikunda@urbanemissions.info)

Rising incomes, combined with growing propensity for personal mobility and inadequate (and uncomfortable) mass transportation facilities[1], has resulted in a pronounced increase in automobile ownership and its utilization in Delhi (and other major cities) in India. In 2000's the vehicle population has doubled and currently averages ~1,000 new vehicle registrations a day[2].

Figure 1: Travel statistics in India[3]



Color code: red = mega cities; blue = secondary cities; light blue (ash) = tertiary cities

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[1] Most often reasons quoted for not taking a public transport bus are uncomfortability while in the bus and lack of enough public transport facilities like the number of buses, frequency, and proper bus stops. While the later is being addressed under the JNNURM funds (http://www.urbanindia.nic.in/programme/ut/main.htm) to procure buses and improve the infrastructure facilities, the former should be dealt with a proper public awareness campaign. See "Making buses cool again" @ http://urbanemissions.blogspot.com/2009/10/making-buses-cool-again-cap.html

[2] Presentation by Ms. Anumita Roychoudary, at the Integrated Environmental Strategies program, December, 2007 @ http://www.epa.gov/ies/india/apportionment_documents.htm

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

Growing motorization, coupled with an absence of appropriate road traffic reduction strategy on major corridors, an ageing and ill-maintained vehicle stock, a sizeable share of two-stroke engine technologies, absence of an efficient public transport system, and inadequate separation between working, living, and moving space, have all led to traffic congestion resulting in longer travel times[4], extra fuel consumption[5], high-level pollution, discomfort to road users, and degradation of the urban environment. **Figure 1** presents the changing trends in urban transportation among the Tier I, Tier II, and Tier III cities in India, with Delhi highlighted as one of the red dots. In Delhi, the service index, defined as the work trips accessible in less than 15 minutes, is low, along with a low share of non-motorized transport and a correspondingly high congestion rate. In the Tier I cities, the public transport facilities are improving and carry the larger share of passenger kilometers, but not merely enough to tackle the growing congestion problems or the air pollution.

An intervention of converting the bus fleet, para-transit vehicles (taxis and 3-wheelers) and some passenger cars (on voluntary basis) from diesel to Compressed Natural Gas (CNG) improved the air quality significantly in Delhi[6]. **Box 1** presents the chronology of actions implemented in the transport sector in Delhi. While it is hard to judge the improvement in air quality at each step, with limited number of monitors in the city, **Figure 2** presents a summary of particulate matter (PM_{10}) and Nitrogen Oxides (NO_x) concentrations observed at two stations in Delhi.

Box 1: Chronology of actions to improve Transport Sector in Delhi, India

1994-95: Unleaded gasoline

1996: 0.5% sulfur diesel; govt. vehicles converted to CNG

1996-97: 1160 industries closed or relocated

1998: Phasing out old vehicles; Metro construction

1999: 0.25% sulfur diesel; trucks during night time only

2000: Bharat-II; 0.05% sulfur diesel; old buses/3Ws to CNG

2001-02: Full conversion of buses/3Ws/Taxis to CNG

2003: Supreme Court order for source apportionment

2006-07: Metro opens in the North

2009: BRT opens, with limited success

2010: Commonwealth Games & expected metro completion

The largest gain in the air quality was observed at the peak of the CNG conversions in 2001-2002. And since, the air quality levels have declined gradually over the years, in the residential areas and along the major corridors. Motor vehicles also emit carbon monoxide (CO), sulphur dioxide (SO_2, primarily from diesel vehicles), and other toxic substances. The slow moving traffic during rush-hours puts the environment and lives in high danger and consequently stretches the health facilities beyond their capacities[7]. In 2009, the Central Pollution Control Board (CPCB) announced that Delhi is now the "Asthma Capital" of India[8].

[4] Down to earth reference on reduction in speeds?
[5] Refer to SIM-air paper No.18 "Indicative Impacts of Vehicular Idling on Air Emissions" @ http://www.urbanemissions.info/simair/simseries.html
[6] SIM-air working paper No.22 "Air Quality Management in Delhi: Then, Now, and Next" @ http://www.urbanemissions.info/simair/simseries.html
[7] BBC, 2009, "Road Particles Pose Higher Health Risk" @ http://news.bbc.co.uk/2/hi/science/nature/8092182.stm
[8] Mail Today, March 2009, "Delhi is India's Asthma Capital" @ http://www.intoday.in/index.php?id=24240&option=com_content&task=view&sectionid=5

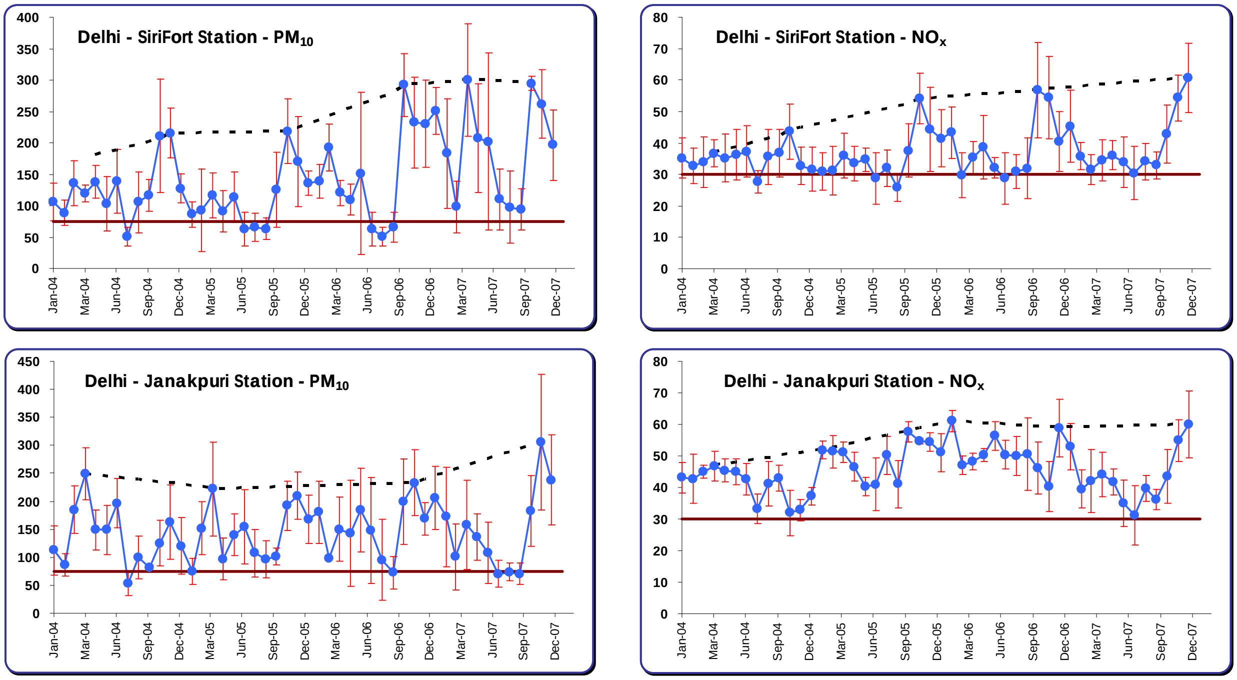

Figure 2: Air pollution in Delhi – 24hr monthly averages with variance over each month

In general, an increase in the number of vehicles is a reason to higher air pollution levels in the residential areas and along the transport corridors. Within that, the largest increase has come from the diesel vehicles. **Figure 3** illustrates how the benefits of CNG conversion are lost to the rising diesel vehicle population. Not only the passenger cars doubled in the 2000's, but also the share of the diesel vehicles more than doubled from 20 percent to 50 percent and thus increasing the PM emissions by at least three folds[9].

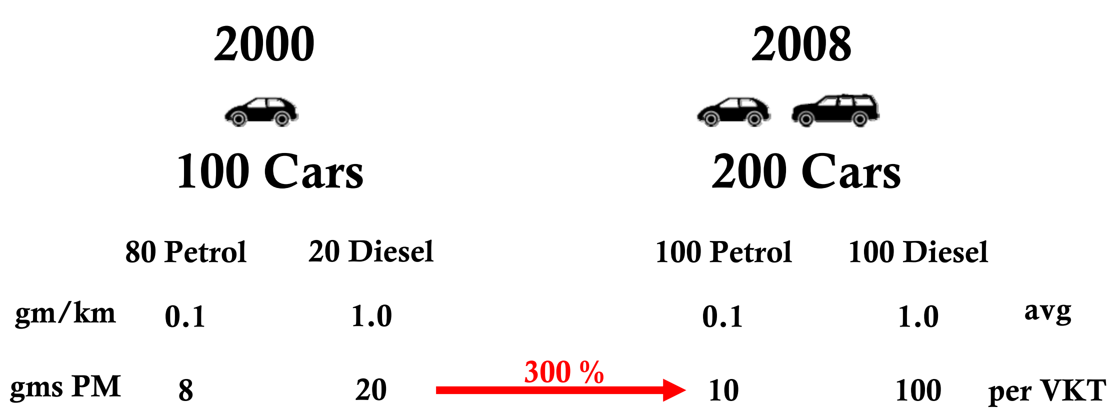

Figure 3: An illustration of how benefits of CNG conversion are lost to diesel cars

[9] For this back-of-the-envelope calculation, average emission factor for PM_{10} is used. Refer to the resources on emission factors @ http://urbanemissions.blogspot.com/2009/01/average-vehicular-emission-factors.html

Transport Sector is NOT Always the Main Culprit

Air pollution is rising in the city and the sources are many – inside and outside the city. A source apportionment the PM pollution in Delhi describes in detail the seasonal variation in the contribution of various sources[10]. A summary of the results is presented in **Figure 4**. Two dominant sources linked to the transport sector are the diesel and road dust, followed by the biomass burning, which is predominantly seen in the winter and spring months.

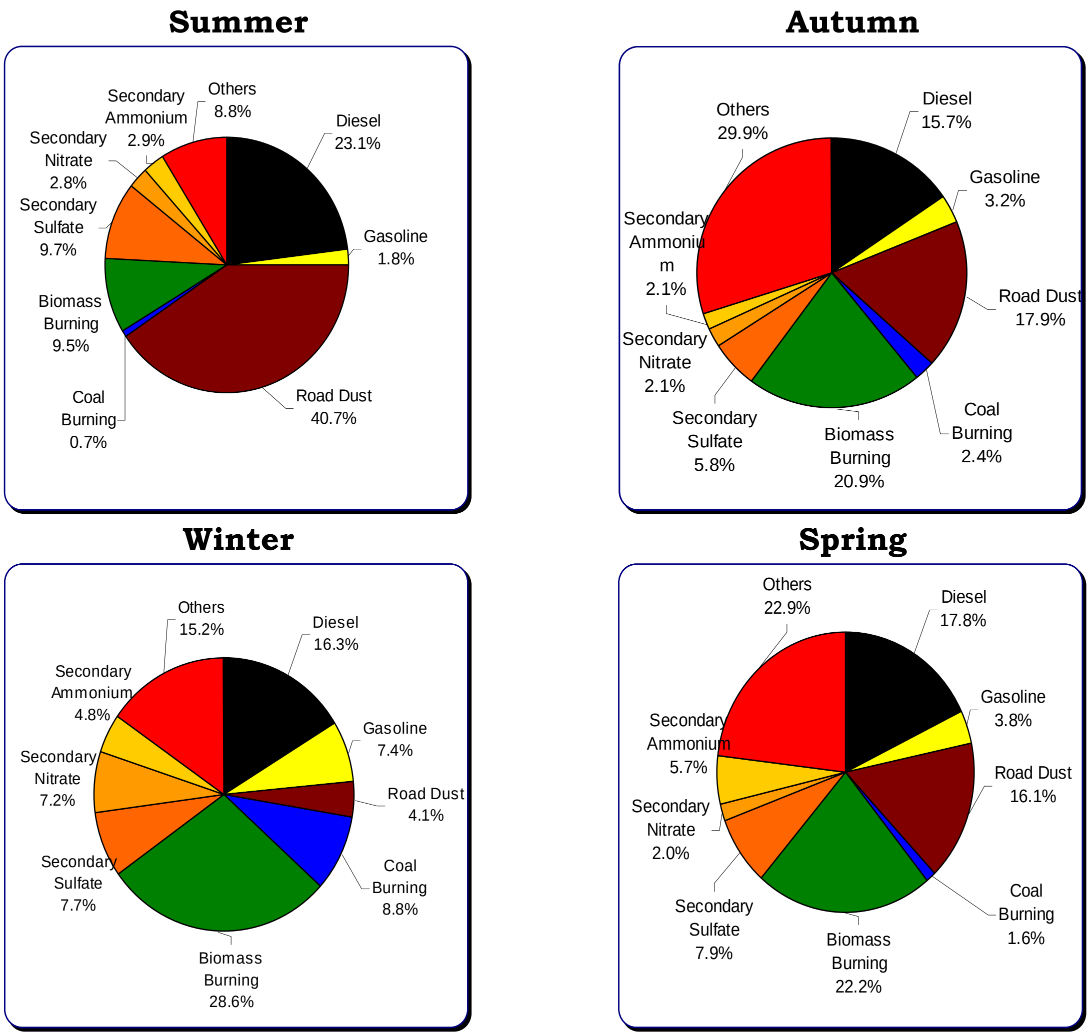

Figure 4: $PM_{2.5}$ Source apportionment results for Delhi

[10] The source apportionment study was conducted in four Indian cities in 2001-02, via hydrocarbon analysis of the measured $PM_{2.5}$ samples, under the guidance of Dr. Ted Russell @ Georgia Tech University. Other cities include Chandigarh, Kolkata, and Mumbai. Please note that the source apportionment results are indicative of the possible shares of various sources in the measured sample, which most often represent the surroundings of the monitoring site, instead of a directive measure for the whole city. The receptor modeling, following the sampling, is a statistical analysis based on the profiles of various sources which could be contributing to the PM pollution. A detail explanation on the methodology is presented in SIM-air Working Paper No.16 “Urban Particulate Pollution Source Apportionment - Part 1. Definition, Methodology, and Resources” @ http://www.urbanemissions.info/pmsa

While the focus is on the transport sector, one should not neglect the lower hanging fruit of the biomass burning and possible higher efficiency in the industrial sector (coal combustion).

Scope of this paper

Air pollution due to all the sources takes a toll on health impacts. A recent monitoring experiment across the Delhi streets, covering ~160km in 10 hours, presents an interpolated spatial map of pollution[11]. The study also estimates ~10,900 premature deaths annually due to the ambient PM pollution levels currently experienced in Delhi.

The impact of air pollution on the human health and the ecosystem is increasingly been linked to the growing transport sector[12]. The emphasis is on the public transport[13]. The JNNURM funds for buses and urban transport strategy of India are promoting the need for infrastructure for new buses (manufactured by Tata and Ashok Leyland). A good public transport system is expected to help reduce the congestion levels, energy demand in the transport sector, and the interlinked air pollution.

A major intervention that Delhi is counting on is the extension of the metro rail system[14], to shift the motorized transport trends to the metro rail. The expected level of shift is uncertain, which depends on a number of factors[15]. An analysis from 2008 estimated a possible reduction of at least 7 percent in the criteria pollutant emissions in 2010, by the introduction of expanded metro rail system in Delhi, India[16].

Question: *What are the health impacts of the current traffic patterns? What is the possible reduction in PM pollution in Delhi due to a possible shift in travel patterns? And what are the health benefits?*

[11] "Monitoring & Mapping Urban Air Pollution: A One Day Experiment in Delhi, India", SIM-air Working Paper No.29 @ http://www.urbanemissions.info/simair/simseries.html
[12] WHO - Directory of resources on transport, health and environment in developing countries @ http://www.who.int/heli/risks/urban/transpdirectory/en/index.html
[13] SIM-air working paper No.24 "Motorized Passenger Travel in Urban India: Emissions & Co-Benefits Analysis" @ http://www.urbanemissions.info/simair/simseries.html
[14] Metro Rail System in Delhi, India @ http://www.delhimetrorail.com/index.htm
[15] Some discussion on the sustran listserve on public transport systems @ http://list.jca.apc.org/public/sustran-discuss/2009-June/006719.html
[16] "Impact of Metro Rail System of Air Emissions in Delhi, India", SIM-air case study @ http://www.urbanemissions.info/simair/simcities.html

Impact of Metro Rail System in Delhi, India

An emissions analysis was previously conducted to study the impact of the expected shift in the travel patterns upon the introduction of the metro rail in Delhi, India[17]. The metro rail layout is presented in **Figure 5**. The red dots indicate the existing metro line and the grey dots indicate the new lines under construction, including an express way to the international airport. The new lines are expected to be operational (**Box 2**) by the start of the Commonwealth Games in October, 2010[18].

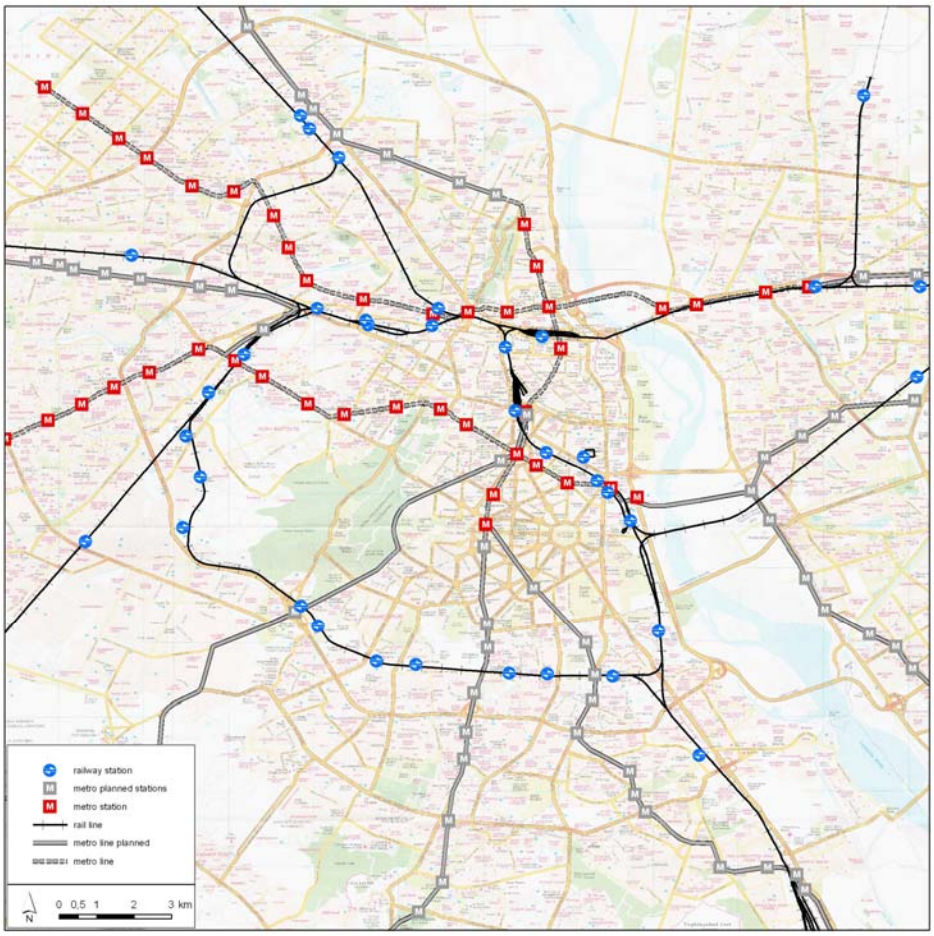

Figure 5: Metro rail layout in Delhi, India

In India, successful metro/subway systems are operational in the cities of Mumbai and Kolkata, which carry the maximum of the public transport load, besides a wide network of on-road support and the new network in Delhi is expected to replicate that experience. Despite the recent construction woes, the Minister of Urban Development proclaimed that

[17] A summary of the analysis is available @ http://www.urbanemissions.info/applications.html. This preliminary analysis was conducted using survey data from the Central Road Research Institute, Delhi, India, and Indian Institute of Technology, Delhi, India.

[18] 2010 Commonwealth Games in Delhi, India @ http://www.cwgdelhi2010.org/home.aspx

the Delhi Metro is the proudest achievement in modern India[19]. Firstly, the Delhi Metro became the first rail based methodology to garner 90,000 voluntary carbon credits for improving the efficiency of the power transmission in the system[20]. Secondly, a shift was also observed from personal mode of transport to metro-rail, which results in a significant reduction in the emissions, estimated at ~7 percent of particulate and CO_2 emissions on road[21].

Box 2: Operational timeline for the Metro rail in Delhi, India

The Phase-I covered 65 km across the city. Another six lines under Phase-II are expected to open before the Commonwealth Games begin in October. With Phase-II completion, the metro network will cover ~180 km.

Phase-II Schedule:

1. Yamuna Bank to Anand Vihar (6.2 km) in January 2010
2. Qutub Minar to Gurgaon (15.0 km) in February 2010
3. Inderlok to Kirti Nagar to Mundka (18.5 km) in February 2010
4. Central Secretariat to Qutab Minar (10.9 km) in June 2010
5. Airport Express linking New Delhi Station (19.6 km) in August 2010
6. Dwarka Sector 9 to Dwarka Sector 21 (2.8 km) in September 2010
7. Airport Express linking Dwarka Sector 9 (3.1 km) in September 2010
8. Central Secretariat to Badarpur (20.0 km) in September 2010

Source: Indian Express, January 1st, 2010
http://www.indianexpress.com/news/metro-network-set-to-double/562101/index.html

Methodology

The emissions analysis was conducted for **tailpipe emissions only** and it does not include the emissions from the construction period nor the electricity consumed during the operational period of the metro rail. The paper is aimed at estimating the changes in the emissions, concentrations, and exposure levels in the city, due to the traffic patterns – without and with metro rail – in 2010.

The methodology utilized for the analysis is presented in **Figure 6**. The emissions from various vehicular categories (discussed in the later sections) are analyzed for multiple scenarios, defined as expected shares of shifts from various modes, and modeled to estimate

[19] India Press Information Bureau, November, 2009 @ http://pib.nic.in/release/rel_print_page.asp?relid=53825
The cities of Hyderabad, Chennai, and Bangalore also have plans for a metro rail system.
The Hindu, November, 2009, "Delhi Metro crosses billion passenger mark"
@ http://www.thehindu.com/2009/11/28/stories/2009112858440100.htm
[20] DMRC prevents emission of 90,000 tons of eCO2
@ http://www.delhimetrorail.com/commuters/whats_new.html#DMRC_Prevents_Emission
[21] The analysis was conducted using the Smart-CART (Smart Carbon Analysis for Road Transport) model. The model and an operational manual is available for download @ http://www.urbanemissions.info/simair

the ambient pollution levels. For each scenario, the health impacts due to the estimated concentrations are evaluated using dose-response functions for mortality and morbidity[22].

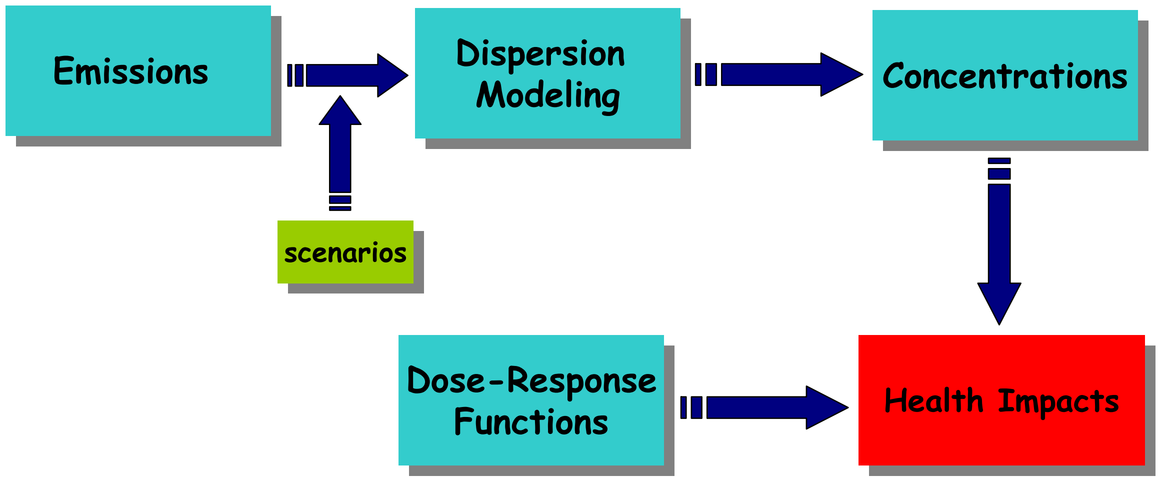

Figure 6: Schematics of the emissions, pollution, and exposure modeling

It is important to note that modeling was conducted for the road emissions only and the pollution maps presented SHOULD NOT be construed as total pollution in the city. The analysis also does not include any long-range pollutants like ozone nor considers their influence on the local pollution (PM) levels. The analysis is conducted assuming that the transport emissions as one of the sources and estimated their impact on the exposure levels and the benefits of shifting large masses of people to metro rail system.

Emissions & Scenarios

For the analysis, similar to the statistics used in a 20-city co-benefit analysis of air emissions from passenger transport in urban India[23], a bottom-up analysis of the passenger traffic using activity levels (vehicle kilometers traveled) was developed. An example estimate of the activity levels is presented in **Box 3**, comparable to estimates from previous studies[24]. The public transport and non-motorized transport are the primary modes of transport (also evident in **Figure 1**), though the public transport facilities are currently not enough to meet

[22] Details of the methodology and resources for dose-response functions are discussed in SIM-air working paper No.6, "Estimating Health Impacts of Urban Air Pollution" @ http://www.urbanemissions.info/simair/simseries.html

[23] SIM-air working paper No. 24, "Motorized Passenger Travel in Urban India: Emissions & Co-benefits Analysis" presents the emissions analysis of the motorized "in-city" passenger travel from 20 cities in India, covering the current trends in four modes of transport (passenger cars, motorcycles, 3 wheelers, and buses), estimated energy consumption for the assumed growth patterns, and possible co-benefits of three combined scenarios (public transport, policy reforms, and non-motorized transport). The cities included in this analysis are Delhi, Mumbai, Kolkata, Chennai, Hyderabad, Bangalore, Kanpur, Agra, Pune, Ahmedabad, Bhopal, Jaipur, Surat, Pondicherry, Bhubaneswar, Panaji, Patna, Kochi, Nagpur, and Guwahati. Detailed report is available @ http://www.urbanemissions.info/simair/simseries.html

[24] Mohan, D. (2008) Mythologies, Metros & Future Urban Transport. TRIPP Report 08-01, New Delhi: Transportation Research and Injury Prevention Programme, Indian Institute of Technology, Delhi

the current mobility demands in the city. For 2010, the total motorized vehicle kilometers traveled is estimated ~115 million per year[25].

The emissions inventory for the scenarios was developed using the average emission factors, developed utilizing emission standards for the newer vehicles, applying deteriorating factors gradually over time, and adjusting to the vehicular mix of the current fleet. Mathematically, the calculations are represented as below[26]. A summary of the baseline emissions is presented in **Table 1**.

$$VKT = Trips * Avg.Trip.Length$$

$$EF_{age} = EF_{new} * (1 + drate)^{\wedge 5}$$

$$EF_{effective} = \sum_{age=1}^{age=5} EF_{age} * \frac{NV_{age}}{NV_{total}}$$

$$Emissions = VKT * EF_{effective}$$

Box 3:

What is the percentage of motorized and non-motorized transport in Delhi, India

This type of assessment is generally based on on-road surveys and statistics of vehicular usage. However, one can also develop an estimate of motorized and non-motorized transport based on a bottom-up analysis of vehicular and population statistics.

In the National Capital Region, the estimated population is 16 million. Lets assume that 35 percent of the population is under-age and non-mobile (for various reasons), which leaves 10.4 million people mobile. If each person makes a back and forth trip, this translates to a total of ~20.8 million trips a day.

In 2010, an estimated number of cars = 1.35 million; 2-wheelers = 1.6 million; 3-wheelers = 80,000; and Buses = 16,000; 10% of the cars are assumed to be operated as taxis.

Say, cars and 2Ws make a back and forth trip; Buses make ~8 trips a day carrying ~40 persons a trip; and 3Ws make ~8 trips a day carrying ~1.5 persons per trip. This translates to 2.43 million trips by cars; 0.54 million trips by taxis; 5.12 million trips by Buses; 3.2 million trips by 2Ws; and 0.96 million trips by 3Ws.

The already operational metro rail in the northern sector carries ~900,000 passengers a day.

This leaves 7.65 million trips by either walking or cycling mode.

In percentages, trip share of cars = 12%; Taxis = 3%; Buses = 25%; 2Ws = 15%; 3Ws = 5%; Metro = 4%; and the Non-motorized transport = 37%

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[25] An estimate based on a survey by CRRI puts the VKT at 792 Lakhs (~79.2 million) for 2002. Source: Presentation Mr. K. Ravinder, CRRI @ IAAPC workshop, October, 2008

[26] Details of the methodology and average emission factors are presented in "VAPIS tool – Vehicular Air Pollution Information System" @ http://www.urbanemissions.info/simair/vapis.html

Table 1: Vehicular usage and emissions for 2010 from passenger travel ONLY

		millions	tons/year (Sc00)				
Vehicle	**% Trips**	**VKT/yr**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**NO_x**	**CO_2**
Cars	12%	48.6	8,160	4,577	3,583	10,998	3,902,580
Taxis	3%	10.8	3,942	2,365	1,577	4,928	985,500
2Ws	15%	48.0	1,752	876	350	2,628	700,800
3Ws	5%	6.4	234	117	-	818	163,520
Buses	25%	1.3	78	42	47	1,518	228,928
Metro rail	4%						
NMT	37%						
	Total	**115.1**	**14,166**	**7,976**	**5,557**	**20,890**	**5,981,328**

The emissions are divided into two main categories.

- Baseline emissions, as presented in **Table 1**, with the current mode of operations
- Scenario emissions with the metro rail extended and operational in the entire city. Since, this scenario depends on the expected level of shifts from other modes of transport, this is sub-divided into six scenarios (**Table 2**) with varying percentage of shifts in the number of trips.

Table 2: Emissions scenarios with varying levels of shifts

	Sc01		Sc02		Sc03	
Vehicle	**% Shift**	**% Trips**	**% Shift**	**% Trips**	**% Shift**	**% Trips**
Cars	20%	9%	42%	7%	71%	3%
Taxis	20%	2%	9%	2%	16%	2%
2Ws	20%	12%	55%	7%	93%	1%
3Ws	20%	4%	16%	4%	28%	3%
Buses		25%		25%		25%
Metro rail		15%		22%		32%
NMT	10%	33%	10%	33%	10%	33%

	Sc04		Sc05		Sc06	
Vehicle	**% Shift**	**% Trips**	**% Shift**	**% Trips**	**% Shift**	**% Trips**
Cars	30%	8%	45%	6%	51%	6%
Taxis	30%	2%	10%	2%	11%	2%
2Ws	40%	11%	59%	6%	67%	5%
3Ws	30%	3%	18%	4%	20%	4%
Buses	10%	22%	7%	23%	19%	20%
Metro rail		21%		25%		30%
NMT	10%	33%	10%	33%	10%	33%

The scenarios simulate "what if" cases for individual modes of transport. These are designed to estimate a band of possible reductions in the number of trips from each mode. Summary of the emissions under each scenario is presented in **Table 3**.

<u>*Scenario 01*</u>: Following basic assumptions, this scenario assumes a constant 20% cut in the number of trips from each mode, except for the bus sector.

<u>*Scenario 02*</u>: This scenario was developed under "target mode" via an optimization scheme fixed to achieve a combined 80% share of public transport (via buses and metro) and NMT. The largest benefits originate from shifting the trips from the passenger car section.

<u>*Scenario 03*</u>: This scenario was developed under "target mode" via an optimization scheme fixed to achieve a combined 90% share of public transport (via buses and metro) and NMT. This is an extreme scenario for the amount of reductions expected in the passenger car sector and the 2W sectors. For example, among the motorized transport, Hong Kong experiences ~85-90% of the trips by public transport.

<u>*Scenario 04*</u>: This scenario is a mixed bag of assumptions for each of mode. Assuming a 30% reduction in the car trips is at the high end. For example, in a city like Stockholm, Sweden, with a full fledged public transport system, when the congestion pricing was introduced, only ~20% of reduction was observed. In case of the 2Ws, most likely the short trips along the main corridors are expected to shift to metro rail reducing ~20% of the trips.

<u>*Scenario 05*</u>: This scenario was developed under "target mode" via an optimization scheme fixed to achieve a combined 25% share of metro rail trips.

<u>*Scenario 05*</u>: This scenario was developed under "target mode" via an optimization scheme fixed to achieve a combined 30% share of metro rail trips.

Table 3: Estimated reduction & emissions under each scenario

	Avg. emissions	**tons/year**				
Scenario	**reduction (%)**	**PM_{10}**	**$PM_{2.5}$**	**SO_2**	**NO_x**	**CO_2**
Baseline		14,166	7,976	5,557	20,890	5,981,328
Scenario 01	20%	11,349	3,661	4,455	17,015	4,830,848
Scenario 02	33%	9,411	5,356	3,730	14,288	3,857,104
Scenario 03	54%	6,082	3,521	2,450	9,665	2,369,432
Scenario 04	29%	9,909	5,580	3,899	14,845	4,216,363
Scenario 05	34%	9,046	5,155	3,588	13,687	3,680,921
Scenario 06	40%	8,373	4,784	3,328	12,581	3,356,621

The scenarios present a spectrum of options, ranging from ~20% reduction to as much as ~54% reduction in the overall emissions. For a high share of metro trips, a large shift is required from all the major sectors and most will be dependent on the available transport facilities and public awareness.

Assumptions include

- Any change in the traffic patterns is not linear and is expected to have some trickle down effect of moving further NMT to motorized transport, especially in the short-distance category. A minimum of 10% change in the NMT patterns is assumed.
- No change in the emissions factors is included in the calculations. However, any improvement resulting in reduction of congestion on the roads is bound to increase some fraction of vehicular speeds and thus improving the on-road emission factors, and further leading to reduction in emissions.
- The metro rail is considered as a no-emission source. This is true as a local source, but not true as a pollution source. The electricity used to drive the metro-rail is generated using fossil fuels at a power plant, which results in some level of PM pollution and not included in this study. The study analysis is limited the on-road emissions and not the life-cycle emissions.
- In a city like, the fugitive dust forms a large part of PM sample, as evident from the source apportionment study presented in **Figure 4**, but not modeled in this study. A full scale study of all the emission sources in Delhi is underway and presented at a later time.

Air Pollution Modeling & Health Impacts

The air pollution modeling for this exercise was conducted utilizing the ATMoS dispersion model[27]. The emissions from the baseline and the six scenarios were distributed to a gridded domain presented in **Figure 7**. For the emissions distribution, population from the GPW-SEDAC was used at 2.5 min resolution. The 2W and 3W emissions were distributed closer to the Delhi metropolitan to represent short distance travel and the Cars and Bus emissions were distributed to the national capital region to represent long distance travel. The gridded emission files are also available for download.

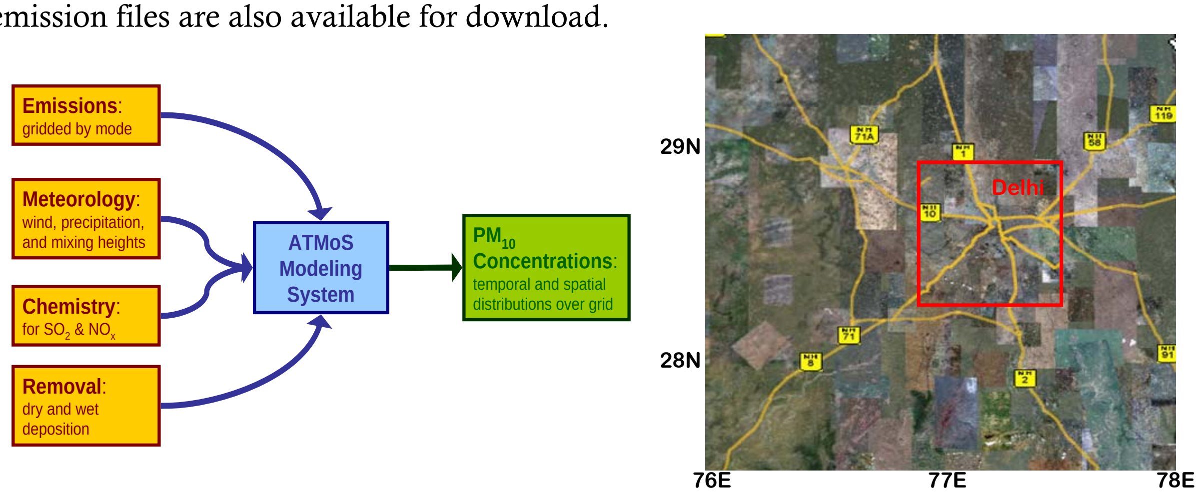

Figure 7: Dispersion model schematics and the modeling domain

[27] The dispersion model was conducted using the ATMoS lagrangian puff transport model described in SIM-air working paper No.30 "Simplified ATMoS-4.0" @ http://www.urbanemissions.info/simair/simseries.html

The concentration maps of $PM_{2.5}$ presented in **Figure 8** include both the primary and secondary contributions. The secondary contributions include sulfates and nitrates from chemical conversion of SO_2 and NO_x emissions. A key assumption in this analysis is the linearity in the pollution contribution from various sources. It is important to NOTE that the concentrations represent only the contribution of passenger travel emissions, presented in **Table 1** and the scenarios in **Table 2**, and these should NOT be construed as total pollution in the city. The pollution patterns are also dependant on the uncertainties in emission distribution schemes; this analysis, the emissions are weighted according to population distribution[28].

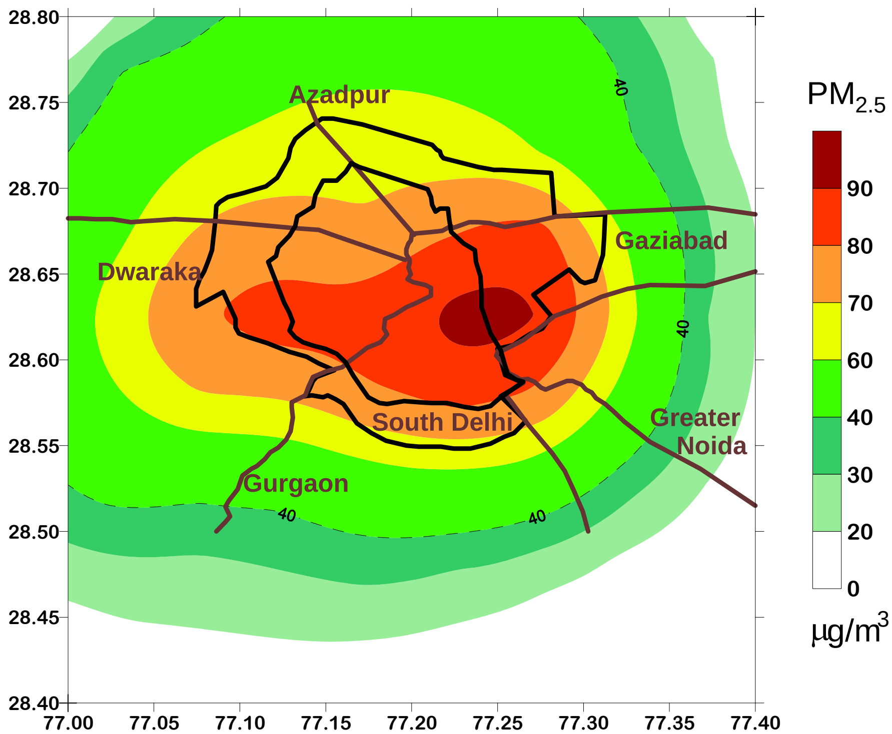

Figure 8: Modeled $PM_{2.5}$ concentrations due to passenger road transport emissions

The $PM_{2.5}$ pollution due to passenger travel forms a major part of the every pollution measured in the city (**Figure 2** and **Figure 4**). The domain average presented in **Figure 8** is ~53 µg/m^3. A recent monitoring campaign along the roads measured an average $PM_{2.5}$ concentration of 163 µg/m^3 over 160 km in one day[29]. The annual average presented in **Figure 2** range from 120-150 µg/m^3. According to **Figure 4**, the estimated contribution of motorized transport is ~30% of the measured samples in the city; equivalent of ~40-50 µg/m^3. The modeled results present a spread of pollution across the city, with hot spots around the ring roads. The highest spot is center for traffic junctions on the east side, which

[28] Global Population of the World (GPW, SEDAC) @ 2.5 minute resolution @ http://sedac.ciesin.columbia.edu/gpw/global.jsp

[29] "Monitoring & Mapping Urban Air Pollution: A One Day Experiment in Delhi, India", SIM-air Working Paper No.29 @ http://www.urbanemissions.info/simair/simseries.html

also includes two monitoring stations at Nizamuddin and ITO, with the measured pollution originating mostly from the transport sector.

The scenarios are also modeled using the same meteorological conditions as the baseline scenario and **Figure 9** presents the $PM_{2.5}$ concentration difference between baseline and scenario simulations. All the plots are mapped using same color codes for quick comparison. The reductions across the domain range from ~5μg/m^3 to ~63μg/m^3 (in Scenario 3); for varying degrees of reductions presented in **Table 2** and **Table 3**.

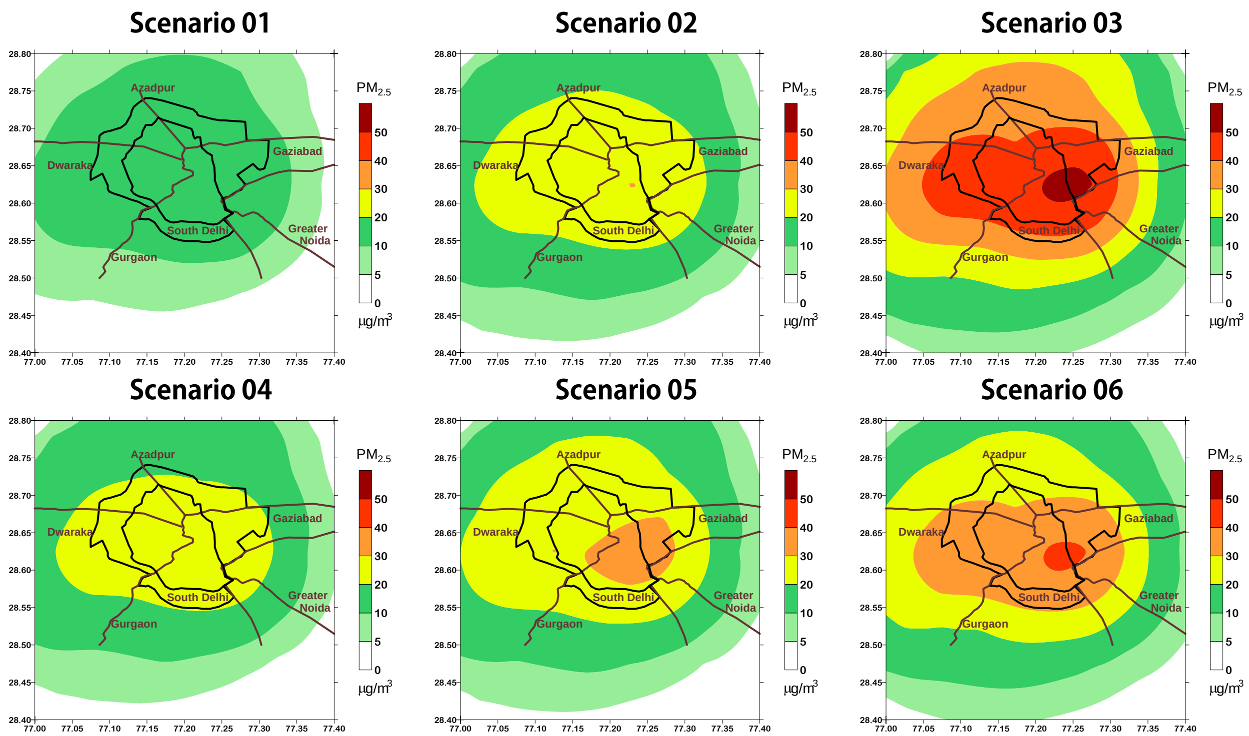

Figure 9: Modeled % reductions in $PM_{2.5}$ concentrations under various scenarios

The reductions are the highest when the passenger cars and 2Ws trips are substituted with the metro rail trips and the benefits are also visible in the scenario differences. The largest reduction in concentrations is ~63% on $PM_{2.5}$ in Scenario 3.

Health Impact Benefits

The estimated reductions in the concentrations were further analyzed for health benefits using the dose response functions for mortality and morbidity[30]. The Health Effects Institute (USA) conducted a detailed literature survey on the impact of outdoor air pollution on human health[31] includes an extensive list of references for follow-up on the dose response functions for various end points and methodologies to conduct epidemiological studies to develop these dose response functions. The following equation was utilized for estimating the health benefits under various scenarios and the results are presented in **Table 4**.

$$\delta E = \sum_{i=1}^{ngrids} \beta * \delta C_i * \delta P_i$$

Where,

$\delta E =$ number of estimated health benefits (of premature mortality and morbidity)

$\beta =$ the dose response function

$\delta C_i =$ the reduction in concentrations in each grid

$\delta P_i =$ the population exposed in each grid

Table 4: Health benefits – premature mortality & morbidity

	Premature Mortality	Estimated health costs saved (mil USD)	
Scenario	**Cases saved**	**Mortality**	**Morbidity**
Scenario 01	1,322	66	98
Scenario 02	2,205	110	163
Scenario 03	3,784	189	280
Scenario 04	2,052	103	152
Scenario 05	2,418	121	179
Scenario 06	2,963	148	219

For morbidity, eight health endpoints are included - adult chronic bronchitis, child acute bronchitis, respiratory hospital admissions, cardiac hospital admissions, emergency room visits, asthma attacks, restricted activity days, and respiratory symptom days. It is important to note that the analysis presented is ONLY for the health impacts of PM pollution. Other impacts like ground level ozone on health and agriculture yield, sulfur on agricultural crops

[30] The dose response function (DRF) various health endpoints as defined the change in number cases per unit change in pollution per capita. This is established via epidemiological studies conducted over a period of time, analyzing the trends in hospital records and air pollution monitoring. A summary of the dose response functions and detailed methodology is described in SIM-air working paper No.6, "Estimating Health Impacts of Urban Air Pollution" @ http://www.urbanemissions.info/simair/simseries.html

[31] HEI, 2004, "Health Effects of Outdoor Air Pollution in Developing Countries of Asia: A Literature Review" @ http://pubs.healtheffects.org/view.php?id=3

due to acid rain, etc., should be taken into consideration for full cost-benefit analysis and similar methodology can be applied to estimate those impacts.

The mortality and morbidity effects are further valuated using the "willingness to pay" methodology. The premature mortality cases were valued @ USD 50,000 (~Rs. 25 Lakhs). The estimated benefits (or savings) in health costs for the six scenarios (**Table 4**) range between 164 to 469 million USD due to reduction in $PM_{2.5}$ pollution from shifting motorized road transport to metro rail.

Policy Implications

The main impetus to consider improvements to public transportation systems can be distilled to distinct motivating factors for cities. They include

- *National/Global Events*: Hosting events that draw significant participants and tourists is one of the main catalysts in getting public transportation projects off the ground. For example, the Commonwealth Games in Delhi and Pune.
- *Citizen and Civil Society Activism*: A call to improve transportation systems by citizens and organizations is a powerful motivation for city governments, especially in areas where public systems have reached saturation points.
- *Planned Industrial and Urban Development*: Creation of satellite cities or industrial development areas is one way to ease pressure from the main city center. As an incentive to draw people to the new developments, public transport is improved to ease access. For example, Navi Mumbai was developed as a satellite area, at the same time the local rail and bus services to the area were considerably improved. Similarly, the metro rail system to "Dwarka" in Phase 1, to the west of Delhi.
- *Population growth and expanding city limits*: As cities grow in population, area, and with the increasing level of activity – infrastructure needs to improve and keep up with the demands on it. For example, Jaipur is in the process of improving its public transport as the city has grown.

While we recognize that ultimately transportation policy is a multi-faceted area that involves several departments and stakeholders, and cannot be determined by any single agency, we hope that these calculations would serve as indicators towards ensuring that policy is sustainable in every sense – social, economic, as well as environmental.

With urbanization and raising levels of industrial activity in India, public transport is a crucial aspect of urban planning. The JNNURM scheme has also identified 63 cities in India that need assistance in improving their road infrastructure. One of the prerequisites of assistance is however compliance with the National Urban Transport Policy – which calls for improvements in public transport and promotion of non-motorized transport options.

Figure 10 illustrates these differences in modal shares[32] and Mohan (2008) estimates that a large share of trips made in urban areas (especially in India) is less than 5 kms. This is a

[32] Mohan, D. (2008), « Mythologies, Metros & Future Urban Transport » TRIPP Report 08-01, New Delhi; Transportation Research and Injury Prevention Programme, Indian Institute of Technology, Delhi

short enough distance for city officials to promote options such as NMT or public transport. The shares across the various modes differ in cities depending on several factors. The scenarios discussed in this paper (**Table 2** and **Table 3**) resonate these shares.

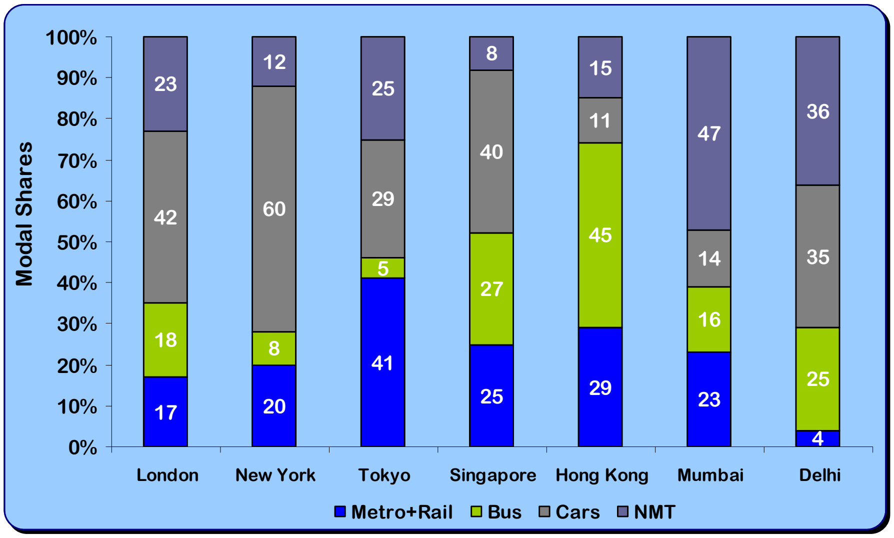

Figure 10: Percent share of trips in cities across the world

Despite such a high share of NMT, most public transport projects place much larger emphasis on improving infrastructure for private vehicles at the cost of neglecting the non-motorized sector. This is indeed regressive both environmentally as well as socially.

The metro rail operations are expected to increase the public transport share substantially, but this has to be conducted in conjunction to other modes. Most of the existing projects are considering the Bus Rapid Transport systems as one way to improve public transport. While in itself, this could work well and result in substantial improvements – implementation is crucial and it would work only with a parallel investment in infrastructure that promotes NMT, adequate bus fleet, and proper enforcement of bus, pedestrian and bicycle lanes. A city should hence consider a range of options and back them with institutional support.

The services of the public transport system, like the metro rail, and the number of buses should be increased to ply all major commuting routes to deal with the rising number of vehicles on our roads. The choice of public transport option will have an impact on the emission and air pollution levels of a city – apart from the social and economic impacts – as demonstrated in this paper.

In conclusion, the results of this study are intuitive. Policies that promote public transportation and allow for NMT result in lower pollution levels and lower greenhouse gas emissions. What is interesting however is quantifying the numbers. Promoting alternative transport options is not only environmentally sustainable but it is also a socially progressive policy. This study only captures the air pollution benefits, and does not even begin to quantify the various externalities that would spin off, including a more cohesive urban community, better health and equity.