Atmospheric Pollution Research 2 (2011) 99-105

Atmospheric Pollution Research

www.atmospolres.com

Air quality modelling study to analyse the impact of the World Bank emission guidelines for thermal power plants in Delhi

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ABSTRACT

Recent strategies for air pollution control in Delhi have largely neglected the emission reduction measures from thermal power plants (TPPs), which are the second most polluting sources. The present study investigates how the ambient air quality of Delhi would improve if the World Bank emission guidelines (WBEG) for the TPPs were to be implemented. To accomplish this, a comprehensive inventory of point, area, and line sources was conducted in the selected study area, primarily aiming to estimate the sectoral emission contributions to ambient air quality. The Industrial Source Complex Short–Term Model, Version 3 (ISCST3) was used to predict the ambient concentrations of total suspended particulates (TSP), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2) at seven monitoring sites (receptor locations) operated by the Central Pollution Control Board (CPCB) for the period from July 2004 to June 2005. The ISCST3 model predictions for TSP and NO_2 were satisfactory at all receptor locations. However, for SO_2, the model predictions were satisfactory at only two receptor locations. The vehicles contributed 58% of the total ambient air pollution, followed by TPPs contributing 30%. The study estimates that adoption of WBEG may reduce the ambient air pollution due to TPPs emissions by 56% to 82%, bringing it within the National Ambient Air Quality Standards (NAAQS) set for industrial areas in India, except at one location where TPP's contribution to ambient air pollution is negligible compared to vehicular emissions.

Keywords:
Emissions
Source apportionment
World Bank emission guidelines
Thermal power plants
Dispersion modelling

Article History:
Received: 20 April 2010
Revised: 20 August 2010
Accepted: 21 August 2010

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doi: 10.5094/APR.2011.012

1. Introduction

Delhi is one of the most polluted cities in the world due to its unrestricted growth (Khare and Kansal, 2004). Urban transport, manufacturing industries, and thermal power plants (TPPs) are the major sources of anthropogenic pollution (CPCB, 1995). As a consequence, the assimilative capacity of atmosphere is being stressed. To tackle the problem, a number of measures have been adopted in the past for the control of vehicular and manufacturing industry emissions. These include tightening vehicular emission limits, switching to cleaner fuels (i.e. unleaded gasoline, reduction of sulphur in diesel, reduction of benzene content in gasoline), phasing–out of old vehicles and maintenance of in–use vehicles, conversion of all buses and public transport vehicles to natural gas, introduction of Metro Rail, and closing or relocating polluting industries and industries operating in non–conforming areas (Khare and Kansal, 2004). However, in spite of these measures, the ambient air quality of Delhi does not comply with National Ambient Air Quality Standards (NAAQS) (Kandlikar, 2007). The situation calls for imposing stringent control measures on other air pollution sources, such as TPPs.

The remediation first requires a detailed understanding of sectoral emissions (point, area and line sources) and their contribution to ambient air pollution (source apportionment) and second, to predict the impact of regulatory interventions or stricter emission standards on ambient air quality. In the past, a number of source apportionment studies have been conducted in India (Kulshrestha et al., 1995; Meenakshy et al., 1996; Bandhu et al., 1998; Bandhu et al., 2000; Kumar et al., 2003). However, most of these studies have apportioned the total suspended particulates (TSP) using statistical methods based on principal component analysis and factor analysis. These methods are site specific and fail to generate what–if scenarios required for policy intervention analysis. In other studies, only mass emissions for various pollution sources are reported for Delhi (CPCB, 1995; Kandlikar and Ramachandran, 2000; Gurjar et al., 2004). All studies have identified vehicular and TPP emissions as the major contributor to air pollution in Delhi.

The World Bank (WB) has proposed some environmental guidelines for the TPPs in 1998 as a part of its pollution prevention and abatement handbook. The guidelines state maximum plant emission levels to be followed in achieving the site–specific emission standards to reduce pollution mass loadings to acceptable levels, achieve emission standards based on commercially proven and widely used technologies, and follow the current regulatory and technological trends. The present study analyses how the ambient air quality of Delhi would improve if the WB emission guidelines (WBEG) for the TPPs were to be implemented. This was done by estimating the sectoral emission contributions for TSP, sulphur dioxide (SO_2), and nitrogen dioxide (NO_2) in ambient air, and then estimating the reduction in ambient air pollutant due to TPPs under the WBEG guideline scenario. The

Industrial Source Complex Short–Term Model, Version 3 (ISCST3) was used to predict ambient concentrations of pollutants for the period from July 2004 to June 2005. ISCST3 is based on steady–state Gaussian plume algorithm, applicable for estimating ambient concentrations from point, area, and line sources up to a distance of 50 kilometres (http://www.epa.gov/scram001/). The Central Pollution Control Board (CPCB), an apex regulatory body in India, has accepted ISCST3 as a preferred model for regulatory studies (CPCB, 1998). Available input meteorological and emission data have led to the choice of ISCST3 model over other competing models. Further, the performance of ISCST3 for which, no studies have been undertaken for Delhi, was evaluated by comparing monthly estimated and observed concentrations at seven receptor locations such as Ashok Vihar, ITO, Shazadabagh, Janakpuri, Shahdara, Sirifort, and Nizamuddin using statistical model performance indices.

2. Description of the Study Area

Geographically, Delhi is 160 km south of the Himalayas, at an elevation of 216 m above mean sea level. It has a semi–arid climate with extremely hot summers, heavy rainfall in the monsoon season and very cold winters. The annual mean temperature is 25.3 °C and the annual mean rainfall is 715 mm (IMD, 1999). North–westerly winds normally prevail while in June and July, south–easterly winds predominate. Wind speeds are typically higher in summer and monsoon; in winters, calms are frequent. Pre–monsoon dust storms are westerly from the Great Indian Desert, carrying large concentrations of TSP into the ambient air of Delhi. Inversion conditions mostly prevail in winters, increasing the pollution concentration (CPCB, 2000). Delhi, with an area of 1 485 km^2, is inhabited by about 13.85 million people (population density 9 294 per km^2), of which 12.90 million are in urban areas (Census of India, 2001). Besides, various other urban pressures, such as industrial activity, transport infrastructure, construction activities and migration also confer a continued growth trend to Delhi. It has three coal based TPPs – the Rajghat, the Indraprastha (IP) and the Badarpur, and two natural gas (NG) based – the Indraprastha Gas Turbine (IGT) and the Pragati Power (see Tables S1 and S2 in the Supporting Material, SM). There are about 126 000 industrial units in Delhi (GNCTD, 1999). Delhi accounts for about 8% of the total registered vehicles in India (MoST, 1996).

3. Source Emission Inventory

TSP, SO_2, and NO_2 emissions from point, area, and line sources in the study area were computed and compiled for each month during the study period. Selection of SO_2, NO_2, and TSP as criteria pollutants is based on the rationale that: a) these are the significant pollutants emitted from TPPs, b) they are the only air pollutants which are subject to current Indian standards and WBEG, c) they are measurable/continuously monitored by regulatory authorities, d) changes in parameters can be predicted by the modelling process.

3.1. Emissions from TPPs – business–as–usual (BAU) scenario

Monthly emissions from TPPs during the study period were obtained from Central Electricity Authority (CEA), Delhi Pollution Control Committee (DPCC), and individual TPPs. At Rajghat and IP TPPs, only TSP and SO_2 are monitored, whereas, in gas–based TPPs, only NO_2 is monitored as emissions of TSP and SO_2 are very low. At Badarpur TPP, all the three pollutants i.e. TSP, SO_2 and NO_2 are monitored. The NO_2 emissions from other coal–based TPPs were estimated using an emission factor of 2.64 kg/ton for coal, whereas, NO_2 emissions from fuel–oil consumption were estimated using an emission factor of 7.5 kg/ton (CPCB, 1994). Fuel–oil is used as an auxiliary fuel in coal–based TPPs. For gas–based TPPs, the emission factors for TSP and SO_2 were taken as 0.008 g/m^3 and 0.0096 g/m^3, respectively (TERI, 1992). Average emission characteristics of TPPs are shown in Table 1.

Table 1. *Average emission rates and characteristics of TPPs*

TPP	Temperature[a] (K)	Exit velocity[a] (m/s)	TSP (g/s)	SO_2 (g/s)	NO_2 (g/s)
Rajghat[c]	366.4	4.0	22.3[a]	73.2[a]	21.5[b]
IGT[d]	384.0	1.6	0.36[b]	0.1[b]	12.6[a]
IP[d]	402.1	8.2	14.5[a]	45.1[a]	28.8[b]
Badarpur[c]	401.7	25.2	237.9[a]	1 233[a]	405.4[a]
Pragati[c]	372.0	2.3	0.7[b]	0.08[b]	23.8[a]

[a] *Values taken from DPCC and CEA records for actual in field monitoring*
[b] *Values derived from emission factors and specific fuel consumption for the given month*
[c] *Average of 12 months of two stacks*
[d] *Average of 12 months of three stacks*

3.2. Emissions from industries

A door–to–door survey was conducted between May 2005 and July 2005 in 27 recognized industrial estates of Delhi to ascertain the type of industries, number of air polluting industries, their production capacities, types and quantities of fuels used, air pollution control devices installed, and stacks (i.e., heights and diameters) and emission characteristics (see Tables S3 and S4 in the SM). Most of the industries are small–scale, clustered together and operated on a plot area of approximately 200 m^2. The average stack height is approximately 2.5 m above the roof, or about 11 m from the ground. Industries in Delhi mostly use conventional blast cupola, having low blast rate and pressure. The hood for collecting gases is 1.5 to 1.8 m above the source (cupola). As a result, fugitive emissions from cupola are high, resulting in low emission concentrations of pollutants from stacks. Table 2 presents the emissions from recognized industrial areas of Delhi (Kansal, 2006).

Table 2*. Estimated average emissions from representative stacks in industrial areas*

Industrial area	Temperature (K)	Exit velocity (m/s)	Stack Diameter (m)	TSP (g/s)	SO_2 (g/s)	NO_2 (g/s)
Okhla PhI	356	7	1.2	0.21	0.08	0.04
Okhla PhII	352	5	1.1	0.11	0.05	0.03
Okhla PhIII	357	4	1.4	0.16	0.05	0.03
Smaipur	346	7	0.9	0.11	0.03	0.02
Badli	345	6	1.4	0.32	0.10	0.06
Udyog Nagar	367	5	0.8	0.06	0.03	0.01
Zakhira	341	8	0.7	0.09	0.02	0.01
Shazadabagh	350	6	0.6	0.04	0.02	0.01
Jhilmil	353	8	1.0	0.19	0.08	0.05
Najafgarh	341	7	1.1	0.15	0.05	0.03
Nangloi	352	6	0.8	0.06	0.02	0.01
Naraina	343	5	1.3	0.20	0.07	0.02
Wazirpur	354	4	2.2	0.42	0.15	0.06
S.M.A	340	8	0.7	0.06	0.03	0.02
Rajasthan	347	9	0.5	0.05	0.01	0.01
S.S.I	351	7	0.4	0.05	0.02	0.01
Mayapuri	355	6	1.4	0.33	0.2	0.08
Narela	356	5	1.5	0.34	0.15	0.07
Patparganj	359	4	0.5	0.05	0.01	0.01
Kirti Nagar	350	7	0.9	0.09	0.05	0.02
Viswas Nagar	362	6	1.0	0.11	0.03	0.02
New friends colony	341	8	0.8	0.05	0.01	0.01
Mohan cooperative	347	3	0.5	0.05	0.02	0.01
Mangolpuri PhI	346	4	0.8	0.07	0.02	0.01
Mangolpuri PhII	353	7	0.8	0.08	0.02	0.01
Bawana	349	6	0.7	0.06	0.02	0.01
Alipur	346	3	0.6	0.10	0.02	0.01

3.3. Emissions from vehicles

A 24–hour traffic volume count survey was conducted during the study period with the help of trained manpower. Depending on the traffic volume, a number of enumerators were allocated to count different categories of vehicles independently for the same period. The traffic volume count was done for two days – one weekday and one Sunday – of every month during the study period of 12 months. Average hourly vehicle flow was then calculated using a weighted mean over the weekend and weekday data. Similarly, average vehicle speed was estimated on the day of monitoring by doing trial runs where an enumerator with a stopwatch was allowed to sit in each vehicle category in 6 hours rotation. The time required to travel a distance of one kilometre by the vehicle was used to estimate the average vehicle speed. Therefore, the average vehicle speed includes the idling time of the vehicle at bus stops as well as at traffic intersections. Emission factors (g/km) for pollutants from different vehicle categories were taken from Kandilkar and Ramachandran (2000) (see Table S5 in the SM). Table 3 shows the pollutant emissions from roads near receptor locations (Kansal, 2006).

Table 3. *Pollutant emissions (g/s) from roads*

Receptor station	TSP	SO_2	NO_2
ITO	33.4	0.42	8.60
Shazadabagh	8.80	0.04	2.60
Janakpuri	6.4	0.50	2.60
Ashok Vihar	2.5	0.10	2.10
Shahdara	24.4	1.15	7.60
Sirifort	21.9	0.12	7.70
Nizamuddin	14.1	0.04	6.70

3.4. Emissions from area sources

A door–to–door household survey (sample size of 700) in the study area was conducted to obtain data on consumption of cooking fuel (see Table S6 in the SM). Emission factors for Indian cooking chulhas (household stoves) are taken from TERI (1997), Reddy and Venkataraman (2002) and USEPA (2000) (see Table S7 in the SM). Equation (1) was used to estimate emissions from household stoves:

$$P_j = \sum_{i=0}^{n}\left(\left(F_i \times EF_{ij} \times C_i \times H\right)/86400\right) \quad (1)$$

where, P_j is the emission of pollutant j (g/s); F_i is the consumption of fuel per fuel type (i) (kg/day/household); EF_{ij} is the emission factor of pollutant j per unit of fuel (i) consumed (g/kg); C_i is the percentage of households consuming fuel (i); H is the total number of households; and n is the number of fuel types.

The Ministry of Statistics and Program Implementation (MSPI), Government of India has reported that 492 g of solid waste is produced by one person per day (MSPI, 2000). Shah and Nagpal (1997) have reported that municipal solid waste burning is one of the major sources of ambient air pollution in India. In Delhi, approximately 10% of the municipal solid waste generated is burned in the open (Pachauri and Batra, 2001). Equation (2) was used to estimate total emissions of pollutants as a result of open solid waste burning using emission factors of 37 g/kg for TSP (Economopoulos, 1993), 1.7 g/kg for SO_2 (EEA, 2001), and 1.8 g/kg for NO_2 (EEA, 2001).

$$P_j = \left(492 \times 0.1 \times p \times EF_j\right)/86400 \quad (2)$$

where, P_j is the emission of pollutant j (g/s); p is the human population; EF_j is the emission factor of pollutant j (g/kg).

Table 4 gives the estimated pollutant emissions from household fuel consumption and domestic refuse burning in various administrative zones of Delhi.

The fugitive emission contributions to the ambient air pollution from solid waste laden truck movements and existing landfills were taken from a study conducted by the National Environment Engineering Research Institute, Nagpur, India (NEERI, 1996).

3.5. Background concentrations

Kumar (2005) has reported the annual average background concentration of TSP in Delhi as 40 $\mu g/Nm^3$ and that of SO_2 and NO_2 as negligible. These values were used in the present study.

3.6. Emissions from TPPs under the WBEG scenario

Table 5 compares existing Indian and WBEG for TPPs. WBEG for TSP are much more stringent than existing Indian standards (TERI, 1998). The adoption of WBEG, therefore, will affect the ambient TSP in Delhi. The WBEG for SO_2 are concentration based, whereas, Indian standards are based on the stack height. The Indian coal has low sulphur contents (0.2–0.3%) compared to imported coal, where the sulphur content is in the range of 0.6–1.5% (NTPC, 1995). The adoption of WBEG for TPPs may not affect ambient SO_2 concentrations significantly. The existing Indian standards are more stringent than WBEG for NO_2. As a consequence, the adoption of WBEG is not likely to affect significantly the ambient NO_2 concentrations unless they exceed the existing emission norms.

Table 4. *Estimated pollutant emissions (g/s) from household fuel and refuse burning*

Site No.	Name of the administrative zone	TSP		SO_2		NO_2	
		Fuel	Refuse	Fuel	Refuse	Fuel	Refuse
1	City	1.48	12.00	1.79	0.55	14.55	0.59
2	Central	3.49	28.40	4.22	1.30	34.32	1.38
3	Civil Lines	2.58	21.00	3.12	0.96	25.35	1.02
4	Cantonment	11.04	2.80	0.41	0.13	3.31	0.13
5	Karol Bagh	7.15	33.50	2.00	0.62	16.23	0.65
6	Najafgarh	4.79	39.00	5.80	1.79	47.13	1.90
7	Rohini	3.73	30.3	4.50	1.39	36.62	1.50
8	NDMC	0.79	6.50	0.96	0.30	7.84	0.32
9	Sadar Paharganj	1.02	8.33	1.24	0.38	10.07	0.40
10	Shahdara North	4.64	37.76	5.62	1.74	45.65	1.84
11	Shahdara South	4.08	33.16	4.93	1.52	40.08	1.61
12	South	3.03	24.60	3.66	1.13	29.74	1.20
13	West	4.28	34.80	5.17	1.60	42.05	1.69
14	Narela	1.44	11.7	1.74	0.54	14.02	0.70

Table 5. *Indian and the WBEG for TPPs*

Pollutant	**Capacity**	**Indian standards**	**WBEG**	**Control options**	**Main concerns**
TSP	Less than 200/210 MW	350 mg/Nm^3	50 mg/Nm^3	Existing technologies (ESP or bag houses to achieve emissions below 50 mg/Nm^3	Fine particulate: PM_{10} and $PM_{2.5}$
	200/210 MW and above	150 mg/Nm^3	If not achievable, 99.9% removal efficiency	Coal cleaning	
SO_2	Less than 200 MW	$H=14Q^{0.8}$ m	2 000 mg/m^3	Use of gas or low sulphur fuels	Local impacts of SO_2 and sulphates on health
	200 MW and less than 500 MW	220m stack height	Maximum level 0.2 TPD per MW up to 500 MW plus	Furnace sorbent injection (30-60% removal)	
	500 MW and above	275m stack height	0.1 TPD per MW for each additional MW over 500 MW	Dust injection, dry or wet scrubbers (up to 95% removal), or fluidised bed combustion (up to 95% removal)	Long range transport-acidification and visibility
NO_2	All existing units	150 ppm at 15% excess oxygen	750 mg/Nm^3 (coal) 460 mg/Nm^3 (oil) 320 mg/Nm^3 (gas)	Low NO_x burners with or without other combustion modifications	Contribution to creation of ground level ozone, acidification and visibility impacts
	New units >400MW	NG - 50 ppm Naphtha – 100 ppm			
	100-400 MW	NG - 75 ppm Naphtha – 100 ppm		Re-burning, Water/steam injection	
	<100 MW	NG - 100 ppm Naphtha - 100 ppm		Selective catalytic or non catalytic reduction	

ESP- electrostatic precipitator; Q - emission rate of SO_2 in kg/h; ppm - parts per million; TPD - tons per day; MW – mega watt.

Table 6. *Estimated emissions (g/s) from TPPs under the WBEG scenario[a] (July 2004 - June 2005)*

Month	**TSP from Rajghat**		**TSP from Badarpur**		**SO_2 from Badarpur**	**NO_2 from Badarpur**	**TSP from IP**		
	Stack 1	**Stack 2**	**Stack 1**	**Stack 2**	**Stack 1**	**Stack 1**	**Stack 1**	**Stack 2**	**Stack 3**
July	4.65	4.89	27.32	29.12	1 102	409.86	6.09	3.04	3.09
August	4.67	4.65	27.45	29.15	1 107	411.72	6.07	3.06	3.08
September	4.67	4.73	28.05	29.13	1 132	420.82	6.10	3.05	0[b]
October	4.65	4.99	27.40	29.17	1 105	411.05	6.09	3.07	3.10
November	4.64	0	27.42	29.20	1 106	411.21	3.05	3.06	3.13
December	4.89	4.9	20.64	29.19	832	309.54	6.10	3.04	3.09
January	4.94	4.95	27.73	29.21	1 119	415.93	6.08	3.04	3.08
February	4.78	4.99	22.15	29.17	894	332.31	0[b]	3.03	3.12
March	4.68	4.96	27.58	29.17	1 113	413.74	6.10	3.04	3.09
April	4.66	4.97	27.56	29.14	1 112	413.57	3.06	0[b]	3.10
May	4.65	0	27.61	29.15	1 114	414.25	6.09	3.05	3.13
June	4.5	4.96	27.53	29.16	1 110	412.90	6.09	3.05	3.11

[a] *Only those emissions are reported where the emission characteristics changed under WBEG scenario*
[b] *not in operation*

The TSP and SO_2 emissions from TPPs under WBEG scenario were considered to be 50 mg/Nm^3 and 2 000 mg/Nm^3, respectively (for TPPs < 200 MW capacity), and additional SO_2 emissions of 0.2 tons per day (TPD) (for TPPs up to 500 MW capacity) with further increment of 0.1 TPD (for TPPs > 500 MW capacity). The NO_2 emissions under WBEG scenario were considered as 750 and 320 mg/Nm^3 for coal and gas–based TPPs, respectively. The stack emission characteristics (e.g. stack diameter, release height, gas velocity and temperature), power generation and fuel consumption patterns were assumed equivalent to existing. Further, the existing emissions are considered to be operational under the WBEG scenario, wherever the stack emission characteristics under the WBEG scenario are greater than the existing emissions. Therefore, the TSP, SO_2 and NO_2 emissions in gas– based TPPs are considered same as existing because the adoption of WBEG may cause an increase in their emissions. The SO_2 and NO_2 emissions in all coal based TPPs are considered to be the same as existing except in Badarpur TPP. Table 6 gives emissions from different stacks of TPPs under the WBEG scenario.

4. Methodology

The modelled atmospheric conditions in the study area are defined in the meteorological pathway pre–processed by Rammet View package (see Table S8 in the SM). The hourly–average meteorological data for observations such as wind speed and direction, temperature, humidity, cloud cover, mixing and ceiling height were collected from Indian Meteorological Department (IMD), for the study period. IMD monitors meteorolo-gical parameters at two locations in Delhi, i.e. Palam and Safdarjang. Between these two, the study has used Safdurjang data, which is closer to the receptor locations and emission sources. The prevailing wind direction of Delhi is Northwest in all seasons except for monsoon, when it is East–South–East.

The model performance was evaluated by comparing the monthly estimated and observed values at seven receptor locations using coefficient of determination (R^2) and index of agreement (d) (Willmott et al., 1985). R^2 represents the percentage of the variability explained by the model. Models with R^2 above 55% are considered to be satisfactory, with less than 30% as suspect, and above 75% as excellent (Woodfield et al., 2003). Similarly, the index *d* determines the relation of observed deviations with respect to the estimated deviations about the mean observed value (Rao et al., 1985). Being dimensionless and having the limits of 0.0 (indicating no agreement) and 1.0 (indicating perfect agreement), *d* may be viewed as a standardized (by the variability in the predictions and observations about the observed mean) measure of mean square error.

5. Results and Discussions

5.1. Model performance and sectoral contribution

Figure 1 shows scatter–plots for respective pollutants at all receptor locations. The R^2 for TSP at all receptor locations taken together is 0.789 and *d* is 0.90. The model predictions were satisfactory at Janakpuri (R^2 = 0.906, *d* = 0.965), ITO (R^2 = 0.671, *d* = 0.838), Ashok Vihar (R^2 = 0.618, *d* = 0.835) and Nizamuddin (R^2 = 0.578, *d* = 0.716). The model predictions were also satisfactory for NO_2 receptors Shazadabagh (R^2 = 0.819, *d* = 0.946) and Sirifort (R^2 = 0.571, *d* = 0.397). When all receptor locations were considered together, the model predicted NO_2 concentrations satisfactorily (R^2 = 0.778 and *d* = 0.922). However, the model failed to explain the variance for SO_2 satisfactorily (R^2 = 0.058, *d* = 0.313) at an aggregate level except at two locations, Janakpuri (R^2 = 0.671, *d* = 0.894 and Shahdara (R^2 = 0.708, *d* = 0.91), where the predictions were satisfactory (see Tables S1–S11 in the SM). This may be due to different traffic volumes and composition at these receptors (at Shahdara, 16 708 diesel trucks per day, which is 9.8% of the total traffic volume; and at Janakpuri, 7 846 trucks per day, which is 5.7% of traffic volume). As a result, a significant amount of SO_2 is emitted into the ambient atmosphere. Besides, these receptors are located downstream of the prevailing wind direction of the major roads (Kansal, 2006).

Table 7 describes source specific details at various receptor locations. The background concentration for TSP was taken as 40 μg/Nm^3 and zero for SO_2 and NO_2 as estimated by Kumar (2005). Vehicular emissions are the major sources of TSP (54%), followed by TPPs (32%), background concentration contributes 13%, and industries contribute 1%. For SO_2, the major contributors are TPPs (67%) and vehicles (33%). Further, vehicles and TPPs contribute 90% and 10% of NO_2, respectively. Overall, vehicles contribute 58.5% of the total air pollution, followed by TPPs, which contribute 30%. The contribution of vehicular emissions to ambient air pollution levels is high due to the large traffic count, low release height, proximity to the monitoring stations and restricted dispersion due to street canyon effects.

5.2. Impact of WBEG on air quality of Delhi

Table 8 shows average annual ground level concentrations (GLCs) of pollutants at receptor locations from TPPs under BAU and WBEG scenario. Adoption of WBEG by TPPs can reduce ambient pollutant (TSP, SO_2 and NO_2) concentrations between 56% and 82%. The reduction is primarily due to decreases in ambient TSP levels. The stringent WBEG for TSP (when compared to CPCB standards) motivate TPPs to use beneficiated coal, gas, and/or adopt efficient pollution control devices (Table 5). The WBEG for NO_2 are not stringent compared to existing CPCB standards. However, some reduction in NO_2 concentration is observed under the WBEG scenario due to less emission from Badarpur TPP. The stack is emitting about 10–20% excess NO_2 emissions compared to the prescribed emission norms (150 ppm/v). The adoption of WBEG for SO_2 has negligible effect in reducing its ambient concentrations at all receptor locations, as Indian coal has lower sulphur content (0.2–0.3%). Table 9 shows estimated ambient concentrations of the pollutants at various receptor locations under WBEG scenario, which is within the NAAQS as specified for industrial areas in India i.e. 360 μg/m^3 for TSP, and 80 μg/m^3 for NO_2 and SO_2 (CPCB, 2001). However, at the ITO receptor location, adoption of WBEG has minimal effect on reduction of ambient TSP concentrations, since the dominant pollution source is vehicular exhaust.

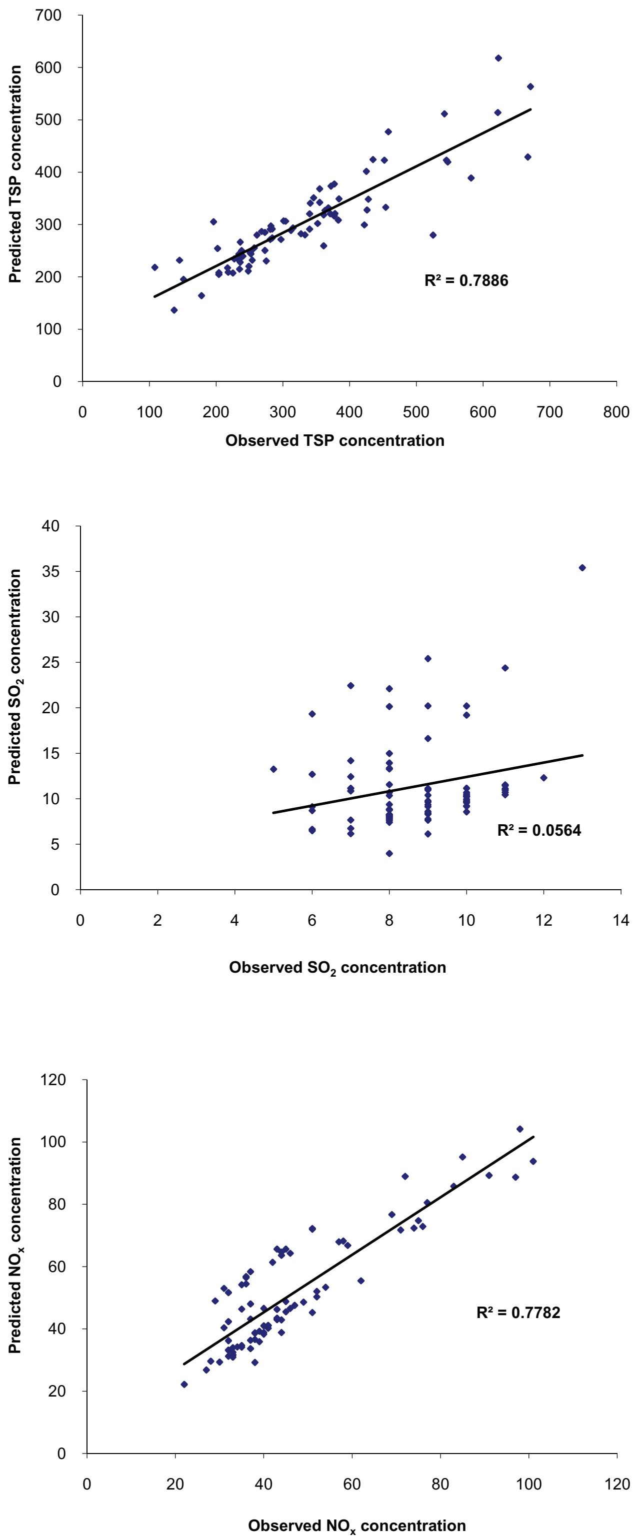

Figure 1. *Scatter plots for various pollutants at receptor locations (concentrations in μg/Nm^3).*

Table 7. *Estimated annual average ground level concentrations (μg/m³) of pollutants at various receptor locations from various sources*

Location	TSP					SO_2				NO_2			
	TPPs	Ind.	Veh.	B	Total	TPPs	Ind.	Veh.	Total	TPPs	Ind.	Veh.	Total
ITO	63.8	1.5	326.5	40	431.8	6.3	0.03	3.6	9.9	10.8	0.02	74.1	84.8
Shahzadabagh	120.6	2.2	110.8	40	273.6	7.6	0.06	2.9	10.5	3.4	0.03	40.0	43.4
Janakpuri	57.8	0.8	180.2	40	278.7	2.9	0.01	7.1	10.00	3.2	0.01	42.2	45.3
Ashok Vihar	125.7	2.5	109.4	40	277.6	9.3	0.04	2.1	11.5	4.2	0.02	46.7	50.9
Shahdara	22.9	2.9	193.8	40	259.6	1.6	0.05	7.4	9.1	0.7	0.04	44.0	44.8
Sirifort	110.5	1.3	143.7	40	295.4	6.3	0.01	3.2	9.5	2.8	0.01	45.2	48.1
Nizamuddin	168.1	2.3	66.4	40	276.7	19.2	0.04	0.1	19.3	11.0	0.03	31.5	42.6

Ind.- industries, Veh.- vehicles, B- background

Table 8. *Average annual GLCs (μg/m³) of pollutants at CPCB air quality monitoring stations in Delhi due to TPPs emissions*

Site No.	Pollutant	BAU scenario	WBEG scenario	Percent reduction
		ITO		
1	TSP	63.8	20.6	67.8
2	SO_2	6.3	6.1	2.1
3	NO_2	10.8	7.6	8.1
		Shazadabagh		
1	TSP	120.6	14.0	88.4
2	SO_2	7.6	6.7	11.4
3	NO_2	3.4	3.1	10.3
		Janakpuri		
1	TSP	57.8	9.3	83.9
2	SO_2	2.9	2.7	6.6
3	NO_2	3.2	2.6	17.8
		Ashok Vihar		
1	TSP	125.7	14.5	88.4
2	SO_2	9.3	7.8	16.7
3	NO_2	4.2	3.5	15.7
		Shahdara		
1	TSP	22.8	4.6	79.8
2	SO_2	1.6	1.6	2.4
3	NO_2	0.7	0.7	6.9
		Sirifort		
1	TSP	110.5	14.5	86.9
2	SO_2	6.3	5.6	11.0
3	NO_2	2.8	2.5	11.0
		Nizamuddin		
1	TSP	168.1	27.0	83.9
2	SO_2	19.2	17.2	10.0
3	NO_2	11.0	9.2	16.6

6. Conclusions

The ISCST3 model was estimated TSP and NO_2 concentrations satisfactorily. However, for SO_2, the model yielded satisfactory results only at two receptor locations, Shahdara and Janakpuri. This is because these receptor locations have a higher density of diesel vehicles on the roads, emitting a significant amount of SO_2 into the atmosphere. The industrial sector contribution to the receptor locations is less, due to the Government's initiative to either close or relocate the industries out of the Delhi city–limits following the Indian Supreme Court directives or strict vigilance pursuing the polluters to adopt efficient pollution control devices and cleaner fuels. In the domestic sector, liquefied petroleum gas (LPG) consumption has almost doubled when compared to 1990/91, and kerosene consumption has dropped by 20%, decreasing the total emission load from domestic sources (GNCTD, 1995; GNCTD, 1999).

Table 9. *Estimated ambient concentration of the pollutants (μg/m³) at various monitoring stations in Delhi under the WBEG scenario*

Site No.	Name of the location	TSP	SO_2	NO_2
1	ITO	453.0	7.9	82.7
2	Shahazadabagh	188.5	8.6	43.4
3	Janakpuri	237.7	9.6	41.5
4	Ashok Vihar	162.9	6.4	43.4
5	Shahdara	280.0	8.3	35.3
6	Sirifort	254.1	7.6	34.1
7	Nizamuddin	157.3	7.5	41.1

The implementation of WBEG shows a significant reduction in TSP concentrations, thus bringing TSP within the NAAQS as specified for industrial areas in India (CPCB, 2001). There is a small reduction in ambient NO_2 concentrations, which is attributed to reduction in emissions of NO_2 from one of the TPPs, i.e. the Badarpur. Impact of WBEG on SO_2 levels is not significant, since the Indian coal has already lower sulphur content, and the current emissions are not affected significantly under the WBEG scenario. The significant reduction in TSP emissions under the WBEG scenario from the TPPs is noteworthy, since targeting the transport sector alone for pollution abatement may not help significantly in achieving the end result of improving the ambient air quality of Delhi, particularly with respect to the TSP concentrations.

Acknowledgements

We thank Dr. M.P. George (Senior Scientist, DPCC), Mr. S.K. Nanda (Deputy Director, CEA), and Mr. V.P. Garg (Deputy General Manager, NDPL) for sharing the emission data for TPPs and industries. We also thank M.Sc. students of batch 2003–05 of GGS Indraprastha University, Delhi for helping in conducting the traffic surveys.

Supporting Material Available

Characteristics of TPPs in Delhi (Table S1), CPCB ambient air quality monitoring stations and their locations (Table S2), Number of air polluting industries in Delhi (Table S3), Stack emission characteristics of industries in Delhi (Table S4), Emission factors (g/km) for pollutants from different vehicle categories (Table S5), Domestic cooking fuel consumption pattern in Delhi (Table S6), Emission factors for cooking stoves (Table S7), ISCST3 input values and assumptions (Table S8), Comparison of estimated and observed GLC for TSP and model performance indices (Table S9), Comparison of estimated and observed GLC for SO_2 and model performance indices (Table S10), Comparison of estimated and observed GLC for NO_2 and model performance indices (Table S11). The information is available free of charge via the internet at http://www/atmospolres.com.

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