Sailesh N. Behera, Jayprakash Rout, Mukesh Sharma And Prashant Gargava / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622
www.ijera.com Vol. 3, Issue 4, Jul-Aug 2013, pp.2278-2294

Development and Evaluation of Control Strategies for Reduction of Ambient PM_{10} Levels in Urban Environment: Application of GIS and Dispersion Modeling

Sailesh N. Behera[1], Jayprakash Rout[2], Mukesh Sharma[3] And Prashant Gargava[4]

[1]Department of Civil and Environmental Engineering, NUS- 117411, Singapore
[2]Wipro Technologies, Bangalore- 560035, India
[3] Department of Civil Engineering, Indian Institute of Technology Kanpur- 208016, India
[4]Central Pollution Control Board, Delhi -110032, India

ABSTRACT

Geographic information system (GIS) based emission inventory of particulate matter of aerodynamic diameter less than 10 µm (PM_{10}) for the base, 5th and 10th year was developed for Kanpur, an urban area in India. It has been observed that the 5th and 10th year will experience increased emission by factors of 1.5 and 2.2 of the base year. Twenty one control options (e.g. introduction of Euro 6 to vehicles, banning of 15 year old private vehicles, use of natural gases as fuels for industries etc.) were considered for evaluation. The effectiveness of each control option was assessed in terms of PM_{10} reduction potential using Industrial Source Complex Short Term (ISCST3) model. A total of four control scenarios were developed as combination of several control options and these scenarios were evaluated for their effectiveness. The evaluation process through air quality modeling revealed that the control scenario comprising control options of: (i) implementation of Euro 6 for vehicles, (ii) compressed natural gas (CNG) to commercial and public vehicles, (iii) banning of 15 year old private vehicles, (iv) particulate control systems in industries etc., was found to be most effective in reducing the ambient PM_{10} levels that could attain 24 hr average air quality standard.

Keywords: Air quality management, particulate matter of aerodynamic diameter less than 10 micron, Scenario development, Control option, Euro 6, Geographical Information System

I. INTRODUCTION

Air pollution is recognized as a serious public health problem [1, 2] and it is on rise in developing economies like India due to growth of population, urbanization, industrialization and transportation [3–5]. With the intent to control air pollution, the countries promulgate regulations both in terms of emission and air quality standards. Formulation of standards alone cannot improve the air quality unless it is backed up with a cost-effective and technologically feasible air pollution control action plan. Among air pollutants, particulate matter (PM) is of special interest in the current researches due its significant role in atmospheric visibility reduction through the formation of haze, human health effects and climate change from the regional to global scale [6, 7]. This paper describes a methodology for developing and evaluating an air pollution control action plan, which is meaningful and accounts for future emissions. The focus of control action plan and development of strategies in this paper is on particulate matter of aerodynamic diameter less than 10 µm (PM_{10}) using an air quality dispersion model.

The specific methodology for air pollution control action plan has been demonstrated for the City of Kanpur (Latitude 26°26′ N and Longitude 88°22′ E; Figure 1; population 4.0 million, 2001 census), India. In the past, several studies had investigated about the insights of air quality in the study area [8–12] and these studies concluded that very high particulate pollution prevails throughout the year (24 hr average PM_{10} levels: 50–600 μgm^{-3}). The study area is a city with large proportion of population in the low economic strata which is vulnerable to higher particulate exposure. From global context on status of air pollutants, it may be noted that there are several cities like Kanpur in India and in other developing countries (e.g. Lucknow, Varanasi, Patna, Kolkata, Dhaka, and Lahore). Therefore, approaches made in this study can be emulated by other cities similar to the study area to reduce particulate pollution.

In spite of social, economical, political and legal constraints, air pollution control strategies can be developed if convincing scientific arguments can be put forward. This requires quantification of ground-level pollutant concentrations and linkage of these concentrations to the impacting sources through meteorology. It is important for the strategies to be time sensitive so that the action plan ensures attainment of air quality standards in future. Air quality monitoring and modeling are the principal activities involved in air quality assessment and preparation of action plans [12 –16]. Air dispersion modeling is widely used to estimate the ground-level pollutant concentrations and in preparation of air pollution control strategies [12, 17]. Most countries have adopted a standard modeling procedure for regulatory purposes; Industrial Source Complex Short Term (ISCST3) model of the U.S. Environmental Protection Agency (USEPA) is widely used [18, 19].

From the literature reviews, it is evident that ISCST3 has been used in several air-quality modeling studies in the past [20 – 25]. However, these studies are limited to model validation and prediction of ambient air pollution levels from a specific source. Previous studies [14, 26] utilized the capabilities of ISCST3 to assess contribution of various source emissions towards ambient levels of air pollutants. Huang et al. [15] investigated the PM_{10} source apportionment with Comprehensive Air Quality (CAMx) model in Beijing for finding contributions of various sources contributing to PM_{10} level. Kardis et al. [16] predicted inorganic components of PM_1 (fine) and PM_{1-10} (coarse) through simulation using CAMx model and estimated the effect of mineral dust on the formation of secondary inorganic aerosol in Mexico City Metropolitan area. Im et al. [27] predicted spatial distribution of PM_{10} composition in Istanbul using the high resolution WRF/CMAQ (Community Multiscale Air Quality) modeling system. Im et al. [27] concluded that the contributions of local sources are significant towards PM_{10} and they recommended the need of control strategies focusing on primary particulate emissions. Our previous study, Behera et al. [12] was concerned with dispersion modeling of PM_{10} by utilizing the capabilities of ISCST3 to find contributions of different primary sources to PM_{10}.

From the above cited studies on dispersion modeling and to the best of our knowledge, it could be inferred that no study has attempted to develop, evaluate and propose control action plan for reduction of PM_{10} from primary sources keeping the future emissions in view. The novelty of the present work is in demonstrating a systematic and powerful methodology utilizing the entire capability of ISCST3 to provide relative importance of specific source impacts and integrate the various source specific control options leading to a comprehensive air pollution control plan. This will require examining the efficacy of control options (using ISCST3) and combining the options into various scenarios. The scenario analysis is the basic approach among other analyses (e.g. cost-benefit analysis and cost-effectiveness analysis) for evaluating efficacies of alternative emission reduction options [28, 29]. The scenario which ensures compliance with air quality standards and is most effective in air quality improvements can be accepted by the community [30, 31].

The specific objectives of the present study were: (i) development of GIS-based emission inventory of $PM_{10,}$ for the base year and future years (i.e., the 5th year and 10th year from the base year), (ii) identification of various control options and assessment of their efficacies for air quality improvements, and (iii) development of scenarios (through the combination of control options) and selection of an effective and optimal scenario that ensures attainment of the air quality standards. To achieve these objectives, the present study was performed in Kanpur, India from December 1, 2007 through January 31, 2008. This is to be noted that objectives of the present study were part of the scopes of a project that aimed to arrive at policies that will reduce air pollution in megacities of India and the project was sponsored by a regulatory body in India, Central Pollution Control Board (CPCB), Delhi.

II. MATERIALS AND METHODS

Figure 2 describes the steps to arrive at proposed control plan for particulate pollution. Gridded digitized maps with various thematic layers (e.g. road maps, population maps) are generated in ArcGIS and air pollution source activity data (e.g., location, population, production, fuel use, height of release, temperature, etc.) for area, line and point sources are collected from field surveys. To get the future prediction of PM_{10} emissions, the activity data are projected for the 5th and 10th year from the base year. The emission factors along with the activity data are used to develop GIS-based emission inventories of PM_{10} for the base, 5th and 10th year. In the next step, efficacy of each of the control options is examined (using ISCST3 model) for its sensitivity to reduce ambient air pollution. Control options with better capabilities for PM_{10} reductions are combined to generate control scenarios. Then the efficacies of these control scenarios are examined by using ISCST3 to arrive at options that are able to reduce PM_{10} levels substantially.

2.1 The study area

Kanpur city is a large industrial city having cotton, leather and wool industries of small and medium scales with a total area of about 270 square kilometer. The source activities of air pollution in the city can be broadly classified as: transport, commercial, industrial, domestic and institutional activities, and fugitive sources. At several places in the city, garbage burning (mostly in the evening) is a common practice, which can be an important contributor to air pollution. Winds in the study area are generally light and are mostly from directions between south-west and north-west.

2.2 GIS-based emission inventory of PM_{10}

2.2.1 GIS and emission estimation methodology

The Geostatistical Analyst extension of ArcGIS (ArcMap, version 9.2; ESRI Inc., Redlands, WA, USA) was used for this study because of its relative user friendliness and its frequent use by local authorities and research institutes for air pollution management [12, 32]. The topographical map, issued by the Survey of India (SOI) (prepared in 1977) having scale of 1:50,000 was geo-coded as the base map in the form of polygons for geo-referencing the other maps. This base map was transformed to Universal Transverse Mercator projection with Everest 1956 as the datum. The other three maps, (a) land use, (b) road and railway intersection (from Central Pollution Control Board (CPCB), New Delhi, India), and (c) ward (smallest political unit in a city) boundary (from Kanpur Municipal Corporation) were geo-referenced. Various thematic layers of gridded maps (2 km x 2 km) were generated in GIS (e.g., road maps, population map). All these sources were broadly classified into three categories: (1) point sources, (2) area sources, and (3) line sources. For details on source categorization, activity data survey, selection of emission factors and emission estimation equations, [12] can be referred. However, in this paper we have given one general equation (Eq(1)) that represents the overall estimation approach of PM_{10} emissions from various sources. The total emission in the grid was estimated using Eq(1):

$$\text{Emission}=\sum_{\text{source\_cat}}(\text{Activity data}_{\text{source\_cat}})\times(\text{Emission factor}_{\text{source\_cat}}) \quad (1)$$

Where, Emission is the emission of PM_{10} from a specific identified source category, Activity $\text{data}_{\text{source\_cat}}$ is the amount of the specific source category that generates emissions, Emission $\text{factor}_{\text{source\_cat}}$ is the emission factor of PM_{10} from that particular source category (i.e. emissions per unit of activity data utilized).

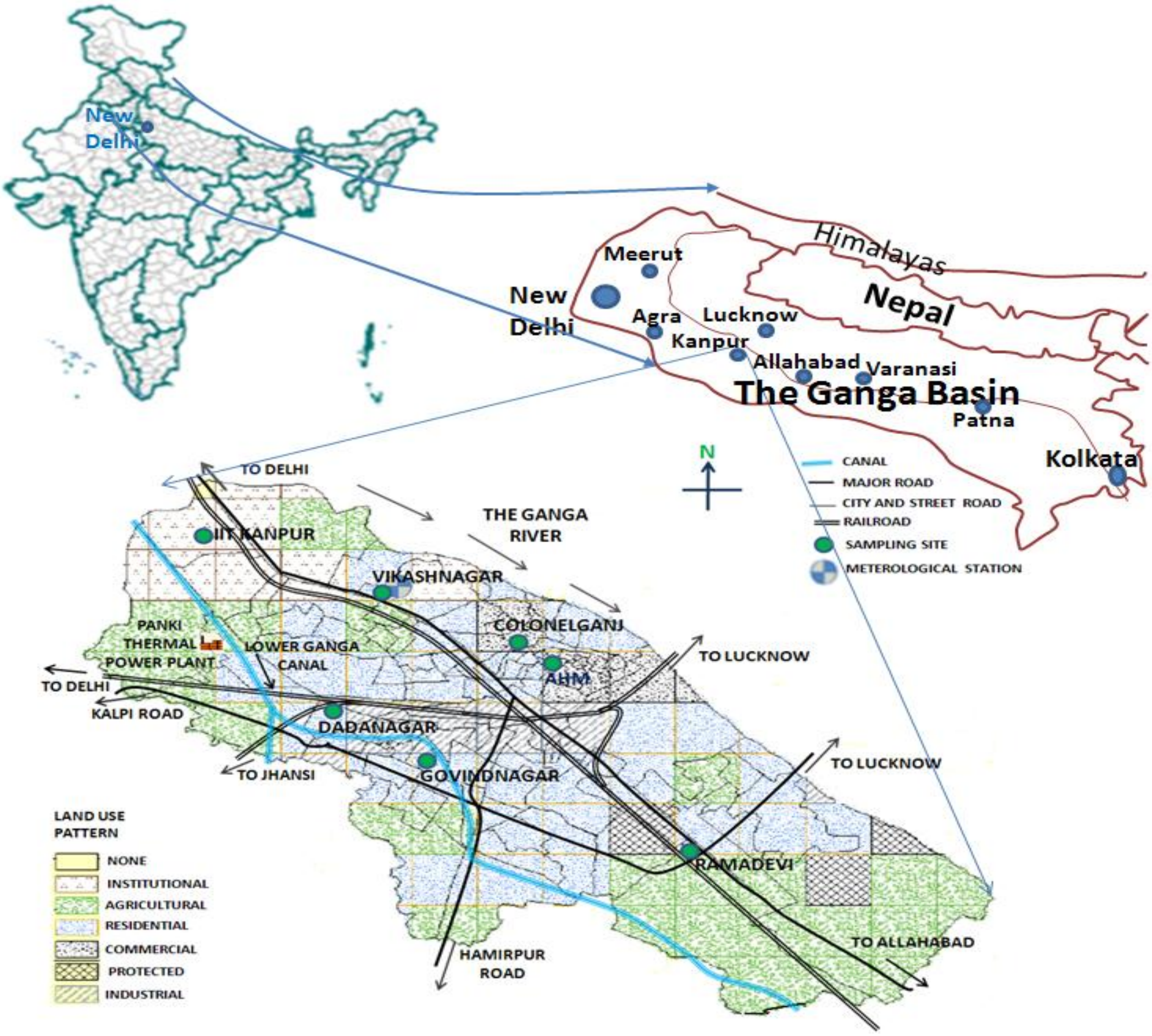


Figure 1. The Ganga basin, India and study area, Kanpur city with sampling sites on a gridded map (2 km × 2 km) showing land-use patterns

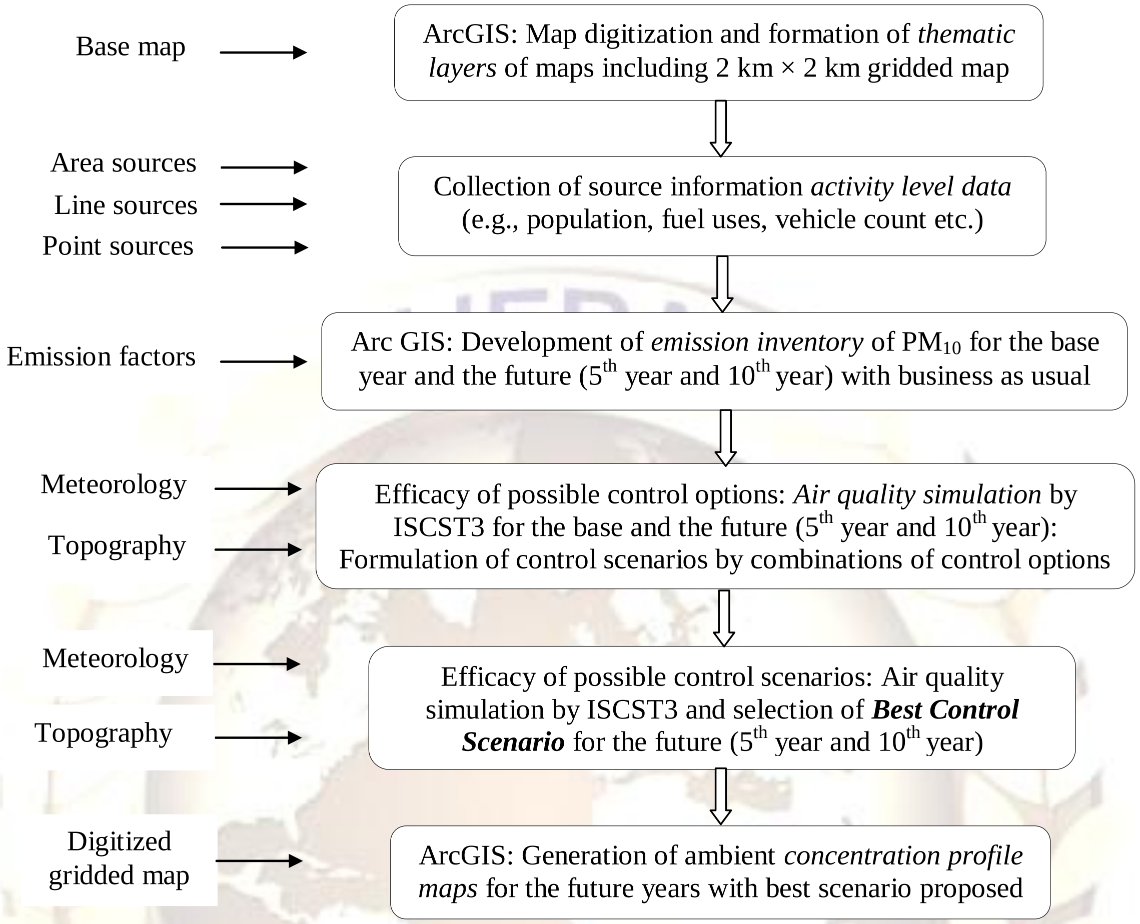


Figure 2. Summary of the steps for methodology of the study

2.2.4 Business as usual (BAU) emission inventory

In the development of emission inventory, it was considered 2007 as the base year, 2012 as the future 5th year, and 2017 as the future 10th year assuming that the source specific activity levels will grow following the current trends. This projected emission inventory of PM$_{10}$ was referred to as having obtained from BAU scenario. In Kanpur city, the vehicles and population are growing rapidly (annual growth: 13% for vehicles and 2.8% for population; Census India 2011) and the industrial growth is negligible. The vehicle registration records for the last five years were obtained from the Regional Transport Office, Kanpur and based on vehicular growth rate, the numbers of vehicles in different categories were projected for the future years. The study assumed the population growth is spatially independent. The activity data for most of the area sources (e.g. domestic cooking, garbage burning) were predicted following the population growth rate. In reference to the projected source activity data, emission inventory was developed in each grid for the future years. In the subsequent sections on discussions, these emission inventories will be referred to as ‘Emission BAU base year’, ‘Emission BAU 5th year’ and ‘Emission BAU 10th year’.

2.3 Air-quality monitoring and modeling of PM$_{10}$

2.3.1 Air quality monitoring

For assessment of air quality status and validation of dispersion modeling, air quality monitoring was undertaken at seven sampling sites (Figure 1). The duration of sampling was from December 1, 2007 to January 31, 2008 in the winter season. The Partisol® model 2300 4-channel speciation samplers (Thermo Fisher Scientific Inc., USA) were used to collect air through an inlet (at a flow rate of 16.7 LPM) that removes particles with aerodynamic diameters greater than 10.0 µm; the remaining particles (i.e. PM$_{10}$) were collected on the Teflon filter (Whatman grade PTFE filters of 47 mm diameter) and mass concentration of PM$_{10}$ was determined gravimetrically following the standard operating procedures [33]. Filter paper exposure for each sample was 8 hr. Reporting and interpretation of results in this paper have been done on the basis of a 24 hr average data. Meteorological parameters (temperature, relative humidity, wind speed and wind direction) were recorded using a wind monitor (WM251 Envirotech, New Delhi, India).

2.3.2 Dispersion modeling

Keeping in view the industrial, vehicular, road dust, domestic and fugitive sources, meteorology, topography and data availability, USEPA model ISCST3 model was identified as an appropriate model for prediction of ground level concentration of PM_{10} [34]. The model is based on Gaussian dispersion plume algorithm derived from steady state assumption in three-dimensional advection diffusion equation. The ISCST3 model is a popular model among the modelers and it has unique features such as the capability to handle polar or Cartesian co-ordinates, simulate point, area and volume sources, considers wet and dry deposition, makes terrain adjustments, building downwash consideration, etc. For details of ISCST3, readers can refer to [34, 35].

The input data to the model were receptor site information (location), meteorological and detailed characteristic of the source emission. The detailed characteristics of source emission include pollutant emission rate, flue gas exit velocity and temperature, stack height and its top inner diameter. Meteorological data include wind speed and direction, ambient temperature, atmospheric stability class and mixing height. In this study, PM_{10} concentrations were predicted at eighty-five receptor locations (one in each grid of 2 km × 2 km). Although ISCST3 does not take into account the secondary sources, but the control of primary sources will indirectly reduce the secondary formation. The reason may be due to the fact that the precursor gases responsible for formation of secondary particle formation (e.g., nitrogen oxides, sulfur dioxide, ammonia, volatile organic compounds) will be controlled, when there will be decrease in emission of primary sources [27].

2.3.2 Performance evaluation of dispersion model

The model performance is tested by comprehensive statistical analyses [12, 18, 22, 36]. These include: (i) fractional bias (*FB*), (ii) normalized mean square error (*NMSE*), (iii) coefficient of correlation (*r*), and (iv) index of agreement (*d*). The expressions for these statistical measures are as follow:

$$FB = \frac{\left(\bar{O} - \bar{P}\right)}{0.5 \times (\bar{O} + \bar{P})} \qquad (6)$$

$$NMSE = \frac{N^{-1} \sum_{i=1}^{N} (O_i - P_i)^2}{\bar{O} \times \bar{P}} \qquad (7)$$

$$r = \frac{N^{-1} \sum_{i=1}^{N} (O_i - \bar{O})(P_i - \bar{P})}{\sigma_o \times \sigma_p} \qquad (8)$$

$$d = 1 - \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(\left| P_i - \bar{O} \right| + \left| O_i - \bar{O} \right| \right)^2} \qquad (9)$$

Where, the terms P_i and O_i are the predicted and observed PM_{10} concentration, $\bar{O}$ and $\bar{P}$ are mean of observed and predicted PM_{10} concentrations, σ_o and σ_p are the standard deviations of observed and predicted concentrations of PM_{10} in a data set.

2.4 Development of control options

There is a need to explore control options with respect to technological feasibility and management viability pertinent to each source for reducing the levels of PM_{10}; a list of control options (21 numbers) considered is presented in Table 1. The growth scenario trends revealed that the vehicular sources will be the dominating polluting source in the future. Therefore, more possible control options were considered for vehicular emissions in this study. These control options mentioned in Table 1 were tested to check their efficacies in reducing levels of PM_{10} concentration. For this purpose, the modeling exercise was performed through ISCST3 and the details of this simulation exercise is discussed in Section 3.3.

III. RESULTS AND DISCUSSION

3.1 BAU Emission inventory of PM_{10}

The spatial distributions of PM_{10} emissions from all identified sources are demonstrated in Figs. 3(a), (b) and (c) under the BAU activities for the base, 5th and 10th year, respectively. The clear observations were made with emissions that it will increase dramatically in the 10th year as compared in the 5th year. In spatially distributed maps, it was also observed that the high pollution areas were identified as the city centre and the industrial area, where most of the pollution activities and congestion problems exist. The overall assessment at city level revealed that the total emission will be increased by a factor of 1.5 in 5th year and by a factor 2.2 in 10th year of the base year. It can be seen in Figure 3 that the area emitting PM_{10} in the range of 251-500 kg/day was 8 km^2 in the base year and for the same emission range, the area will be increased to 12 km^2 in the 5th year and 20 km^2 in the 10th year. The major increase in emission from the base year to the future years has been seen from vehicular sources.

The BAU emissions in the base and the future years with details of contributions of identified sources to the total emission are presented in Table 2. In the base year, the highest emission was from the industrial point sources, mainly from a 200 MW coal-based thermal power plant (Panki thermal power plant; Figure 1). In the 5th and 10th year, vehicles will be the predominant source contributing 24% and 29% to total PM_{10} emission loads (compared to 20% in the base year). Similarly next to vehicles, domestic cooking and road dust will be among the top contributors to PM_{10} in the 5th and 10th year. The estimated emission suggests that there are many important sources and a composite emission abatement including most of the sources will be required to attain the desired air quality.

Table 1. Details of possible particulate control options with their reduction efficiencies in emission factors

Option No.	Details of control option	Expected % reduction in emissions factor (EF) of PM_{10}	Details of possible implementation scheme in the future years[+]
Option- 1	Implementation of Euro 5 norms	80% reduction of emissions in comparison to the Euro 4 standard	Euro 3 is in progress for the base year, Euro 4 to be implemented from 3rd year, Euro 5 will be possible from 8th year
Option- 2	Implementation of Euro 6 norms	No difference between Euro 5 and Euro 6 for PM_{10} (NOx reduction is more in Euro 6)	Euro 6 will be possible from 8th year, if proposed
Option- 3	Electric vehicles introduction	100% PM_{10} reduction (Zero emissions)	Share electric vehicles as total fleet of city as: 1% of 2W, 5% of 3W, cars and public buses by the 5th year , and 2% of 2W, 10% of 3W, cars and public buses by 10th year
Option- 4	Compressed natural gas (CNG) to commercial and public vehicles	EF reduction by 75% as compared to Euro 3	25% conversion by 5th year 100% conversion by 10th year
Option- 5	Bio-diesel (B5/B10: 5 – 10% blend)	EF reduction by 10% of the existing stage	Share of biodiesel fuel to 5% by the 5th year and 10% by 10th year
Option- 6	Retro fitment of diesel oxidation catalyst (DOC)	EF reduction by 22.5 % compared to Euro 3	25% conversion by 5th year and 100% conversion by 10th year to 4 wheeler public transport city buses
Option- 7	Retro fitment of diesel particulate filter (DPF)	EF reduction by 70% compared to Euro 3	25% conversion by 5th year and 100% conversion by 10th year to 4 wheeler public transport city buses
Option- 8	Inspection/ maintenance (I and M) of vehicles	EF reduction as compared to Euro 3: public transport vehicles and 3W – 12.5%, 4-W (diesel) –7.5%	New I & M regulation introduced and compliance by 50% anticipated by 5th year and 100% anticipated by 10th year
Option- 9	Banning of 15 year old private vehicles	100% reduction of off-road vehicles	Old vehicles of 15 years or older to be banned by 5th year and 10th year
Option- 10	Improvement of public transport	Improvement of public transport: % share on VKT of 4W cars, 2W bikes and buses	10% shift in VKT by 5th year and 20% shift in VKT by 10th year
Option- 11	Industry fuel change	EF reductions by 100% for natural gas to be used as fuel	Change solid fuels to natural gas by 5th year
Option- 12	Particulate control system (PCS) in industry	Particulate control systems have 95% collection efficiency of PM	Implementation of use of particulate control system such as cyclone, bag filter (BF) etc. by 5th year
Option- 13	Shifting of air polluting industries to out of the city	Deduction of emission load from shifted industries	50% air polluting industries shifted out by 5th year and 100% air polluting industries shifted out by 10th year
Option- 14	Domestic-use of liquefied petroleum gas (LPG)	Appropriate EF to be used	50% of solid fuel, kerosene to be shifted to LPG by 5th year, and 75% of solid fuel, kerosene use to be shifted to LPG by 10th year
Option- 15	Inspection and maintenance (I and M) of large DG sets	EF reductions by 15%	Strict compliance to be followed for proper inspection and maintenance by 5th year
Option- 16	Adequate supply of grid	Zero emissions from DG sets	50% power from DG sets by 5th year and 100%

	power		power (0% from DG sets) from grid power by 10th year
Option- 17	Better construction practices	EF reductions by 50%	50% reduction from construction activities in 5th year and 10th year
Option- 18	Converting unpaved roads to paved roads	Appropriate EF for emissions from respective roads to be used	Conversion of 50% unpaved roads to paved by 5th year, 100% unpaved roads to paved by 10th year
Option- 19	Wall to wall paving with brick	EF reduction by 15% on paved roads and by 40% on unpaved roads	Applied to major roads by 5th year, Applied to major roads and minor roads with heavy traffic by 10th year
Option- 20	Sweeping and watering (S and W) (mechanized)	EF reduction by 20% on paved roads and by 50% on unpaved roads	Applied to major roads by 5th year, Applied to major roads and minor roads with heavy traffic by 10th year
Option- 21	Strict compliance to ban of open burning	Suitable EF reductions to be used	50% compliance to be achieved by 5th year and 100% compliance to be achieved by 10th year

*2W for two wheeler motor bikes, 3W for three wheeler auto and tempo, DG sets for diesel generator;
+the future year is with respect to the base year (e.g., 5th year means, the future 5th year from the base year)

Table 2 BAU emissions in the base year and the future for PM_{10}

Particular of source	Base year		Future 5th year		Future 10th year	
	ton day^{-1}	% of total	ton day^{-1}	% of total	ton day^{-1}	% of total
Industry (point source)	2.9	25	2.9	17	2.9	11
Industry (area source)	0.8	7	0.8	5	0.8	3
Vehicles	2.3	20	4.1	24	7.3	29
Domestic cooking	2.1	18	3.4	20	5.5	22
Paved and unpaved road dust	1.6	14	3.0	17	5.0	20
Open burning[1]	1.0	9	1.5	9	2.3	9
Hotel and restaurant uses	0.4	4	0.7	4	0.9	4
DG sets	0.1	1	0.4	2	0.6	2
Rest other sources[2]	0.2	2	0.3	2	0.4	2
Total	11.4	100	17.1	100	25.6	100

[1]Open burning includes: garbage and agricultural waste; [2]Rest other sources include: bakery, construction and demolition and medical waste incinerators

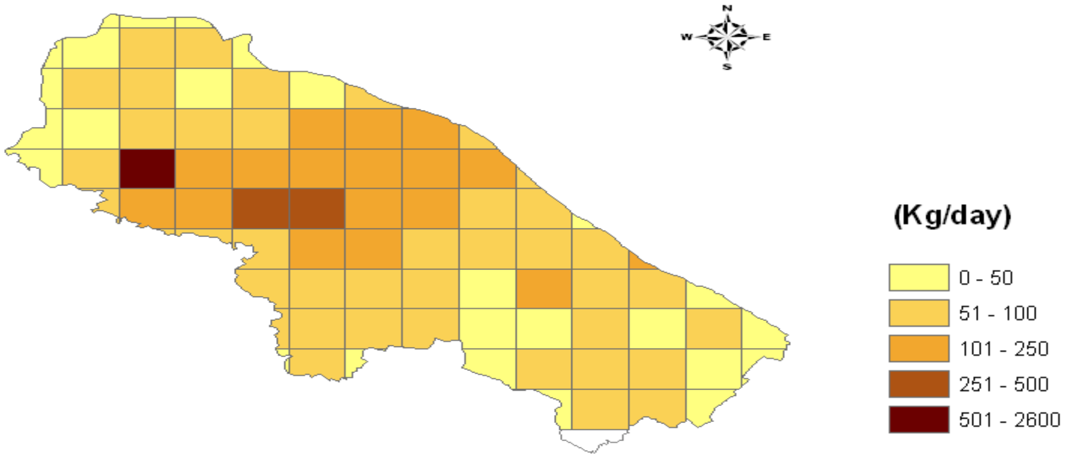
3.2 Ambient air quality status and dispersion modeling

3.2.1 Ambient air quality status

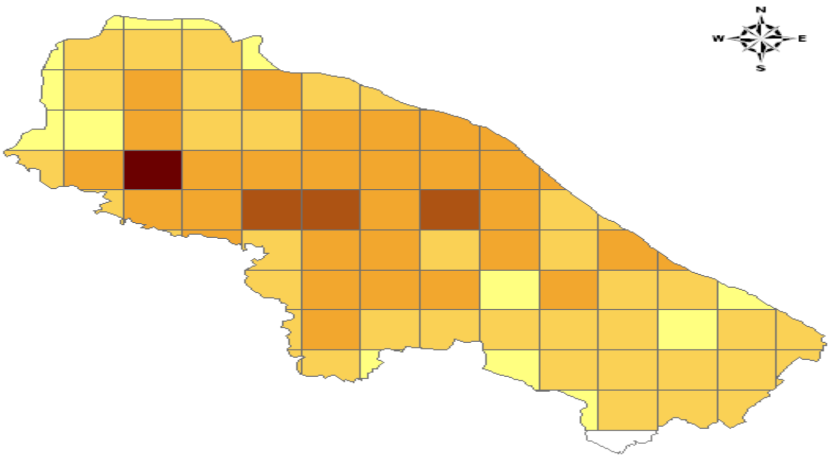
Table 3 presents the 24 hr average observed ambient concentration (mean, standard deviation and number of observations) of PM_{10} mass at seven sampling sites. The average mass concentration of PM_{10} at IIT Kanpur site was the lowest as 196 μgm^{-3} and the highest 24-hr average PM_{10} concentrations were observed at Dadanagar site (industrial site) as 396 μgm^{-3}. The pollution levels were very high at all sites, as 24 hr Indian Standard of 100 μgm^{-3} was not attained. These monitoring results suggest that various control options (Table 1) for reductions of PM_{10} should be explored for their effectiveness.

The meteorological parameters observed during the monitoring program were prevailing wind direction as west and north-west and wind speed as 0.83 ± 0.54 ms^{-1} [37]. The average ambient temperature was 13.51 ± 4.63°C and the relative humidity was 68.54 ± 19.12%. Mixing height varies between 200 m (midnight) and 1600 m (midday) [37]. The atmospheric stability remains unstable, moderately unstable and slightly unstable during daytime and neutral, slightly stable and stable during nighttime [12, 37, 38].

(a) Emission BAU: the base year



(b) Emission BAU: the future 5th year



(c) Emission BAU: the future 10th year

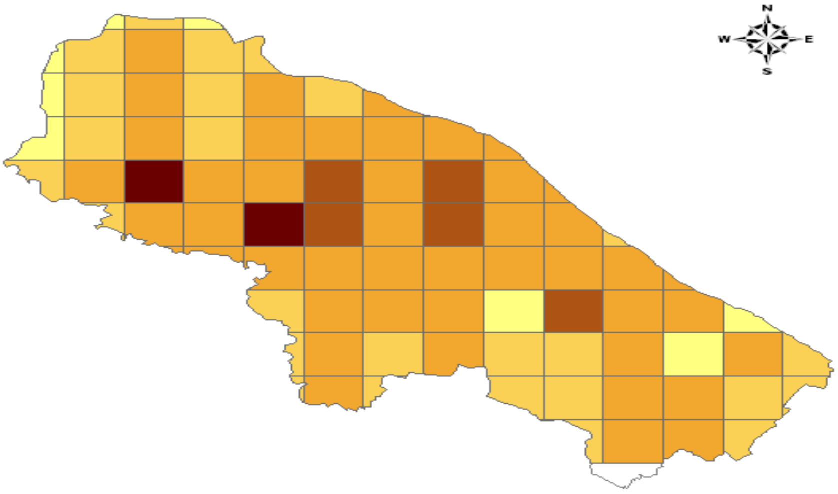


Figure 3. PM_{10} Pollution Load over the City (2 km × 2 km) with Emissions BAU for: (a) the base year (b) the future 5th year (c) the future 10th year

3.2.2 Performance evaluation of dispersion model

For the purpose of model validation, the air quality simulations were carried out using ISCST3 model at seven monitoring sites for the days of measurements. Predictability of ISCST3 model for ambient PM_{10} levels was examined using four statistical parameters (Eqs 6 to 9: Section 2.3.2) by comparing the observed concentration with predicted concentration at seven locations. It has been observed that: (i) values of *FB* are in the range between 0.29 and 0.61, (ii) *NMSE* levels are in the range between 0.28 and 0.62, (iii) *r* varies from 0.64 to 0.78, and (iv) estimated values of *d* are in the range between 0.49 and 0.79 for winter.

The parameter *FB* uses the arithmetic concentrations and indicates the tendency and the sign of the deviation. This is a nonlinear operator that varies between -2 and +2 and has an ideal value of 0 for best model performance ([18, 12] Abdul-Wahab et al. 2003; Behera et al. 2011). A negative *FB* value indicates that model over-predicts and positive value suggests under prediction. In this study, overall values of *FB* is positive, i.e., 0.48 indicating under prediction of PM_{10} concentrations. It has been suggested that preference of *NMSE* over *FB*, which is an unbiased dimensionless statistic and measures the random spread of the values around the mean; i.e., deal with variance or scatter ([20] Kumar et al. 1999). Smaller values of *NMSE* indicate better model performance and a general accepting criterion is: $NMSE \leq 0.5$. In this study, the overall average value of *NMSE* of summer and winter was estimated to be 0.38 and it is reasonable to assume that model performance is satisfactory.

The coefficient of correlation (*r;* Eq. 8) between observed and predicted values is another independent indicator of model performance. In this study the overall *r* was found out to be 0.72 (statistically significant at 5% level of significance) indicating linear association in observed and predicted concentrations. The index of agreement is used because the coefficient of correlation (*r*) cannot account for additive differences or differences in proportionality ([39] Brazell et al. 1993; [36] Dutot et al. 2007). The overall value of *d* was found to be 0.66 and it independently suggests that model is adequate for application and decision making. Figure 4 shows model performance for a large data set of 174 observations. The lines of 1:1, 1:2 and 2:1 agreement between observed and predicted concentration are also shown in Figure 4. Overall, the statistical analyses substantiate that the model can describe physical phenomena well and can be applied for further interpretation and application, limitation being the fact that the model under predicts. This issue of under prediction might be due to the fact that secondary particle formation is not taken into account by the model.

3.3 Evaluation of efficacy of control options

For the purpose of evaluating the efficacies of control options, ISCST3 modeling simulations were performed by considering all emitting sources in the city and highest 150 receptor concentrations exceeding the air quality standards were considered. These grids were considered as critical grids requiring a strategy to control pollution through combination of various control options. The objective is to ensure attainment of air quality standard for PM_{10} in these critical grids. Needles to say that if standard is attained in these critical grids, standard will be attained in the entire city. Figure 5a shows an example of the simulation results in critical 10 grids with their identification numbers. These identified grids will be addressed further. Figure 5b shows predicted ambient PM_{10} levels with BAU activities in the base, 5th and 10th year in these critical grids. It has been observed that in the base year, estimated PM_{10} concentration (in these 10 grids) varied from 158 to 395 μgm^{-3}; average source contributions (to concentrations) were as follows: vehicles (22%), domestic cooking (20%) and road dust (16%). In the 5th year, concentration could range from 216 to 530 μgm^{-3} with contributions from vehicles (29%), domestic cooking (22%) and road dust (17%). In the 10th year, concentration range could be between 280 and 687 μgm^{-3} with contributions from vehicles (35%), domestic cooking (24%) and road dust (18%). It is seen that Kanpur is a highly polluted and the city is distressed under high PM_{10} pollution and massive efforts are required to reduce PM_{10} levels. One needs to know not only relative strength of contributing sources but also examine which control option and combination of options will be most effective.

To test the efficacy of control options (Table 1), modeling was performed twice: with and without the control option for each source (keeping other sources as being absent) and impact on PM_{10} air quality is assessed in 10 critical grids. The modeling results were specifically examined in terms of percent reduction (in PM_{10}) caused by the control option. By doing this, the impact of each control option was estimated in terms of its effectiveness for improving air quality from various sectors (i.e., vehicles, industries, road dust, domestic cooking, open burning and other area sources). Table 4 presents the modeling results on efficacy of individual control option.

Out of 10 vehicular control options, it is noted that control options1 and 2 are having same potential in reduction of PM_{10}. However control option- 2 (introduction of Euro 6) could be preferred over control option 1 (introduction of Euro 5), as control option- 2 will additionally reduce NOx by 55% and hydrocarbons (HCs) + NOx by 26% [37, 40]. This is to be noted that HCs are precursors of ozone formation. From the evaluation results, it could be inferred that the best 4 control options in terms of reduction efficiency of PM_{10} concentration for vehicular sources are: (i) control option- 9; banning of 15 year old private vehicles (30.3% in 5th year and 23.4% in 10th year), (ii) control option- 7; retro fitment of diesel particulate filter (30.3% in 5th year and 27.9% in 10th year), (iii) control option- 4; CNG to commercial and public vehicles (14.7% in 5th year and 40.3% in 10th year), and (iv) implementation of Euro 6 (7.4% in 10th year). It is to be noted that the potential in reduction of PM_{10} levels by these control options are not the same for the 5th and 10th year. The reason could be due to the fact that the growths of vehicles are different for different categories of vehicles.

Among the options meant for industries, most effective options for reduction of ambient PM_{10} levels are: (i) control option- 12; introduction of particulate control system (98.5% in the 5th year and 10th year), and (ii) control option- 11; industry fuel change to natural gas (74.1% in the 5th and 10th year).

For the sources of domestic cooking, control option- 14; use of LPG in place of solid and liquid fuel, could be the effective in reducing ambient PM_{10} levels from this source by 38.8% in 5th and 54.5% in 10th year.

Among the control options for reductions of ambient PM_{10} levels from road dust, the best two control options are: (i) control option- 20; sweeping and watering of roads in mechanized means (48.7% in 5th year and 45.7% in 10th year), and (ii) control options- 18; conversion of unpaved roads to paved roads (14.5% in 5th year and 23.6% in 10th year).

Table 3. Summary of model performance measures PM_{10} at monitoring sites

Particulars		**Sampling sites***							**Overall**
		IIT	**VN**	**GN**	**DN**	**CG**	**AHM**	**RD**	
No. of valid observations		26	24	27	24	28	23	22	174
24 hr average observed monitored ambient concentration (μgm^{-3})	Mean	196	224	247	396	298	284	241	269
	SD	45	62	49	127	98	100	85	81
24 hr average predicted ambient concentration (μgm^{-3})	Mean	104	125	151	293	189	184	145	170
	SD	47	59	66	143	72	88	62	77
Percentage of prediction (%)		53	56	61	74	63	65	60	63
Fractional error (FB)		0.61	0.58	0.48	0.29	0.45	0.43	0.49	0.48
Normalized mean square error (NMSE)		0.62	0.43	0.35	0.28	0.32	0.31	0.34	0.38
Coefficient of correlation (*r*)		0.64	0.73	0.68	0.78	0.76	0.69	0.77	0.72
Index of agreement (*d*)		0.49	0.61	0.68	0.79	0.69	0.67	0.66	0.66

SD for standard deviation; *Details of Sampling sites (Figure 1): IIT- IIT Kanpur, VN- Vikashnagar, GN- Govindnagar, DN- Dadanagar, CG- Colonelganj, AHM- AHM hospital, RD- Ramadevi square

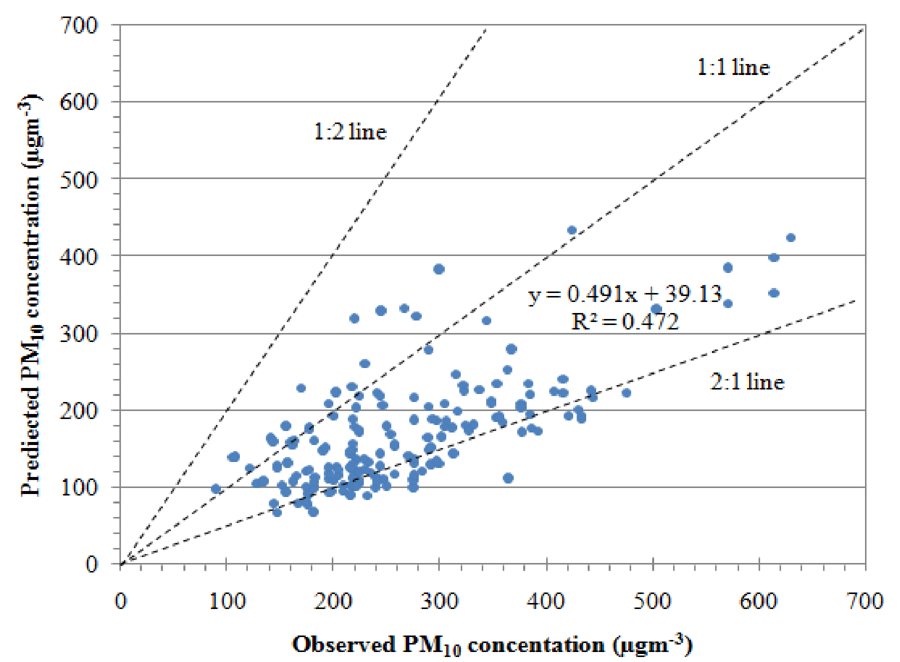


Figure 4. Correlation plot for observed and predicted 24 hr average values of PM_{10} concentrations in the base year

(a)

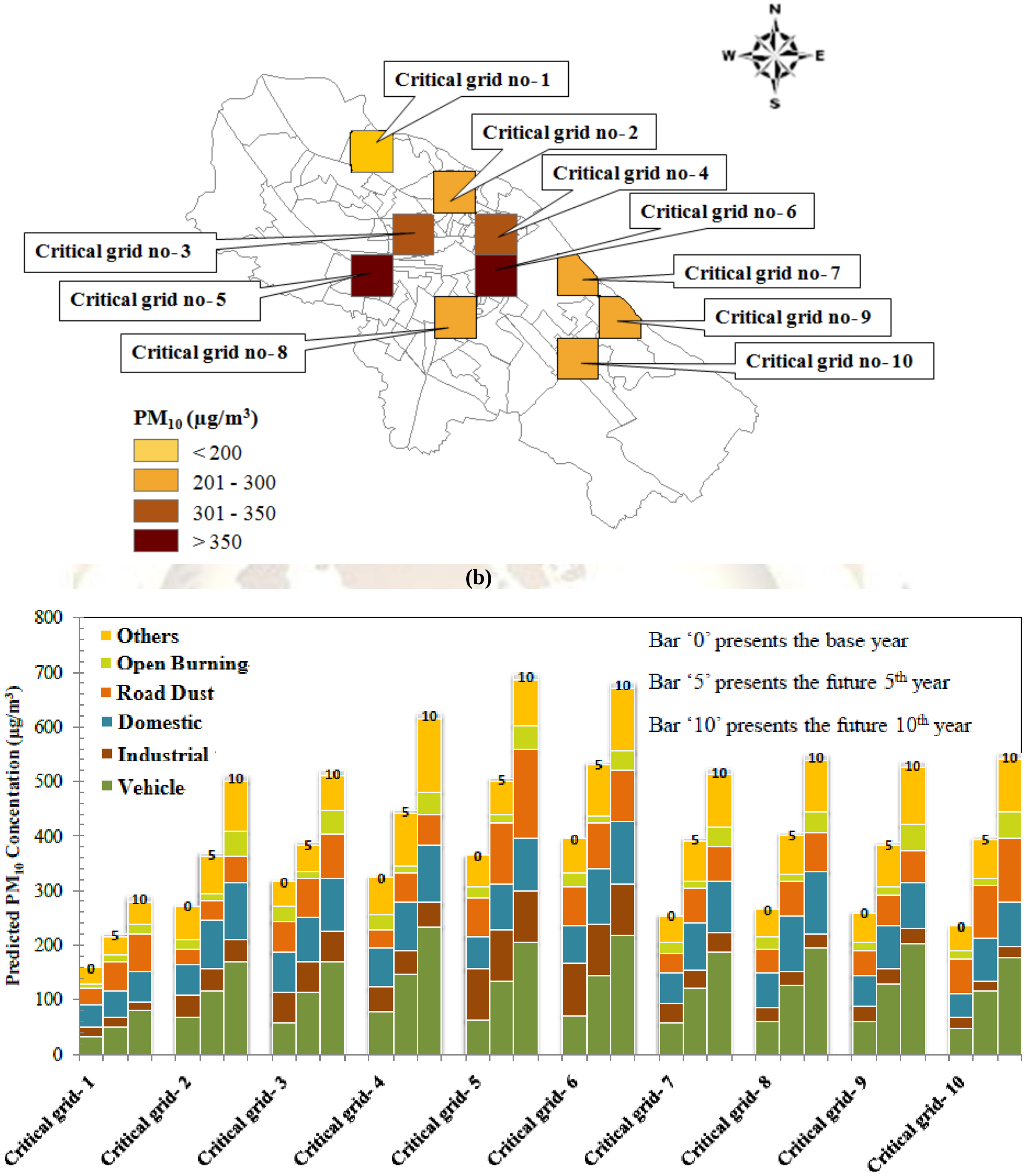


Figure 5. (a) Kanpur city with critical grids with their identities in the process of ISCST3 modeling for examining efficacies of control options of PM_{10} pollution load over the city, (b) PM_{10} predictions in critical grids with Emissions BAU for the base year, the future 5th year and the future 10th year

Table 4. Modeling results of evaluation on efficacy of control options for the 5thand 10th year

Control Option no.*	Pertinent source	Brief of control option	Situation in the 5th year (average of 10 critical grids)			Situation in the 10th year(average of 10 critical grids)		
			Conc. 5th year BAU (μgm^{-3})	Conc. 5th year control (μgm^{-3})	% reduction in ambient air conc.	Conc. 10th year BAU (μgm^{-3})	Conc. 10th year control (μgm^{-3})	% reduction in ambient air conc.
1	Vehicle	Euro 5	119.6	NA	NA	184.0	133.6	7.4
2	Vehicle	Euro 6	119.6	NA	NA	184.0	133.6	7.4
3	Vehicle	Electric vehicles	119.6	113.5	5.1	184.0	173.3	5.8
4	Vehicle	CNG	119.6	102	14.7	184.0	109.8	40.3
5	Vehicle	Bio-diesel	119.6	110.8	7.4	184.0	171.1	7.0
6	Vehicle	DOC Retro fitment	119.6	112.5	5.9	184.0	166.5	9.5
7	Vehicle	DPF Retro fitment	119.6	94.1	21.3	184.0	132.6	27.9
8	Vehicle	I and M	119.6	114.8	4.0	184.0	173.3	5.8
9	Vehicle	Ban of 15 year old	119.6	83.4	30.3	184.0	140.9	23.4
10	Vehicle	Public transport	119.6	114.1	4.6	184.0	174.5	5.2
11	Industry	Natural gas as fuel	45.2	11.7	74.1	45.2	11.7	74.1
12	Industry	PCS introduction	45.2	0.7	98.5	45.2	0.7	98.5
13	Industry	Shifting to outside	45.2	22.3	50.7	45.2	0.0	100.0
14	Domestic	Use of LPG	83.5	51.1	38.8	95.1	43.3	54.5
15	DG sets	I and M	4.0	3.3	17.5	4.6	3.9	15.2
16	DG sets	No power-cut	4.0	0.0	100.0	4.6	0.0	100.0
17	Construct	Better practice	0.1	0.05	50.0	0.2	0.09	55.0
18	Road dust	Unpaved to paved	68.9	58.9	14.5	81.9	62.6	23.6
19	Road dust	Brick wall paving	68.9	63.7	7.5	81.9	60.4	26.3
20	Road dust	S and W	68.9	37.4	48.7	81.9	44.5	45.7
21	Open burning	Strict ban	14.0	9.3	33.6	39.4	0.0	100.0

* For details of options and their implementation scheme, refer Table 1; % reduction is calculated based on individual source; NA is for not applicable, as the implementation of Euro 5 and Euro 6 can be possible from the 8th year from the base year; Construct for construction activities; Conc. for concentration; BAU conc. is the ambient levels of PM_{10} from the individual source without implementing the control option; the control conc. is the ambient levels of PM_{10} from the individual source with implementing the control option

3.4 Development of control scenarios

All twenty one control options were evaluated for their effectiveness in section 3.3. The following control options, showing less that 7% reductions were treated as ineffective: options- 3, 5, 6, 8, 10, 15 and 19 (Table 1). As shifting of all industries outside the city was not agreed by the city authorities, therefore, control option- 13 was considered as infeasible. We did not consider control option- 17 further in the iteration process, as the contribution of this source (better construction) to ambient PM_{10} levels was negligible.

The twelve effective and feasible control options (1, 2, 4, 7, 9, 11, 12, 14, 16, 18, 20 and 21) were selected for scenario formations. This selection method was done as per the modeling outputs. It was considered that implementation of all twelve control options may be cost prohibitive, therefore, combinations of eight options were considered for scenario development; considering less than eight options were not sufficient to attain air quality standards [37]. Finally, four control scenarios were proposed (Table 5). It is to be noted that scenario- 4 is quite different than other three scenarios. The purpose of scenario-4 was to assess the achievement in reduction of ambient PM_{10} levels by applying the control measures to only vehicular sources and to keep the remaining sources as per their usual growths (i.e., no control measures for other sources). These four control scenarios were evaluated for their effectiveness in reduction of ambient PM_{10} levels by ISCT3 modeling for critical grids in the study area. Based on the results of the evaluation of scenarios, it could be concluded that control scenario- 3 is the most promising combination of options in reducing ambient PM_{10} levels in the study area (ambient PM_{10} reduction by 40% in the 5th year and 51% in the 10th year).

A qualitative cost analysis was done for three control scenarios for their cost effectiveness. Scenario-4 was not considered, as the potential in reduction of PM_{10} was less than 20% and this scenario is concerned with the control of vehicular pollution only. The difference between scenarios 1 and 2 is CNG as vehicle fuel (control option- 4) and DPF in vehicle (control option- 7). The scenario- 1 will be relatively cost-effective compared to scenario- 2, as the installation of DPF could be costlier than the installation of CNG kit (readily available in the Indian market). It is to be noted that CNG outlet infrastructure already exists in the city and no new installations are required for CNG usages for vehicles [41].

Compared to Scenario 1, Scenario 3 is certainly more effective in terms of PM_{10} reduction potential and it is expected to be cost-effective as well because the old industries cannot change the technology to use natural gas as fuel. Any fuel change (e.g., coal to natural gas) will require huge investment (piping network, storage, compressors etc.) [42]. Therefore, the best option for the industry to reduce PM_{10} is through particulate control filters (e.g., cyclones, scrubbers) compared to complete change to the new fuel.

Table 5. Possible control scenarios as combination of control options

S. No.	Scenario	Combinations of control options (brief of specific control options)	% reduction of ambient PM_{10} in the 5th year*	% reduction of ambient PM_{10} in the 10th year*
1.	Scenario-1	Control options: 1, 4, 9, 11, 14, 18, 20 and 21 (Euro 5, CNG to vehicles, ban of 15 year old vehicles, natural gas as industrial fuels, LPG in domestic cooking, unpaved to paved roads, sweeping and watering of roads, ban on open burning)	37	47
2.	Scenario-2	Control options: 1, 7, 9, 11, 14, 18, 20 and 21 (Euro 5, DPF retro fitment to vehicles, ban of 15 year old vehicles, natural gas as industrial fuels, LPG in domestic cooking, unpaved to paved roads, sweeping and watering of roads, ban on open burning)	38	45
3.	Scenario-3	Control options: 2, 4, 9, 12, 14, 18, 20 and 21 (Euro 6, CNG to vehicles, ban of 15 year old vehicles, PCS industries, LPG in domestic cooking, unpaved to paved roads, sweeping and watering of roads, ban on open burning)	40	51
4.	Scenario-4	(Control options- 2, 7 and 9, as control measures) + (no control on the sources of control options- 12, 14, 18, 20 and 21): vehicular control by introducing Euro 6, DPF retro fitment to vehicles and ban of 15 year old vehicles	15	19

*Values are based on the average of 10 critical grids; it is to be noted that the scenarios are proposed based on the iterations with combinations of control options depending on the viabilities concurrent options to be implemented by the management.

3.5 Air quality status in the study area with proposed scenario

If one decides to implement control scenario- 3, it is important to reexamine the improvements in air quality with the objective to see if standards are attained both in the 5th and 10th year. To assess the spatial distribution of the ambient levels of PM_{10} with implementation of control scenario- 3, ISCST3 modeling was performed by treating centers of 85 grids as receptors. With the implementation of scenario- 3, it has been observed that the air quality will improve dramatically, but it would fall short of achieving air quality standards for PM_{10} in 1/4th of area for the 5th year and 10th year. Therefore additional efforts are required to prepare specific control strategies to reduce the emission further. Vehicles, road dust and domestic cooking are the important sources in the 5th and 10th year. Therefore, vehicular pollution can be reduced further by 50 percent which can be done by restricting entry of vehicles to 50 percent in these grids (of non-attaining the standard). The entry restriction of the vehicles can be achieved by allowing odd number of vehicles on the first day and even number of vehicles on the next day and repeating the cycle. This can be achieved by education and some spot checking. It is expected that the reduction in 50% vehicle loads will reduce the road dust by more than 50 percent of the earlier emission (estimated by Eq (4) which is dependent on number of vehicles on the road). The reduced numbers of vehicles also eliminate traffic congestion and lead to smooth traffic flow. De Vlieger et al. [43] have reported that during traffic congestions, fuel consumption increases by 20–45%. It was also assumed that construction of flyovers at road-railway intersections (15 numbers in the study area) will help in time saving of about 20 percent and can result in reduction of PM_{10} by 30% (possible range; 20–45%). If proper inspection and maintenance of vehicles are taken into account, 10–20% fuel efficiency can be achieved [44]. We have assumed 15% PM_{10} reduction if strict compliance for inspection and maintenance of older vehicles is enforced. Additionally, if uninterrupted power supply is maintained, no DG sets will be used and their contribution to PM_{10} will be zero, this is expected to happen in the 5th year as power supply and generation will improve. Conversion of all solid fuels and kerosene into LPG by the 5th year, will further reduce emission by 50% in 5th year and 25% in 10th from the domestic cooking (control- 14; Table 1). Complete ban on open burning from the 5th year, which will further enable 50% emission reduction (control option 21; Table 1).

In summary, the additional options to be augmented with the control secanrio-3 to arrive at 'the proposed scenario' include: (i) restriction of vehicles to the areas having non-attainment of air quality standard, (ii) construction of flyovers in traffic congested areas, (iii) strict compliance for inspection and maintenance of older vehicles, (iv) adequate supply of uninterrupted power (v) complete conversion of solid fuel and kerosene into LPG for domestic cooking, and (vi) complete ban on refuse or garbage burning.

ISCST3 modeling for 24 hr average PM_{10} concentrations at 85 receptor locations was performed given that the above control options and scenario 3 are enforceable. Figure 6 shows the spatial distributions of PM_{10} concentration (μgm^{-3}) in winter season for the 5th year BAU, 5th year control and 10th year BAU and 10th year control. It could be observed that (Figures 6b and d) the proposed control scenario will ensure compliance of 24 hr air quality standards of PM_{10} (100 μgm^{-3}) in future.

IV. CONCLUSIONS

A GIS-based emission inventory of PM_{10} for the base, 5th and 10th year was developed for the City of Kanpur, India. The PM_{10} emission of 11.4 ton day^{-1} of the base year will increase by a factor of 1.5 in the 5th year and by a factor of 2.2 in the 10th year. If no control measures are taken, vehicles will be the major emitters in the 5th year (4.1 ton day^{-1}; 24% of total PM_{10}) and in the 10th year (7.3 ton day^{-1}: 29% of total PM_{10}). Next to vehicles, domestic cooking (20% in 5th year and 22% in 10th year) and road dust (17% in 5th year and 20% in 10th year) will be among the top contributors to PM_{10} in the future.

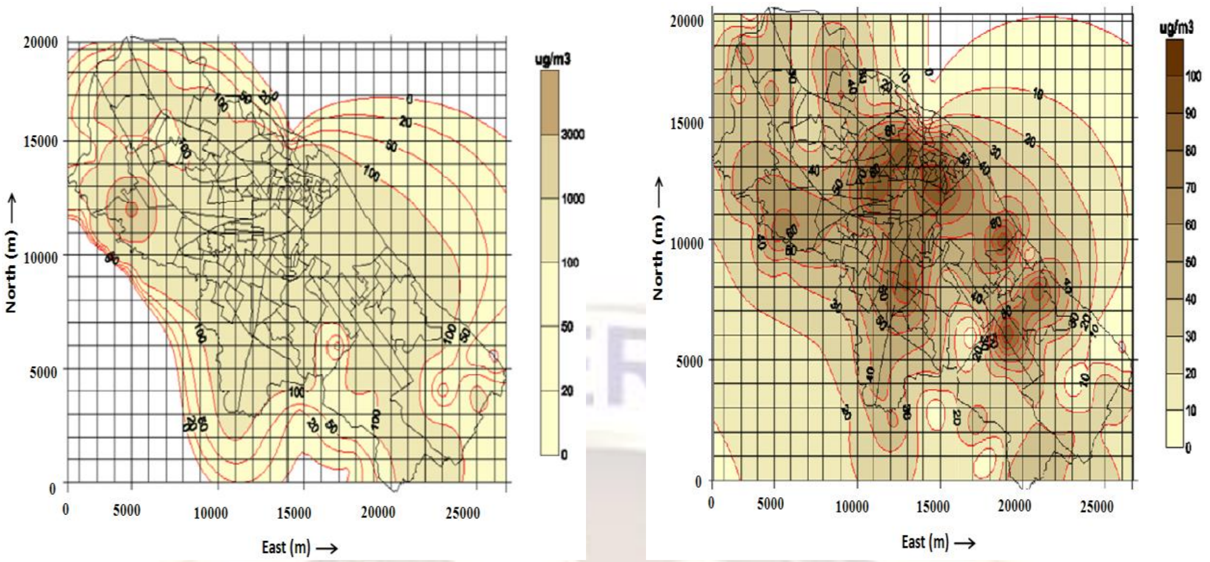
This study has proposed a time-sensitive particulate control scenario for implementation to achieve compliance of 24 hr average air quality standard. For this purpose, twenty one control options (e.g., introduction of Euro 6 to vehicles, use of natural gases as fuels for industries, use of LPG as domestic cooking fuel etc.) were considered for evaluation. The effectiveness of each control option in reducing the PM_{10} concentration was assessed through ISCST3 model. Different control scenarios were developed as a combination of several control options. A scenario comprising control options- (i) implementation of Euro 6 for vehicles, (ii) CNG to commercial and public vehicles, (iii) banning of 15 year old private vehicles, (iv) particulate control systems in industries, (v) LPG for domestic cooking, (vi) converting unpaved roads to paved roads, (vii) sweeping and watering of roads and (viii) ban on open burning, was found to be the most effective. Implementation of this control scenario will substantially improve the air quality in the 5th and 10th year. However, in certain areas, air quality standard for PM_{10} could still be violated. Therefore, additional options should become part of particulate control scenario which include: (i) restriction of vehicles to the areas having non-attainment of air quality standard, (ii) construction of flyovers in traffic congested areas, (iii) strict compliance for inspection and maintenance of older vehicles, (iv) adequate supply of grid power to ensure no power failure, (v) complete conversion of solid fuel and kerosene into LPG for domestic cooking, and (vi) complete ban on refuse or garbage burning.

With all these control options (the scenario along with additional control options), the spatial distributions of 24 hr average PM_{10} concentrations were predicted over the city. The study finally concludes that the proposed time-sensitive control scenario will be able to reduce the ambient PM_{10} levels, so that the 24 hr average air quality standard will be attained in the future 5th year and 10th year.

V. ACKNOWLEDGEMENTS

We acknowledge the Central Pollution Control Board, Delhi for the financial support of the project (Grant No: B- 30062/1/05 (SA)/PCI-I). We thank Mrs. Pranati Behera, Department of Civil Engineering, Indian Institute of Technology Kanpur, India for assistance in preparing this manuscript.

(a) future 5th year BAU (b) future 5th year Control



(c) future 10th year BAU (d) future 10th year Control

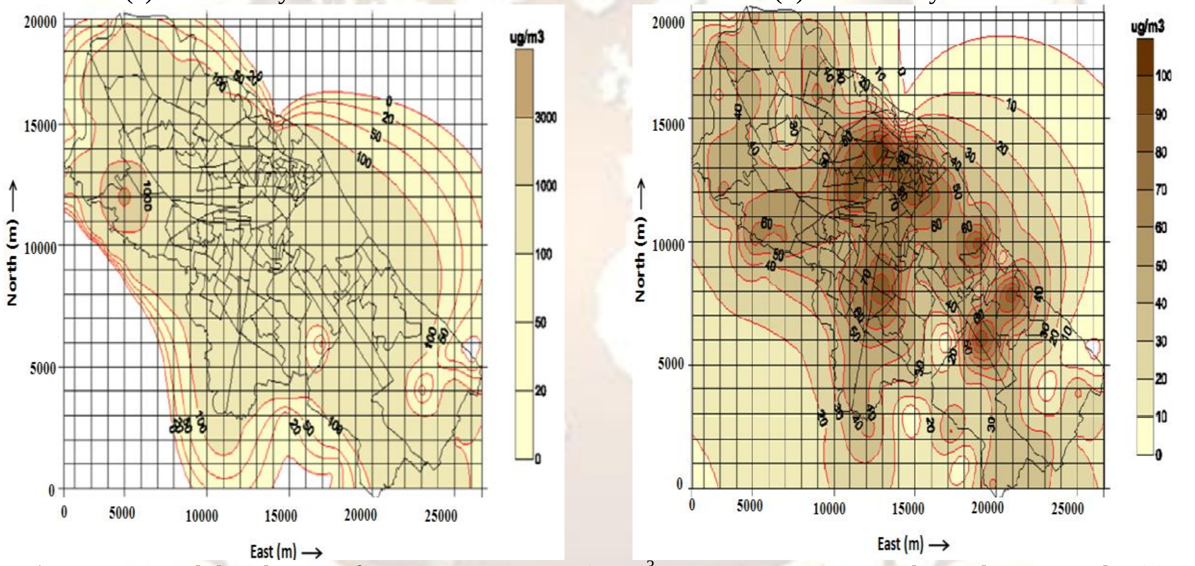


Figure 6. Spatial distribution of PM_{10} concentration (μgm^{-3}) in winter season over the study areas under (a) future 5th year BAU, (b) future 5th year control with proposed control scenario, (c) future 10th year BAU, (d) future 10th year control with proposed control scenario

REFERENCES

[1] M. Sharma, V.N. Kumar, S.K. Katiyar, R. Sharma, B.P. Shukla, and B. Sengupta, "Cohort-based acute health effect study of PM_{10} and $PM_{2.5}$ pollution in the city of Kanpur, India," *Archives of Environmental Health: An International Journal*, vol. 59, pp. 348–358, 2004.

[2] H.Y. Liu, A. Bartonova, M. Schindler, M. Sharma, S.N. Behera, K. Katiyar, and O. Dikshit, "Respiratory Disease in Relation to Outdoor Air Pollution in Kanpur, India," *Archives of Environmental & Occupational Health*, vol. *68*, pp. 204–217, 2013.

[3] X. Cao, Climate change and energy development: implications for developing countries. *Resources Policy*, vol. 29, pp. 61–67, 2003.

[4] K. Hubacek, D. Guan, and A. Barua, " Changing lifestyles and consumption patterns in developing countries: A scenario analysis for China and India," *Futures*, vol. 39, pp. 1084–1096, 2007.

[5] V.P. Aneja, W.H. Schlesinger, J.W. Erisman, S.N. Behera, M. Sharma, and W. Battye, " Reactive nitrogen emissions from crop and livestock farming in India," *Atmospheric Environment*, vol. 47, pp. 92–103, 2012.

[6] R.J. Charlson, J. Langner, and H. Rodhe, "Sulfate aerosols and climate," *Nature*, vol. 348, pp. 22-22, 1990.

[7] G. Myhre, T.F. Berglen, M. Johnsrud, C.R. Hoyle, T.K. Berntsen, S.A. Christopher, D.W. Fahey, I.S.A. Isaksen, T.A. Jones, R.A. Kahn, N. Loeb, P. Quinn, L. Remer, J.P. Schwarz, and K.E. Yttri, "Modelled radiative forcing of the direct aerosol effect with multi-observation evaluation," *Atmospheric Chemistry and Physics*, vol. 9, pp. 1365–1392, 2009.

[8] M. Sharma, and S. Maloo, "Assessment and characterization of ambient air PM_{10} and $PM_{2.5}$ in the City of Kanpur, India," *Atmospheric Environment*, vol. 39, pp. 6015–6026, 2005.

[9] NILU, Norwegian Institute for Air Research, "Environmental Health Assessment: Respiratory Disease in relation to Air Pollution in Kanpur, Uttar Pradesh, Final Report". Project no. O–106082, ref.nr. IND3025 05/51, 2008.

[10] S.N. Behera, and M. Sharma, "Degradation of SO_2, NO_2 and NH_3 leading to formation of secondary inorganic aerosols: An environmental chamber study," *Atmospheric Environment*, vol. 45, pp. 4015–4024, 2011.

[11] S.N. Behera, and M. Sharma, "Transformation of atmospheric ammonia and acid gases into components of $PM_{2.5}$: an environmental chamber study," *Environmental Science and Pollution Research*, vol. 19, pp. 1187–1197, 2012.

[12] S.N. Behera, M. Sharma, O. Dikshit, and S.P. Shukla, "GIS-based emission inventory, dispersion modeling, and assessment for source contributions of particulate matter in an urban environment," *Water, Air, & Soil Pollution*, vol. 218, pp. 423–436, 2011.

[13] K.-J. Liao, E.Tagaris, K. Manomaiphboon, S.L. Nepelnok, J.-H. Woo, S. He, P. Amar, and A.G. Russel, "Sensitivities of ozone and fine particulate matter formation to emission under the impact of potential future climate change," *Environmental Science & Technology*, vol. 41, pp. 8355–8361, 2007.

[14] J.B. Wang, M-S. Wang, E.M-Y. Wu, G-P. Chang-Chien, and Y.-C. Lai, "Approaches adopted to assess environmental impacts of PCDD/F emissions from a municipal solid waste incinerator," *Journal of Hazardous Materials*, vol. 3, pp. 968–975, 2008.

[15] Q. Huang, S.Y. Cheng, Y.P. Li , J.B. Li, D.S. Chen, and H.Y. Wang, "An integrated MM5-CAMx modeling approach for assessing PM_{10} contributions from different sources in Beijing, China," *Journal of Environmental Informatics*, vol. 15, pp. 47-61, 2010.

[16] V.A. Karydis, A.P. Tsimpidi, C. Fountoukis, A. Nenes, M. Zaval, W. Lei, L.T. Molina, and S.N. Pandis, "Simulating the fine and coarse inorganic particulate matter formation in a populated megacity," *Atmospheric Environment*, vol. 44, pp. 608–620, 2010.

[17] G. Ying, J. Ma, Y. Xing, "Comparison of air quality management strategies of PM_{10}, SO_2, and NO_x by an industrial source complex model in Beijing," *Environmental Progress*, vol. 26, pp. 23–42, 2007.

[18] S.A. Abdul-Wahab, "SO_2 dispersion and monthly evaluation of the industrial source complex short-term (ISCST3) model at Mina Al-Fahal Refinery, Sultanate of Oman," *Environmental Management*, vol. 31, pp. 276–291.

[19] M. El-Fadel, L.Abi-Esber, and T. Ayash, "Managing emissions from highly industrialized areas: Regulatory compliance under uncertainty," *Atmospheric Environment*, vol. 43, pp. 5015–5026, 2009.

[20] A. Kumar, N.K. Bellam, and A. Sud, "Performance of an industrial source complex model: Predicting long term concentrations in an urban area," *Environmental Progress*, vol. 18, pp. 93–100, 1999.

[21] M. Lorber, A. Eschenroeder, and R.Robinson, "Testing the US EPA's ISCST—Version 3 Model on dioxins: a comparison of predicted and observed air and soil concentration" *Atmospheric Environment*, vol. 34, pp. 3995–4010, 2000.

[22] R. Sivacoumar, A.D. Bhanarkar, S.K. Goyal, S.K. Gadkari, and A.L. Aggarwal, "Air pollution modeling for an industrial complex and model performance evaluation," *Environmental Pollution*, vol. 111, pp. 471–477, 2001.

[23] M.S. Al-Rashidi, V. Nassehi, R.J. Wakeman, "Investigation of the efficiency of existing air pollution monitoring sites in the state of Kuwait," *Environmental Pollution*, vol. 138, pp. 219–229, 2005.

[24] T.V.B.P.S. Rama Krishna, M.K. Reddy, R.C. Reddy, and R.N. Singh, "Impact of an industrial complex on the ambient air quality: case study using a dispersion model," *Atmospheric Environment*, vol. 39, 5395–5407, 2005.

[25] W.B. Faulkner, B.W. Shaw, and T. Grosch, "Sensitivity of two dispersion models (AERMOD and ISCST3) to input parameters for a rural ground-level area source," *Journal of Air and Waste Management Association*, vol. 58, pp. 1288–1296, 2008.

[26] G. Wang, S. Bai, and J.M. Ogden, "Identifying contributions of on-road motor

vehicles to urban air polluting using travel demand model data," *Transportation Research Part D*, vol. 14, pp. 168–179, 2009.

[27] U. Im, K. Markakis, A. Unal, T. Kindap, A. Poupkou, S. Incecik, O. Yenigun, D. Melas, C. Theodosi, and N. Mihalopoulos, "Study of a winter PM episode in Istanbul using the high resolution WRF/CMAQ modeling system," *Atmospheric Environment*, vol. 26, pp. 3085–3094, 2010.

[28] P. Thunis, L. Rouil, C. Cuvelier, R. Stern, A. Kerschbaumer, B. Bessagnet, M. Schaap, P. Builtjes, et al., "Analysis of model responses to emission-reduction scenarios within the City Delta project," *Atmospheric Environment*, vol. 41, pp. 208–220, 2007.

[29] C. Carnevale, E. Pisoni, and M. Volta, "A multi-objective nonlinear optimization approach to designing effective air quality control policies," *Automatica*, vol. 44, pp. 1632–1641, 2008.

[30] M. Amann, and M. Lutz, "The revision of the air quality legislation in the European Union related to ground-level ozone," *Journal of Hazardous Materials*, vol. 78, pp. 41–62, 2000.

[31] G. Mitchell, "Forecasting environmental equity: Air quality responses to road user charging in Leeds, UK," *Journal of Environmental Management*, vol. 77, pp. 212–226, 2005.

[32] J.-H. Leem,B.M. Kaplan,Y.K. Shim, H.R. Pohl, C.A. Gotway, S.M. Bullard, J.F. Rogers, M.M. Smith, and C.A. Tylenda, "Exposures to air pollutants during pregnancy and preterm delivery," *Environmental Health Perspectives*, vol. 114, pp. 905–910, 2006.

[33] USEPA, US Environmental Protection Agency, Quality Assurance Guidance Document 2.12. Monitoring $PM_{2.5}$ in ambient air using designated reference or class I equivalent methods, 1998.

[34] USEPA, US Environmental Protection Agency, User's Guide for the Industrial Source Complex (ISC3) Dispersion Models, Vol. I - User Instructions and Vol. II - Description of Model Algorithms. United States Environmental Protection Agency, Office of Air Quality Planning and Standards, September, EPA-454/B-95-003a,b., 1995.

[35] J.H. Seinfeld, and S.N. Pandis, Atmospheric Chemistry and Physics, from Air Pollution to Climate Change, John Wiley, New York, 1998.

[36] A.L. Dutot, J. Rynkiewicz, F.E. Steiner, and J. Rude, "A 24-h forecast of ozone peaks and exceedance levels using neural classifiers and weather predictions," *Environmental Modeling and Software*, vol. 22, pp. 1261–1269, 2007.

[37] S.N. Behera, M. Sharma, P. Nayak, S.P. Shukla, and P. Gargava, "An approach for evaluation of proposed air pollution control strategy to reduce levels of nitrogen oxides in an urban environment." *Journal of Environmental Planning and Management*, DOI:10.1080/09640568.2012.750600, 2013.

[38] B.C.J. Santosh, A methodology to determine minimum stack height for thermal power plants based on dispersion capacity. M. Tech. Thesis, Indian Institute of Technology Kanpur, 2001.

[39] A.J. Brazell, G.J. McCabe, and H.J. Verville, "Solar radiation simulated by general circulation models for the southwestern United States," *Climate Research*, vol. 2, pp. 177–181, 1993.

[40] T.V. Johnson, "Diesel emission control in review," *SAE International Journal of Fuels and Lubricants*, vol. 1, pp. 68–81, 2008.

[41] M. Sharma, M. Jha, and T. Gupta, "Particulate Mass and Number Emission from CNG and Diesel-powered Three-Wheeler: Insight into OC-EC Characteristics," 6th International Symposium on Fuels and Lubricants, New Delhi, March 9-12, 2008.

[42] S. Kaplan, Power Plants: Characteristics and Costs. CRS Report for Congress (Order Code RL34746), 2008.

[43] I. De Vlieger, , D. De Keukeleere, , and J.G. Kretzschmar, "Environmental effects of driving behaviour and congestion related to passenger cars. *Atmospheric Environment*, vol. 34, pp. 4649–4655, 2000.

[44] World Bank, Report on “Improving Urban Air Quality in South Asia by Reducing Emissions from Two-Stroke Engine Vehicles”. The International Bank for reconstruction and Development/THE WORLD BANK Washington, D.C., USA, 2000.