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An Analysis of Ambient Air Quality Conditions over Delhi, India from 2004 to 2009

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Abstract

We analyzed 1-hour, 8-hour and 24-hour averaged criteria pollutants (NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}) during 2004-2009 at three observational sites *i.e.* Income Tax Office (ITO), Sirifort and Delhi College of Engineering (DCE) in Delhi, India. The analysis reveals increased pollutant concentrations at the urban ITO site as compared to the other two sites, suggesting the need to better locate hot spots in designing the monitoring network. There is also significant year to year variation in the design value trends of criteria pollutants at these three sites, which may be attributed to meteorological variations and local-level emission fluctuations. Correlations among criteria pollutants vary annually and spatially from site to site, indicating the heterogeneous nature of air mix. The annual ratios of CO/NO_x are considerably higher than SO_2/NO_x confirming that vehicular source emissions are the primary contributors to air pollution in Delhi. The seasonal analysis of criteria pollutants reveals relatively higher concentrations in winter because of limited pollutant dispersion and lower concentrations during the monsoon period (rainy season). The diurnal averages of criteria pollutants reveal that vehicular emissions strongly influence temporal variations of these pollutants. Weekdays and weekend diurnal averages do not show noticeable differences.

Keywords: Ambient Air Quality Status, Criteria Pollutants, Data Analysis

1. Introduction

Delhi, the capital of India (latitude 28˚4' N and longitude 77˚2' E), is located in central India, covering 1483 km^3. It is the third most populated city in India with a population of more than 16 million. Naturally, this has caused environmental stress and atmospheric concentration levels of criteria pollutants particulate matter, sulfur dioxide and nitrogen oxides continue to pose serious public health risks for sensitive population in Delhi [1]. The pollution levels in Delhi have been rising due to continuous increase in number of motor vehicles [2], counteracting the benefits of control programmes that were implemented. Other sources of pollutants include coal-based thermal power plants, small-scale industries and non-road sources such as construction activities. Meteorological variables, particularly the prevailing winds blowing from northwest in winter and from southwest in summer [3] play a significant role in inducting industrial pollutants and pollutants from roadways into residential areas [4] causing widespread air pollution. Several emission reduction measures such as the use of heavy-duty Compressed Natural Gas engines (CNG) replacing diesel-fueled engines, strict vehicular inspection and maintenance procedures, establishment of alternative mode of transport such as the metro and stricter controls on industrial pollution have been implemented to improve local air quality. Scientists have evaluated the effectiveness of these controls on air pollution and discovered a decrease in air pollutants due to a switch from diesel to CNG in Delhi's transport system [5]. However, an increase in NO_x concentrations after the switch was observed [6,7]. Further, there was no discernible impact on ambient PM_{10} and CO concentrations noted, stemming from CNG implementation [8]. SO_2 and NO_x ($NO + NO_2$) are important primary precursors emitted by fossil fuel combustion from industrial point sources and coal-fired thermal power plants. Heavy-duty vehicles burning diesel fuel are important sources of NO_2 as well. NO_2 and SO_2 are important contributors towards secondary nitrate and sulfate formation through a series of complex reactions, which are major components of fine particulate matter ($PM_{2.5}$). Sources of fine particles include all types of combustion including motor vehicles, power plants, residential wood burning, forest fires, agriculture burning and some industrial processes. The study and subsequent control of secondary pollutants are further complicated by the nonlinear nature of their formation processes and the impact of meteorological variability on their concentrations [9,10].

Evaluation of ambient air quality is a method to verify the effectiveness of the control measures implemented, and for early detection of potentially harmful changes in atmospheric composition. According to a detailed analysis of most of the criteria pollutants in Delhi, except for SO_2, all criteria pollutants exceeded the National Ambient Air Quality Standards (NAAQS) applicable in USA [11,12]. In this study, the period of interest is from 2004 to 2009. However, observed data available varies from site to site and from pollutant to pollutant. The pollutants used in this study are NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10}. Obviously, more observational sites at hot spot locations and residential areas are needed to adequately investigate the spatial variability and to provide a more comprehendsive status of air quality in Delhi.

2. Prototype Data Collection

The observations of pollutants used in this study are obtained from Central Pollution Control Board [13] (personal communication) and website (www.cpcb.nic.in). Currently, CPCB has three fixed continuous air quality monitoring sites in Delhi. These are Income Tax Office (ITO), Delhi College of Engineering (DCE) and Sirifort (**Figure 1**). The operations and maintenance of monitoring sites in Delhi are undertaken by CPCB under the nation-wide National Ambient Air Quality Monitoring Program.

The data availability at these sites is as follows:

- 1-hour and 24-hour averaged data for NO_2, SO_2 at all the three sites (ITO, Sirifort and DCE 2004-2009);
- 1-hour, 8-hour consecutive averaged values and 24-hour averaged data for CO all three sites (ITO, Sirifort and DCE 2007-2009) since CO concentrations are being monitored since 2007 at these sites;
- 1-hour and 24-hour averaged data for $PM_{2.5}$ at one site (ITO since 2007) since $PM_{2.5}$ data is being continuously monitored at this site only;
- 1-hour and 24-hour averaged data for PM_{10} at one site (DCE since 2007) since PM_{10} data is being monitored at this site only.

In this analysis, design value trends, persistence of exceedances of pollutants, monthly averages, pollutant ratios and correlation coefficients between various pollutants have been used to estimate status of ambient air quality in Delhi. In addition, hourly averages were used for diurnal plots of NO_2, SO_2, CO, $PM_{2.5}$ and PM_{10} for the year 2009.

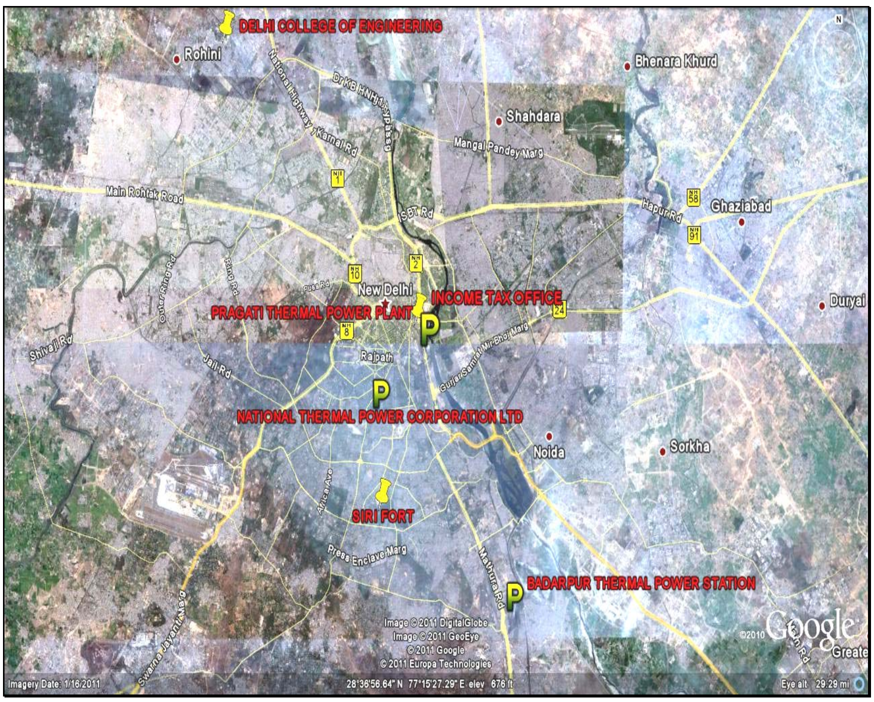

Figure 1. Monitoring sites (ITO, Sirifort and DCE), major roadways and power plants.

Site Description

The ITO monitoring station is located along a major transport corridor connecting the east side of the river "Yamuna". This site not only captures the signals from the transport sector, but also the industrial emissions from the East, primarily from the Ghaziabad industrial sectors [14]. The Pragati power plant with a capacity of 282 MW is within 2 km from this site and substantially influences the emissions at this site. Delhi's outer ring road, a major roadway with a total length of 47 km is within 0.5 km of the ITO site. Sirifort in South Delhi is a semi-urban site enclosed by greenery. However, major roads including the outer ring road are within a kilometre from this site. Though it is far away from industries, the prevailing winds can bring industrial pollutants into this area from the east (The Badarpur coal-based power plant is about 7 km from this site). DCE is a residential location within a University campus, away from traffic junctions. Although vehicular activities are restricted within the campus, it is still influenced by roadside dust.

3. Data Analysis

3.1. Trends of Criteria Pollutants Utilizing Design Values

A pollutant determined to be hazardous to human health and regulated under United States Environmental Protection Agency's (US EPA's) National Ambient Air Quality Standards is termed as criteria pollutant. All the ubiquitous air pollutants considered in this study meet the above definition of criteria pollutant. A design value is a statistic that describes the air quality status of a given area relative to national ambient air quality standards. Since the CPCB standards of air pollutants are exceedance-based (24-hour NO_2, 24-hour SO_2, 8-hour CO, 24-hour $PM_{2.5}$ and 24-hour PM_{10}), design value calculations expressed as a concentration instead of an exceedance count, allow a direct comparison to the level of the standard.

Trends in the design value of criteria pollutants reveal the efficacy of emission controls. The design values for the 8-hour and 24-hour averaged concentrations of pollutants have been computed as per CPCB guidelines (www.cpcb.nic.in) which stipulates that the standards for the pollutants are allowed to be exceeded only 2 percent of time annually in each year but not for two consecutive days. According to the above guidelines for an area to be in attainment, 98 percent of time the pollutant levels have to meet the standards. This means that the 98th percentile of the 24 hr-average values (array size is 365 since there is one 24-averaged value for each day of year) has to meet the standard, which would be the 8th highest value of the pollutant concentration in the sorted array size of 365 values. Similarly for three 8-hour consecutive averages considered in a day as in the case of pollutant CO, the array size would be 1095 values for each year. In this case the 98th percentile is the 22nd highest value in the sorted array, which has to meet the standard. The design values computed on the second aspect of criteria (pollutant levels not exceeding two consecutive days), the lower of two consecutive-days value was stored in the pollutant array and for a given year the maximum if these values was specified as design value criteria which was compared against the NAQQS standard. The results exhibit a similar trend line (Figures not shown).

The time series of design values of criteria pollutants represents 8th highest concentration in a year for the 24-hour averaged concentrations (NO_2, SO_2, $PM_{2.5}$ and PM_{10}) and 22nd highest concentration for the 8-hour averaged values (CO). The longer-term averaging period provides a methodology for reducing the dependence of design values on variable short-term meteorological effects [15], which can mask the impact of regulatory programs on air quality. The trends for 24-hour averaged NO_2 and SO_2 design values have been assessed from observational data collected since 2004 at all the three monitoring sites. Design values of 24-hour averaged $PM_{2.5}$ and PM_{10} concentrations have been analyzed for three years only (2007-2009) at ITO and DCE respectively. The 8-hour design value trends have been analyzed for CO from 2007-2009 for all sites. **Table 1** presents the CPCB standards along with preliminary methods of measurement of each criteria pollutant. The QA/QC procedures are presented in more details at (http://cpcb.nic.in/oldwebsite/Air/cgcm/cgcm.html).

3.2. Persistence of Exceedance

Persistence of exceedance was analyzed for criteria pollutants for each year by grouping number of exceedance days. This type of analysis would indicate the frequency of exceedances occurring on two consecutive days as mandated in the standard.

Data analysis-correlations, ratios of criteria pollutants, time series analysis, monthly and diurnal averages have been used to identify the sources of the pollutants and represent temporal variations of the pollutants on annual, seasonal and diurnal basis.

4. Results and Discussion

4.1. Design Value Trends of Criteria Pollutants

The design value trends of daily 24-hour NO_2 and SO_2

Table 1. National ambient air quality standards (revised since 2009).

S. No	Pollutant	Time Weighted Average	Concentration in Ambient Air: Industrial, Residential, Rural and Other Area	Concentration in Ambient Air: Ecological Sensitive Area (Notified by Central Government)	Methods of Measurement
1	Sulphur Dioxide (SO_2) μg/m^3	Annual	50	20	Improved West and Geake Ultraviolet Fluorescence
		24 Hours	80	80	
2	Nitrogen Dioxide (NO_2) μg/m^3	Annual	40	30	Modified Jacob & Hochheiser (NA-Arsenic Method)
		24 Hours	80	80	
3	PM_{10} μg/m^3	Annual	60	60	Gravimetric TOEM Beta Attenuation
		24 Hours	100	100	
4	$PM_{2.5}$ μg/m^3	Annual	40	40	Gravimetric TOEM Beta Atenuation
		24 Hours	60	60	
5	Carbon Monoxide mg/m^3	8 Hours	02	02	Non Dispersive Infra Red (NDIR) Spectroscopy
		1 Hour	04	04	

values have been illustrated in **Figures 2(a)-(b)** respectively. The initiative to convert public transport from diesel fuel to Compressed Natural Gas (CNG) was launched in April 2001. This led to a considerable decrease of air pollutants [16]. However, as seen in **Figure 2(a)** that at two of the sites (ITO and Sirifort), design concentrations of NO_2 exceed the National Ambient Air Quality Standards of 80 μg/m^3, based on the new standards released by CPCB in November 2009. There is a sharp increase on NO_2 concentration at ITO in 2005 and at Sirifort in 2007 with a decrease thereafter. Emissions at an urban site such as ITO and semi-urban site such as Sirifort are highly variable and affected by traffic flow patterns [17] that can result in fluctuations of concentrations. Sirifort may also be influenced by NO_2 emissions from thermal power plant at Badarpur depending on wind direction. Note, there is again a sharp rise of NO_2 levels at ITO in 2009. ITO recorded unusually high ozone concentrations in 2009 [18,19]. NO is emitted from traffic which is converted to NO_2 by non-linear photochemical reactions governed by ozone concentrations particularly during the early morning rush hours when the sunlight catalyzes the interactions between NO_x and VOC to enhance ground level ozone [14]. It is thus difficult to devise appropriate emission strategies for NO_2 concentrations for a traffic junction like ITO. DCE being a relatively clean site away from major roadways does not feel the vehicular impact and shows a steady decreasing trend.

Design values of SO_2 reveal that concentrations at all sites are mostly well below the standard (**Figure 2(b)**). Industrial emissions are the primary contributors to SO_2 in Delhi [20]. The diesel vehicles in Delhi do not make much impact on SO_2 concentrations at sites such as ITO which is impacted by vehicular emissions [21] such as ITO. ITO and DCE have relatively higher SO_2 concentrations (40 - 60) μg/m^3 as compared to Sirifort. The SO_2 concentrations at ITO can be affected by the Pragati power plant whereas DCE is influenced by wind-borne pollution from surrounding industries.

Design value trends of 8-hour CO concentrations based on 22nd highest values (**Figure 2(c)**) reveal decrease in CO concentrations at observational sites, though concentrations are above the current CPCB standard of 2 mg/m^3. The decreasing trend may be due to lowering of CO concentrations from vehicular sources because of newer improved engines, advanced emission reduction technology and cheaper fuel like diesel and CNG replacing gasoline. DCE maintained constant values slightly above 2 mg/m^3 indicating near compliance with the CO standards. The reason might be that the location of DCE observational site is far away from major roads.

The design values of 24-hour concentrations of $PM_{2.5}$ at ITO (**Figure 2(d)**) disclose that $PM_{2.5}$ concentrations are far above the US and CPCB NAAQS. The exceedance of $PM_{2.5}$ indicates that the stringent measures imposed on vehicular emissions are inadequate in controlling $PM_{2.5}$. Vehicle exhaust, construction activity and road side dust are important sources for fine particulate matter. However, $PM_{2.5}$ concentrations do display decreasing trend. In case of PM_{10} concentrations at DCE (**Figure 2(e)**) which exceeds national and international standards (US NAAQS) the most important contributors in Delhi are industrial sources [20] and roadside dust.

4.2. Persistence of Exceedances

Figure 3 reveals the persistence of exceedances of NO_2 at ITO site, although number of 1-day exceedances are highest in each year, there are episodes of exceedances in each year for other two sites also, which persist for several consecutive days. ITO has the highest number of

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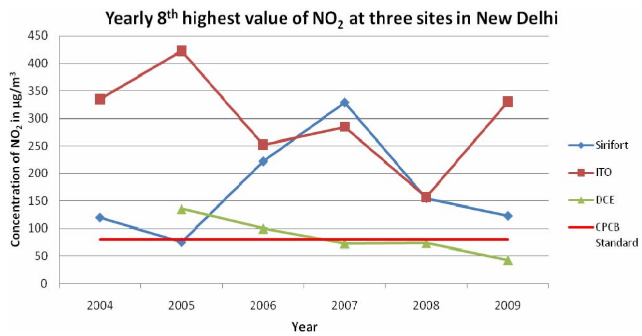

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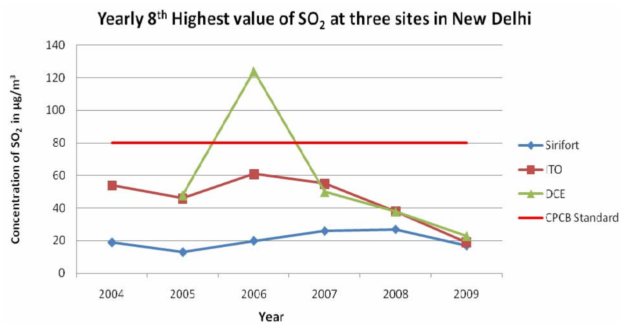

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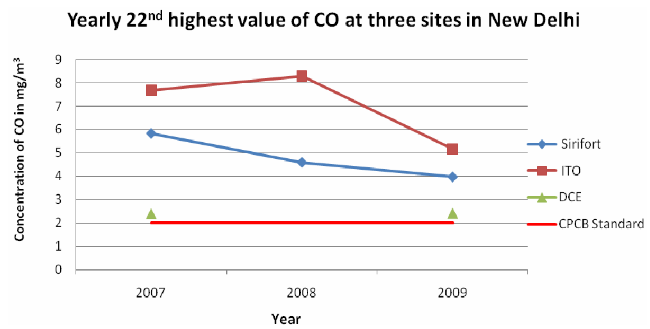

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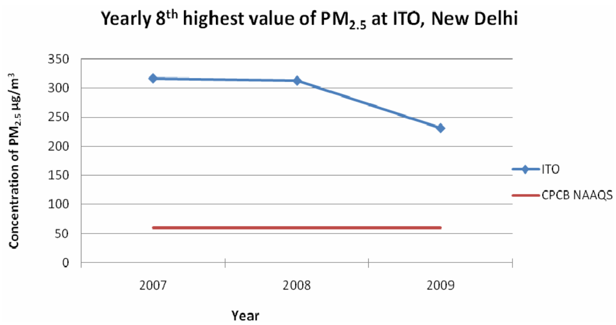

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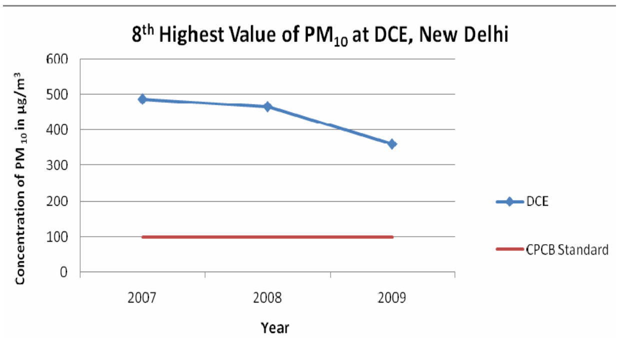


(e)

Figure 2. (a) Design value trends of NO_2 for ITO, Sirifort and DCE, New Delhi; (b) Design values of SO_2 at ITO, Sirifort and DCE, New Delhi; (c) Design values of CO at ITO, Sirifort and DCE, New Delhi; (d) Design values of $PM_{2.5}$ at ITO, New Delhi; (e) Design values of PM_{10} at DCE, New Delhi.

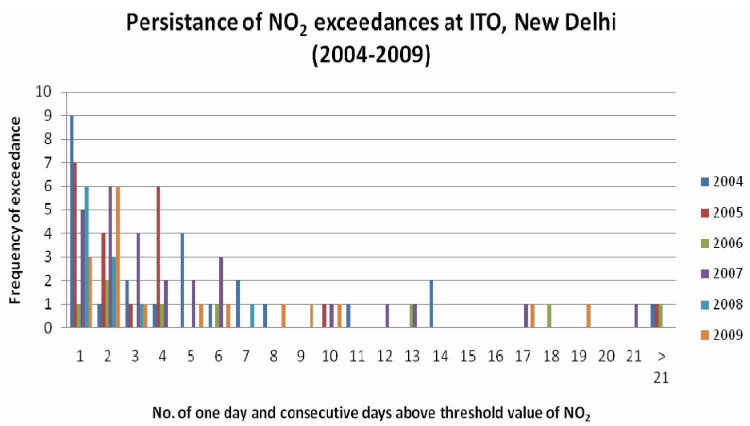


Figure 3. Persistence and count of exceedance.

persistent exceedances amongst the three sites with highest number of consecutive days (> 21) exceeding the threshold values in some years. For urban Sirifort and residential DCE although the number of successive days exceeding threshold values is lower than ITO site, there are consecutive days where the standard is exceeded The persistence analysis indicates high concentrations of NO_2 at traffic junction at ITO due to dominance of diesel vehicles. NO_2 shows noticeable day-today autocorrelation lasting for up to two days exhibiting some temporal dependence on the previous NO_2 levels and atmospheric processes.

The persistence of CO exceedances at ITO and Sirifort (**Table 2**) indicate that unlike NO_2 although there is less tendency for CO exceedances to last for more than two consecutive days, CO does not exhibit significant day-to-day autocorrelations, indicating the ambient concentrations are more random and not influenced as much by previous day's concentrations.

The persistence of $PM_{2.5}$ and PM_{10} exceedances (**Table 3**) every year reveal episodes of 2 consecutive days and above exceedances every year since 2007. Particulate matters also do not divulge autocorrelations. Therefore, persistence of exceedances is influenced by high intermittent emissions of particulate matter.

The persistence of exceedance of pollutants questions the validity of standards based on exceedance of two consecutive days. This persistence needs to be taken into account in developing future policy.

4.3. Monthly Averages of Criteria Pollutants

Monthly averages of NO_2, CO, $PM_{2.5}$ and PM_{10} have been studied. For Delhi, CO is considered to be mostly from gasoline-fuelled vehicles, NO_2 and PM_{10} are influenced by vehicular and industrial emissions; $PM_{2.5}$ by vehicular, industrial and fuelwood emissions in winter. CO does not exhibit noticeable inter-annual variability at any of the three sites, signifying that there is not much variation in emission sources from one year to the next (Figure not shown). However, there is significant inter-annual and seasonal variability in the concentration of other criteria pollutants. $PM_{2.5}$ is characterized by high concentration in winter and low concentrations in the monsoon due to removal by precipitation and wet deposition. High PM_{10} concentrations in summer can be accounted to the effects of winds from WNW direction [5], which brings dust from the Thar Desert into Delhi. High winter averages for $PM_{2.5}$ and PM_{10} occur due to limited pollutant dispersion because of formation of high pressure system over Delhi [11] which results in lower mixing heights with stable boundary layers. The high monthly averages of $PM_{2.5}$ at ITO (**Table 4**) in January have decreased from 219 μg/m^3 in 2007 to 150 μg/m^3 in 2009 exhibiting the impact of control measures on vehicular emission. However, there are also varying sources of emission for PM in the winter months, due to an increase in the bio-mass burning for heating purposes [22] which explains higher peaks of PM_{10} at residential site such as DCE in winter (**Table 4**).

Table 2. Persistence of NO_2 exceedance at Sirifort and DCE (2004-2009).

Year ↓	1 day exceedance		2 day exceedance		3 consecutive days		4 consecutive days		5 consecutive days		6 consecutive days		7 day exceedance		10 consecutive days	
Site →	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE	Sirifort	DCE
2004	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
2005	0	10	0	2	0	0	0	0	0	2	0	0	0	0	0	0
2006	1	1	1	1	2	0	1	0	0	0	0	0	1	0	0	0
2007	8	3	7	0	3	0	3	0	3	0	0	0	0	0	0	0
2008	4	4	2	0	1	0	1	0	0	0	0	0	0	0	1	0
2009	7	4	3	0	1	0	0	0	0	0	1	0	0	0	0	0

Table 3. Count of exceedances for particulate matter.

2007			
$PM_{2.5}$ (ITO)		**PM_{10} (DCE)**	
Count of exceedances	Frequency	Count of exceedances	Frequency
1-day	2	1-day	8
2-day	4	2-day	2
3-day	3	3-day	1
4-day	3	4-day	2
5-day	2	5-day	6
9-day	1	6-day	2
16-day	1	7-day	1
22-day	1	8-day	1
33-day	1	9-day	1
		13-day	1
		14-day	1
		16-day	1
2008			
$PM_{2.5}$ (ITO)		**PM_{10}(DCE)**	
Count of exceedances	Frequency	Count of exceedances	Frequency
1-day	3	1-day	5
2-day	2	2-day	2
3-day	2	3-day	2
4-day	1	4-day	2
5-day	2	5-day	2
9-day	1	6-day	1
11-day	1	7-day	1
23-day	1	14-day	1
28-day	1	33 -day	2
30-day	1	39-day	1
39-day	1		
2009			
$PM_{2.5}$ (ITO)		**PM_{10} (DCE)**	
Count of exceedances	Frequency	Count of exceedances	Frequency
1-day	7	1-day	7
2-day	8	2-day	3
3-day	1	3-day	2
4-day	1	4-day	1
5-day	1	5-day	1
6-day	2	6-day	4
7-day	1	7-day	2
18-day	1	10-day	1
		12-day	1
		15-day	1
		17-day	1
		18-day	1

4.4. Ratios of Pollutants

As stated before vehicles are primary sources of carbon monoxide and nitrogen oxides (NO_x) in urban regions. NO is reactive, is emitted from anthropogenic sources and converted to NO_2. Impacts of mobile source emissions are associated with high CO/NO_2 ratios and low SO_2/NO_2 ratios whereas impacts of point source is seen with lower CO/NO_2 ratios and higher SO_2/NO_2 ratios [13]. Data from three monitoring sites were analyzed for CO/NO_2 ratios and SO_2/NO_2 ratios from 2007 to 2009 (**Table 5**). The annual ratios of CO/NO_2 are considerably higher than SO_2/NO_2 at all the three sites, confirming mobile emissions to be the primary source of air pollutants at the three sites. The uncharacteristic low value of CO/NO_2 ratio at Sirifort in 2007 can be accounted for by the spike in NO_2 emissions (**Figure 2(a)**). ITO has lower CO/NO_2 ratios as compared to Sirifort and DCE. At ITO, the NO_2 emissions are correspondingly higher because of the effect of industrial NO_2 emissions from Pragati thermal power plant and the proximity of outer ring road where diesel-powered trucks run during night hours bringing in excess NO_2 emissions into the site. At ITO the ratio shows a sharp increase in 2008 and this effect might be due to variable impact of NO_2 emissions from Pragati thermal power plant and traffic at crossroads in the vicinity. These results support the findings of analysis with 1998 and 1999 ambient data, which demonstrated higher CO/NO_2 ratios at ITO site in comparison to SO_2/NO_x ratios [11,12]. The seasonal ratios of these pollutants have also been computed (Table not shown). The SO_2/NO_2 ratios do not exhibit significant seasonal variations. However, CO/NO_2 ratios do show an increase during the period (April-September) that includes the rainy season as NO_2 is washed out by precipitation and CO is not as much affected since it is an inert compound. Winter months are characterized by increasing concentration levels of both the pollutants and, thus, the seasonal ratios are not much affected.

4.5. Correlations among Pollutants

The preliminary correlation analysis considered 24-hour averaged values of pollutants since 2007 to maintain consistency amongst pollutants. Linear regression of the statistical data reveals variable correlations between all pollutants for all three sites. Although more NO_x is emitted from diesel vehicles and more CO from gasoline vehicles, higher correlations in 2007 and 2008 at ITO site, indicate the emission mix is more homogeneous at ITO [16] than at Sirifort and DCE. The correlations between NO_x and $PM_{2.5}$ are higher in 2007 and 2008 at ITO since both originate primarily from vehicular exhaust emissions and poor correlation between NO_2 and PM_{10} suggests different sources of origin. In the Delhi region, significant proportions of PM_{10} concentrations are initiated by roadside dust, industrial emissions and long-distance transport from the Thar Desert during summer time.

Table 4. Monthly averages of $PM_{2.5}$ at ITO and PM_{10} at DCE.

Month	PM_{10} at DCE (mg/m^3)			$PM_{2.5}$ at ITO (mg/m^3)		
	2007	2008	2009	2007	2008	2009
January	397	475	254.52	219.67	151.64	149.58
February	232	337	228.2	137.73	137.73	122.57
March	202	271	215.49	79.49	79.49	87.26
April	355	185	264.62	96.84	96.84	55.5
May	225	185	198.25	67.66	67.66	54
June	172	96	150.36	63.33	63.33	69.1
July	102	106	116.13	45.08	45.08	51.65
August	99	89	NA	33.78	33.78	39.19
September	102	115	NA	47.35	47.35	33.85
October	291	307	268	159.89	159.89	138.74
November	370	356	NA	NA	NA	NA
December	373	325	NA	189.32	178.67	NA

Table 5. CO/NO_x and SO_2/NO_x Annual Ratios at ITO, Sirifort and DCE, New Delhi.

Annual Ratios at ITO		
Year	CO/NO_2	SO_2/NO_2
2007	6.40	0.06
2008	15.95	0.10
2009	24.04	0.05
Annual Ratios at Sirifort		
Year	CO/NO_2	SO_2/NO_2
2007	18.39	0.14
2008	32.07	0.22
2009	62.80	0.5
Annual Ratios at DCE		
Year	CO/NO_2	SO_2/NO_2
2007	45.92	0.52
2008	43.08	0.44
2009	77.96	1.1

There is no significant correlation between SO_2 and any of the pollutants for any year (not shown in Table). The significance of correlation test shows no significant correlations between pollutants in 2009. The spatial and annual variability of correlations (poor correlations in 2009 in comparison to 2007 and 2009) between the pollutants (**Table 6**) also depict the uncertainty of emission sources and influence of meteorological parameters such as temperature, wind speed and wind direction on emission mix.

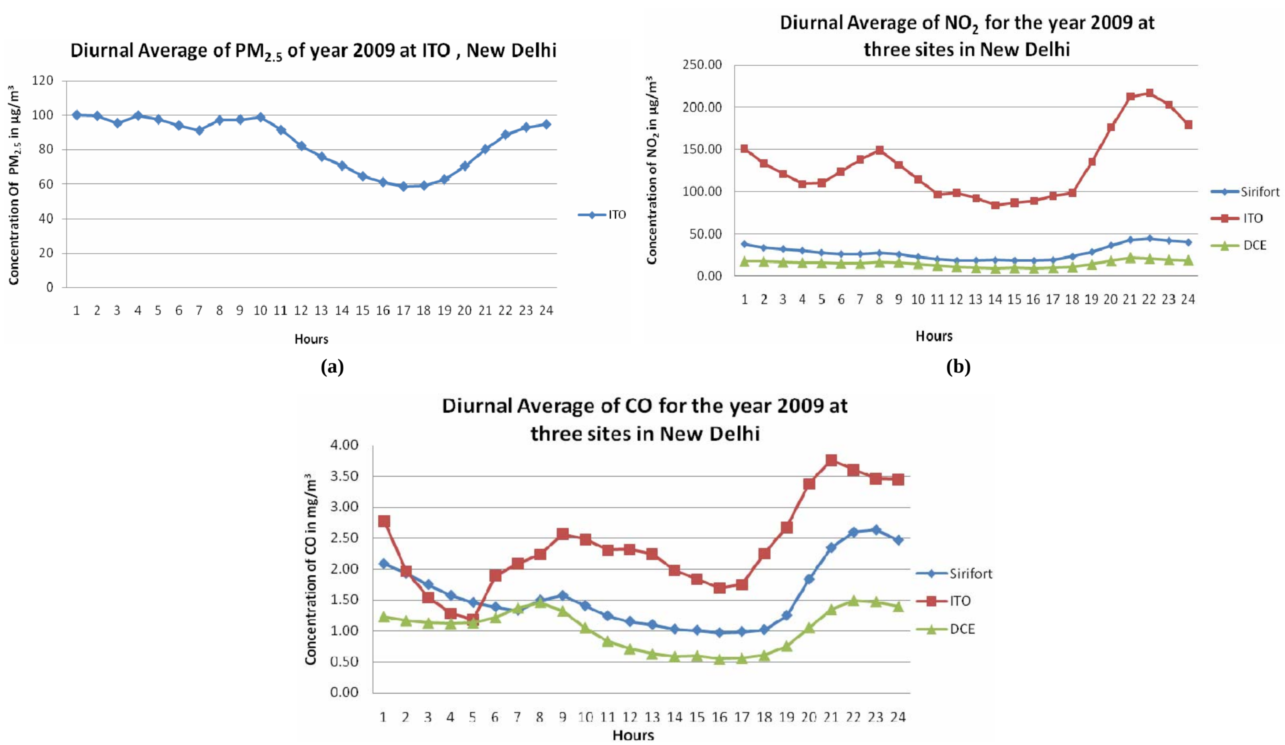
4.6. Diurnal Averages of Criteria Pollutants

Study of spatio-temporal characteristics of criteria pollutants is important to devise appropriate control strategies for them. The diurnal averages of pollutants reveal variations that occur because complex physical and chemical processes, which determine pollutant concentrations, are impacted by factors such as spatio-temporal variations of emission sources, daytime and nighttime chemistry of atmosphere, pollutant transport, and precipitation.

$PM_{2.5}$ averaged diurnal profile at ITO (**Figure 4(a)**), revealing early morning peak at 6 am followed by office rush hour traffic around 10 am. The $PM_{2.5}$ peak is at evening rush hour at 6 pm and rising concentration till mid night because of diesel fueled trucks travelling on outer ring road close to the ITO site and stable boundary layer, which cause nighttime increase in $PM_{2.5}$.

The NO_2 averaged diurnal profile (**Figure 4(b)**) indicates that NO_2 concentrations are much higher at ITO in comparison to Sirifort and DCE. The trend of NO_2 values at ITO is dictated by diesel vehicles and is strongly correlated with traffic rush hours. There is a peak in morning office rush hours during 7 am to 9 am. There is again a rise from 6 pm due to evening rush hour traffic. NO_2 concentrations at Sirifort and DCE are not much affected by traffic as compared to ITO. Weekends do not have any significant impact on NO_2 concentrations at all the three sites.

The CO diurnal (**Figure 4(c)**) profile is traffic related at all the three sites with rush hour traffic signal during morning and evening hours manifested at all the three sites. ITO has the highest CO concentration. Both ITO and Sirifort are characterized by higher nighttime concentrations. The elevated levels of nighttime concentrations of CO persist in the presence of stable boundary layer. CO is not affected by nighttime chemistry in the atmosphere. It is also seen that at the urban ITO site there are no significant differences between weekday and weekend effects. However, at DCE and the Sirifort sites there is a slight drop in CO concentrations over weekend indicating lesser traffic influence during this period.



(c)

Figure 4. (a) Diurnal average of $PM_{2.5}$ at ITO, New Delhi. (b) Diurnal average of NO_2 at ITO, DCE and Sirifort, New Delhi. (c) Diurnal average of CO at ITO, DCE and Sirifort, New Delhi.

Table 6. Correlations of pollutants.

Correlation for NO_2 vs. CO concentration			
Year	**ITO**	**Sirifort**	**DCE**
2007	0.643	0.701	0.085
2008	0.392	0.088	0.207
2009	0.069	0.26	0.121
Correlation for NO_2 vs. $PM_{2.5}$ at ITO, New Delhi		**Correlation for NO_2 vs. PM_{10} at DCE, New Delhi**	
2007	0.545	2007	0.171
2008	0.456	2008	0.054
2009	0.20	2009	0.26

5. Summary

A study was conducted with analysis of 1-hour, 8-hour and 24-hour averaged values of criteria pollutants at three monitoring sites over the Delhi region, to examine the spatio-temporal variability of the pollutants at these sites and examine the status of ambient air quality in Delhi. The results derived from the most recent observations for the years 2004-2009 reaffirmed the conclusions drawn by earlier studies that mobile sources contribute mostly to emissions loading. It is as well revealed that although ambient concentrations of SO_2 are still under control, the design values for NO_2, CO and $PM_{2.5}$ exhibit exceedance. There is considerable variability in the NO_2 design value at ITO, signifying that meteorological uncertainties and emission fluctuations have to be considered in designing emission controls. The persistence of exceedance needs to be taken into account in designing policy that two consecutive days' exceedance can be treated as violation of ambient air quality standards; more realistic procedures should be set as criteria to meet the standards. The variability in monthly averages of pollutants denotes the impact of seasonal variability on concentrations. The high CO/NO_x ratios indicate that gasoline-powered vehicles are significant contributors of air pollution at all the three sites. Low values of SO_2/NO_x indicate that point sources contribute mainly to SO_2 concentrations [11]. Despite exceedance, decrease of annual monthly concentrations of $PM_{2.5}$ suggests the benefits of vehicular emissions reduction measures. Annual ratios indicate traffic emissions as primary source for NO_x, CO and $PM_{2.5}$. The diurnal averages of criteria pollutants disclose that vehicular emissions are the main contributor towards temporal variation of these pollutants. Weekday and weekend diurnal averages do not show noticeable differences. Detailed emissions inventtory and advanced modeling approaches are required to present more realistic future scenarios for developing emissions control programs. A more comprehensive and holistic picture of air quality assessment in Delhi can occur only when better temporal and spatial coverage of emissions, meteorological and air quality data are integrated with appropriate modeling approaches.

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