International Journal of Research in Advent Technology, Vol.5, No.10, October 2017
E-ISSN: 2321-9637
Available online at www.ijrat.org

Interrelating Air Quality and Transport near a Heritage Structure: Victoria Memorial, Kolkata

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Abstract- Several studies have revealed that most of the air pollution load in Kolkata is due to high vehicular densities, coupled with disorganized traffic flow. Existing literatures suggest line source modeling as a way of predicting vehicular pollution in order to mitigate this pertinent problem since a traffic flow is effectively treated as a line source. Among many line source models CALINE4 offers several advantages over the others, and therefore it is chosen for the present study. The roads enclosing the famous architecture in Kolkata - Victoria Memorial Hall (VMH) are selected as the line sources, and relevant traffic, meteorological and pollutant data are collected and measured. Regression models have also been developed and validated, and CALINE4 is separately validated for the air pollutants viz. Carbon Monoxide (CO) Fine Particulate Matter ($PM_{2.5}$) and Nitrogen Dioxide (NO_2). Pollutant concentration contours have been developed using CALINE4. From the results (Pearson's Correlation, r it was observed that CALINE4 is very much efficient for CO prediction and $PM_{2.5}$ prediction, however, the performance dropped drastically predicting NO_2.

Index Terms-$PM_{2.5}$, CALINE4 model, Victoria Memorial, Kolkata, Air Pollution, Traffic.

1. INTRODUCTION

Air pollution has become a most prominent environmental issue in the last decade. Air pollution significantly increases the premature deaths in India [1].Urban air pollution from domestic and industrial sources is now controllable to a great extent due to technological and regulatory interventions. Despite significant improvements in fuel and engine technology, present day urban environment is mostly dominated by Vehicular Exhaust Emissions (VEE). It is now generally recognized that many of the substances directly emitted by vehicles in the ambient air or indirectly produced from the vehicular exhaust through photochemical reactions represent a serious hazard to human health [2]. A number of studies have recently shown an association between respiratory disease and proximity to roads that are busy and those travelled by a high number of heavy vehicles or trucks [3]. Impact of air pollution on monuments and buildings is a serious concern because it can lead to loss of important parts of our history and culture. In recent years, there have been significant changes in both the sources and amounts of emissions of air pollution that have altered the rate and extent of building damage [4].

Kolkata has been placed among 41 most polluted cities in the world concerning Suspended Particulate Matter (SPM) levels [5]. Pollution load from transport sector for Kolkata has been increased from 311 tons/day in 1988 to 417 tons/day in 1996 [6]. In the last ten years, the city has witnessed 63% rise in the number of vehicles. Victoria Memorial Hall (VMH), one of the magnificent monuments of India, located in the heart of the city is of great historical importance. VMH stand today as an absolute icon of the city representing the glorious and majestic British architecture. Four roads are enclosing it from all sides in a polygonal fashion. Air pollutant like oxides of nitrogen (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2) and fine particulate matter ($PM_{2.5}$) are the main source of degrading air quality near VMH. NO_2 and

SO_2 settle on the surface of the marble, corrode it and turning it yellow in colour.

The first systematic monitoring of ambient air quality in Kolkata began in 1970 when National Environmental Engineering Research Institute (NEERI) started measuring SPM, SO_2, and NO_2 at three stations. Subsequently, in 1984, the Central Pollution Control Board (CPCB) and in 1992, the West Bengal Pollution Control Board (WBPCB) started monitoring the air quality of Kolkata. The WBPCB measures respirable particulate matter (RPM or PM_{10}), Ozone (O_3), CO, SO_2, NO_2, and hydrocarbons (HC) by two automatic, six semi-automatics and eighteen manually operated stations [7].
Strategically managing vehicular air pollution problems have been suggested in literature also [8]. These management strategies essentially require establishing proper relationships between vehicles and atmospheric pollutant concentrations distribution [9].Wide-scale continuous air pollution assessment is impractical considering the workforce and the accessibility of point of interest [10]. A predictive model may be prepared to enact the pollution control regulation to achieve ambient standards/ goals [11]. Most of the air pollution assessment utilize simulation of dispersion from a given source to the point of interest [10]. Dispersion model varies in complexity from Gaussian dispersion model to models based on Computational Fluid Dynamics (CFD) [10], [12]. Most of the roadway traffic-based air pollution models depend on Gaussian dispersion model. Sharma et al. [13] indicated that line source air quality modeling plays a vital role in formulating air pollution control and management strategies by providing guidelines for better and more efficient air quality planning. Accordingly, it is always important to evaluate the adaptability and the accuracy of the model for different pollutants [10].

California Line Source Dispersion Model (CALINE) is one such Gaussian dispersion based modeling tool, which is used to assess the concentration of air pollutants. CALINE is designed to predict the roadside carbon-monoxide concentration [14]. CALINE model was initially based on the modified version of Gaussian point source plume model. The latest version of CALINE4 incorporated the line source Gaussian dispersion model and also developed to predict the concentration of particulate matter and nitrogen oxides [14]. However, the reliability of CALINE4 to assess the concentration of particulate matter and nitrogen oxides has not been established. CALROADS View, an available window based CALINE4 modeling tool which has been reported to be applied for vehicular pollution modeling [15] is selected for the study.

2. MATERIAL AND METHODS

2.1. *Field Measurements*

Sampling and monitoring of $PM_{2.5}$, NO_X, and CO were carried near VMH (22° 32' 42" North, 88° 20' 33" East). The four roads enclosing VMH are Queens way in the North, Hospital Road in the

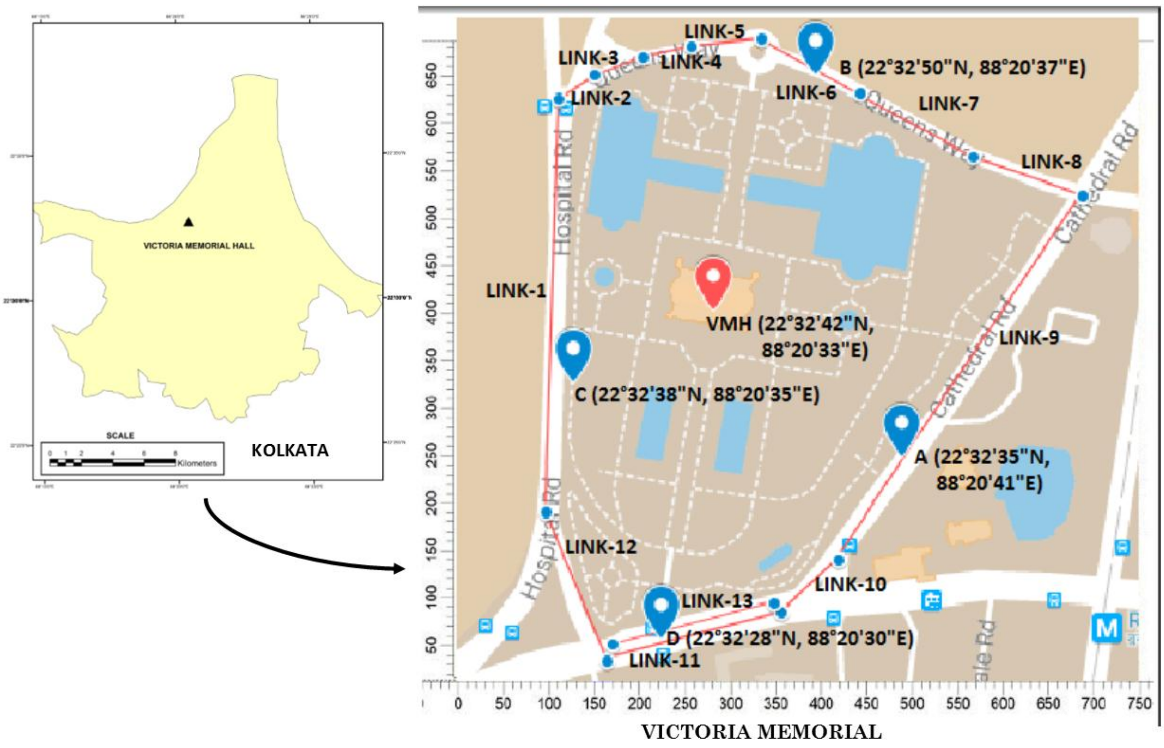


Fig. 1. Aerial view of Monitoring Site (Scales are in meter).

west, Acharya Jagadish Chandra Bose Road in the south and Cathedral road in the east. All roads are a double lane, with A.J.C Bose road being effectively four lanes, since there is a flyover within it that acts as an elevated line source of the average height of 4m from surface level.

The sampling period for this study spanned over the period of six months from October 2010 to March 2011. For sampling of NO_2 at VMH, Respirable Dust Samplers with side attachment for gaseous sampling (Envirotech APM 460 BL) and for sampling particulate matter of size less than 2.5µm ($PM_{2.5}$), Fine particulate samplers (Envirotech APM 550) were used with receptor height being 1.0 m above the ground level. The sampling period was 5 hours. For a conservative analysis, the peak hour between 8 AM to 1 PM was chosen. Total forty-five sets of data were collected near VMH (Ref. Fig. 1.). $PM_{2.5}$ was measured in another four locations: A (22° 32' 35" North, 88° 20' 41" East), B (22° 32' 50" North, 88° 20' 37" East), C (22° 32' 38" North, 88° 20' 35" East) and D (22° 32' 42" North, 88° 28' 30" East) (as shown in the Fig. 1.) by SIDEPAK AM510 Personal Aerosol Monitor. The air pollutant and traffic volume data were collected on weekdays and weekends, twice a week. Weekend's data collection was limited to Saturday only, as authors does not have the permission of carrying monitoring work on Sunday. The traffic volume data of major motorised vehicles, namely taxi/private car, auto, bus/truck and two-wheelers were collected. Correlation analysis amongst the air pollutants and mentioned motorised traffic constituents had been performed to examine if there exists any correlation between them. Linear regression analysis has been done by taking mentioned motorised traffic constituents as independent and measured pollutant concentrations as dependent variables to derive separate regression models for CO, $PM_{2.5,}$ and NO_2. Correlation analysis between $PM_{2.5}$ concentrations measured by Envirotech APM 550 and as measured by SIDEPAK AM510 Personal Aerosol Monitor also performed.

2.2. *Numerical Methods*

A CALINE4 based, free, open accessible model CALROADS View is also validated for predicting CO, $PM_{2.5}$, NO_2 concentration from the same measured traffic and air pollutant concentrations. The model input data for the study are explained here.

Link Geometry: The model is run considering 13 links for no canyon case, the bridge option being exercised on the 13th link. Coordinates are chosen for no canyon case, as the site cannot be treated as a road canyon (partially zig-zag links in Fig1).

Aerodynamic Roughness Coefficient: As the road selected is in a commercial area with dense traffic, a roughness coefficient of 400cm is chosen.

Receptor Co-ordinates (x, y, z): The receptor point for validation is located at Weather Monitoring Station. The coordinates for without canyon case is (384.97m, 411.40m, 3m). There are four more validation point for $PM_{2.5}$: A(453.38m,188.55m,1m), B(379.8m,668.6m,1m), C(106m,331.5m,1m) and D(193.34m, 36.35m, 1m).

Link Height: As the height of the road above the surrounding terrain is negligible, the value of link height has been considered to be zero. Only for link 13, the height is 4m.

Mixing Zone Width: This has been taken as 21m, as the physical road width is being 15m.

Mixing Zone Height: The mixing zone height is calculated with the help of the below-mentioned Eq (1). The values of parameters, in this case, are Z = 16m (from freemeteo website), Z_0=400cm (roughness coefficient) and site latitude for Victoria being 22.50 N. After calculation and due consideration the average mixing height is taken as 1000m.

$$\text{Mixing Height (MIXH)} = \frac{0.185U \times K}{ln\left(\frac{Z}{Z_0}\right) \times f} \qquad \ldots.(1)$$

Where,
U = wind speed (m/s) measured at height Z (m)
K = von − Karman constant (= 0.35)
f = Coriolis parameter ($= 1.45 \times 10^{-4}$ Cos θ) (rad/s)
$\theta = 90° -$ site latitude
Z_0 = Surface Roughness (m)

Stability Class: For moderate solar radiation and wind speed generally ranging between 1.5m/sec to 3.5m/sec, stability class has been taken as B throughout the study period except for three days. On those three days stability class has been chosen as C, as the recorded wind speed was higher than 4m/s on those three days.

Background Concentration: Background concentration is measured on a typical bandh day. For $PM_{2.5}$ and NO_2 they are 21µg/m^3 and 11µg/m^3 respectively as obtained from VMH station on 7th September'2007. For CO the concentration is derived from literature [6].

2.3. *Quality Control and Quality Assurance*

The portable SIDEPAK AM510 Personal Aerosol Monitor is calibrated against a Fine Particulate Samplers (Envirotech APM 550) in the Environmental Engineering Laboratory of Department of Civil Engineering, Jadavpur University for quality assurance of fine particulate ($PM_{2.5}$) concentration in the locations: A, B, C, and D (as mentioned earlier). The result of this study shows an R^2 value of 0.992.

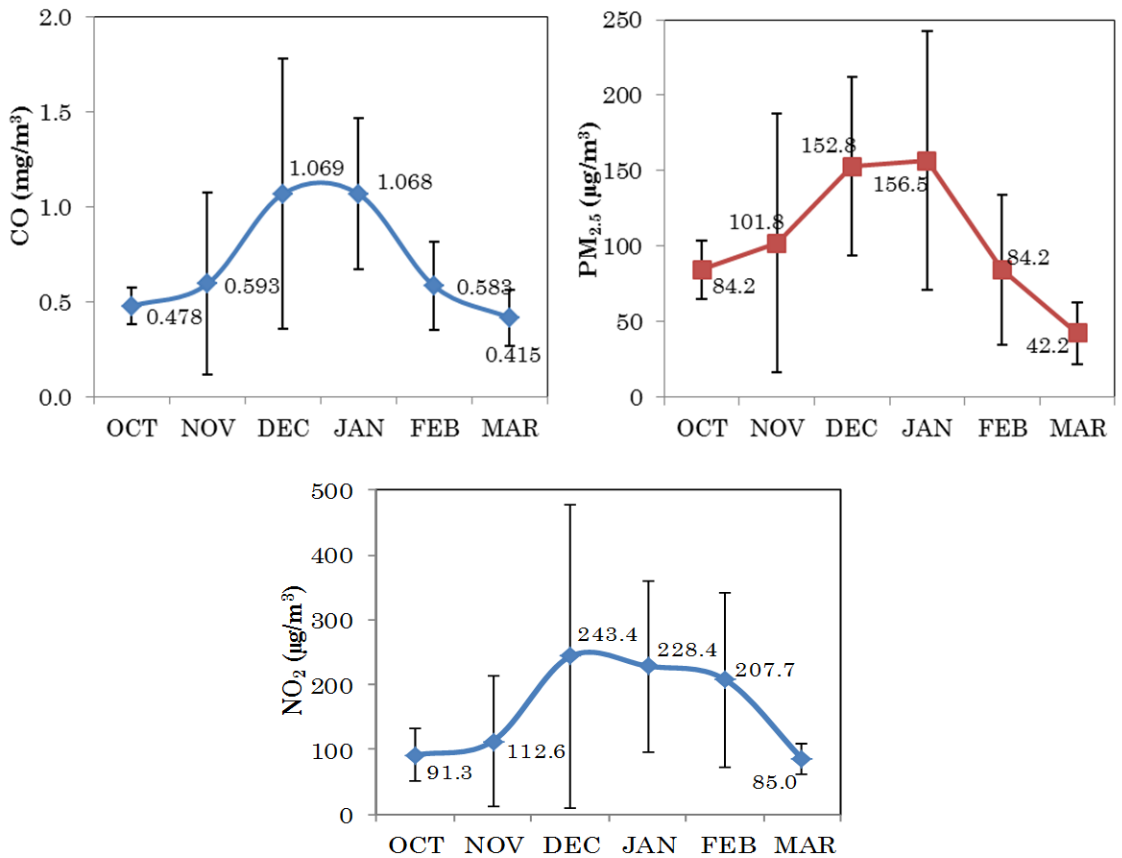


Fig. 2. Monthly averages of $PM_{2.5}$, CO, and NO_2 during the study period.

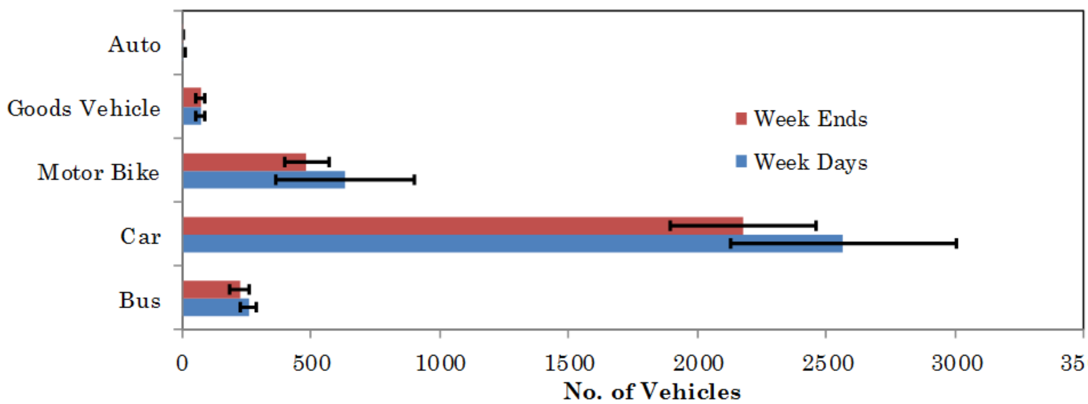


Fig. 3. Average Traffic Variation for a weekday and weekend.

3. Result and Discussion

3.1. *Descriptive analysis of pollutant concentrations and traffic data*

The concentration of $PM_{2.5}$, CO, and NO_2 measured from October'2010 to March'2011. Forty-Five measurements observed for each of the pollutants. The concentration level of CO, $PM_{2.5}$, and NO_2 ranged between 0.15 - 2.39mg/m^3, 12.054 – 322.338 µg/m^3, and 25 – 671.9 µg/m^3 respectively. The maximum concentration of all the three pollutants at VMH was observed in Weekdays.

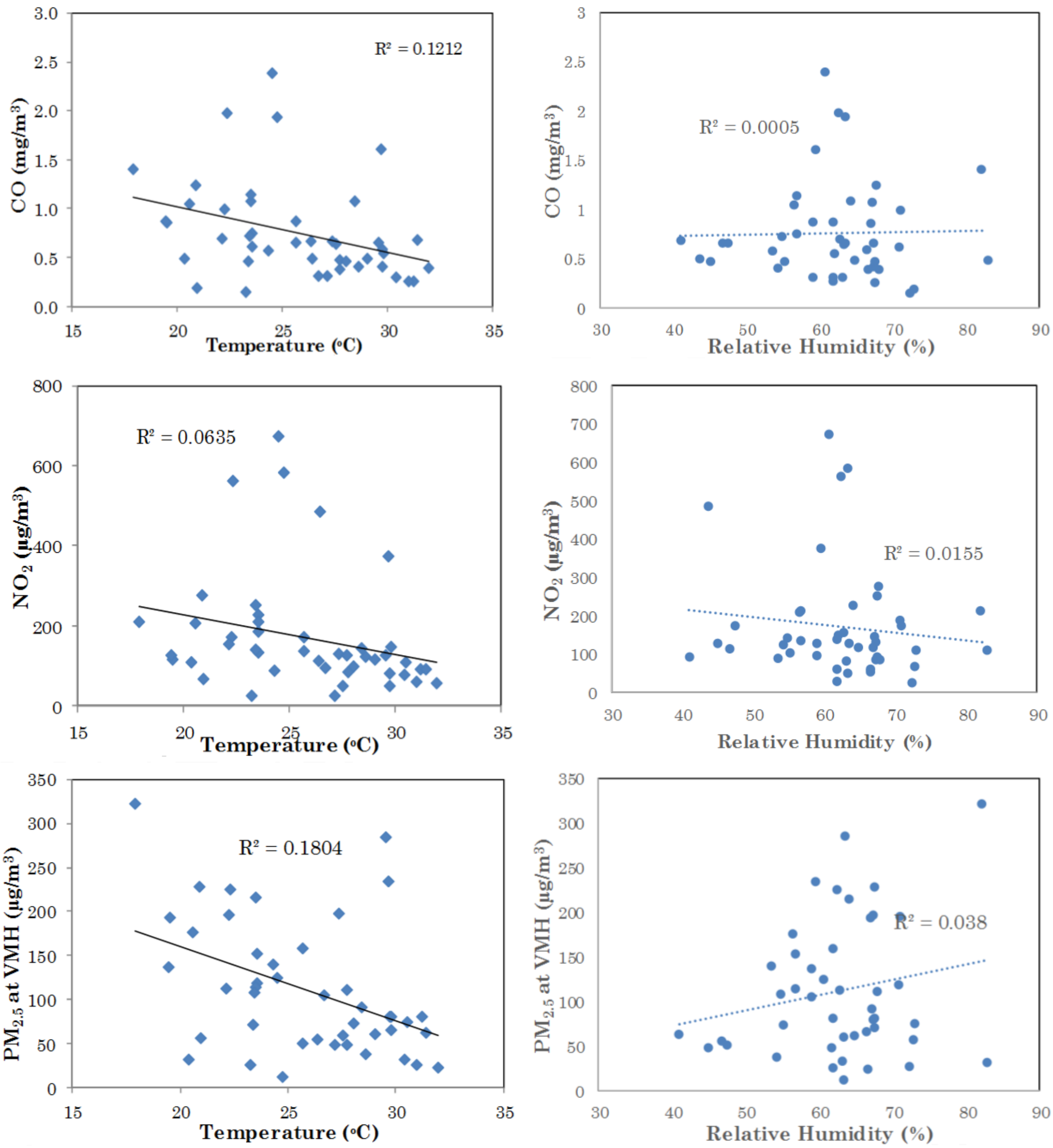


Fig. 4. Statistical relations between pollutant exposure level and temperature and humidity.

The statistical significance of the weekdays and non-weekdays measurement difference at VMH was assessed using Student's t-test, and the observed p-value is 0.23 for CO, 0.14 for NO_2, and 0.80 for $PM_{2.5}$. Which indicates that probability of our null hypothesis is true ($p>0.05$) in every case, i.e., no statistically meaningful difference is detected in case of weekdays and weekends measurement for each pollutant. Fig. 2 represents the pollutants concentration in different months during the study period. It can be observed from the Fig. 2 that the concentrations of the pollutants are increasing during November and December, while they are descending from January to March. This is because winter in Kolkata has a short duration, and temperatures tend to rise from the beginning of February, which in turn increases the air volume for mixing and hence decreases the concentration.

Fig. 3 represents the traffic flow variations of different traffic components for weekdays and weekends (Saturday).The statistical testing for differences in traffic flow characteristics was carried out for weekday's and weekend's traffic flow. p-value of Student's t-test suggests that there were significant differences in traffic flow for each component, although the total volume of traffic flow was almost same for both the cases. The effect of temperature and wind speed also investigated. It was found that when the temperature increases the concentration of pollutant decreases (Fig. 2.).

The moderately inverse correlation found between the pollutant concentration and temperature (0.35 for CO, 0.25 for NO_2 and 0.425 for $PM_{2.5}$). Correlation analysis suggests that relative humidity and pollutant concentration were not significantly correlated (-0.003 for CO, and -0.011 for NO_2), except for $PM_{2.5}$, where a weakly positive correlation was found. Fig. 4 represents the concentrations as a function of temperature and relative humidity. From Fig. 4 it can be observed that when the temperature increases, pollutant concentration decreases. The effect of wind speed on different pollutant concentration was observed and represented in Fig. 5. From Fig. 5 it can be observed that in calm weather (≤ 2 m/s wind speed) the pollutant concentration was higher than the pollution concentration in weather condition where wind speed was more than 2 m/s.

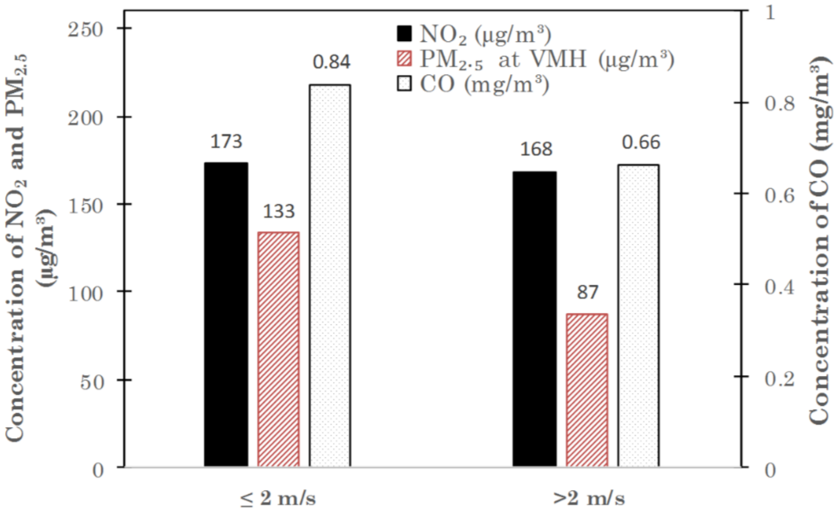


Fig. 5. The relation between pollutant exposure level and temperature

Correlation analysis amongst the air pollutants and mentioned motorized traffic constituents had been performed in SPSS (SPSS Inc. 1999) to examine if there exists any correlation between them and this has been furnished in Table 1. From Table 1 it can be observed that different traffic component was weakly correlated with the pollutant concentration data.

Table 1. Summary of Regression Models.

	CO (mg/m^3)	NO_2 ($\mu g/m^3$)	$PM_{2.5}$ VMH ($\mu g/m^3$)	Bus	Car	Motor Bike	Goods Vehicle	Auto
CO (mg/m^3)	1.000							
NO_2 ($\mu g/m^3$)	0.913	1.000						
$PM_{2.5}$ VMH ($\mu g/m^3$)	0.492	0.303	1.000					
Bus	-0.016	-0.145	0.098	1.000				
Car	0.088	-0.010	0.224	0.686	1.000			
Motor Bike	-0.190	-0.186	-0.186	0.324	-0.031	1.000		
Goods Vehicle	0.103	0.179	0.112	0.017	0.349	0.105	1.000	
Auto	-0.224	-0.168	-0.421	0.166	0.062	0.134	-0.278	1.000

However CO was strongly correlated to NO_2 and $PM_{2.5}$, and $PM_{2.5}$ was moderately correlated with NO_2 data.

A regression model developed to predict roadside pollutant concentration with the measured independent variable (hourly volumes of different motorized vehicles) and dependent variables (measured pollutant concentrations) for the sampling period are taken. The regression model developed with confidence level 95% and Zero constant. The developed regression model has been furnished in Table 2 with necessary multiple R-value.

Table 2. Summary of Regression Models.

Pollutant	Regression Equations	Multiple R
CO	$CO\ (mg/m^3) = 0.002444(Bus) - 0.000050(Car) - 0.000383(Motor\ Bike) + 0.004401(Goods\ Vehicle) - 0.014931(Auto)$	0.844
$PM_{2.5}$	$PM_{2.5}\ (\mu g/m^3) = 0.322033(Bus) + 0.040877(Car) - 0.042964(Motor\ Bike) - 0.004924(Goods\ Vehicle) - 7.393893(Auto)$	0.876
NO_2	$NO_2\ (\mu g/m^3) = 0.706522(Bus) - 0.021203(Car) - 0.125676(Motor\ Bike) + 1.935126(Goods\ Vehicle) - 4.040663(Auto)$	0.781

From the above two tables, it can be inferred that the pollutant concentration does not directly vary with the number of traffic volume and the above regression models are not accurate on predicting the pollutant concentration at the given site. Pollutant concentration actually depends on the air volume available for mixing and which is, in turn, depends on several other meteorological factors like wind speed, angle, temperature, etc. and pollutant concentration may do not vary linearly with every independent parameter.

3.2. *Validation of CALINE4 (CALROADS) Model*

In order to validate the CALINE4 model in the study area, variable values for the sampling period are selected. With the help of mentioned meteorological data and traffic volume data, CALROADS has been

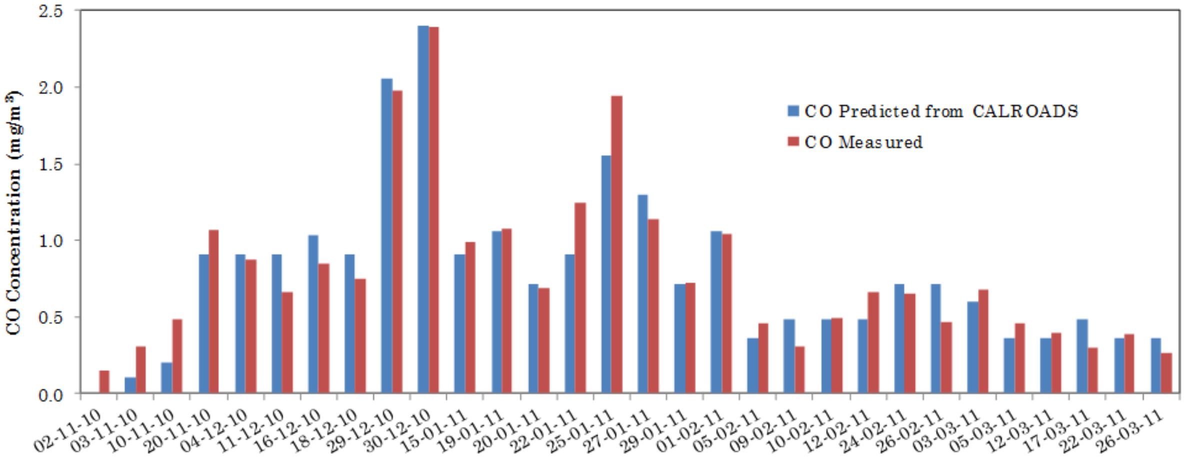


Fig. 6. Observed and Predicted CO concentration at VMH on Several days.

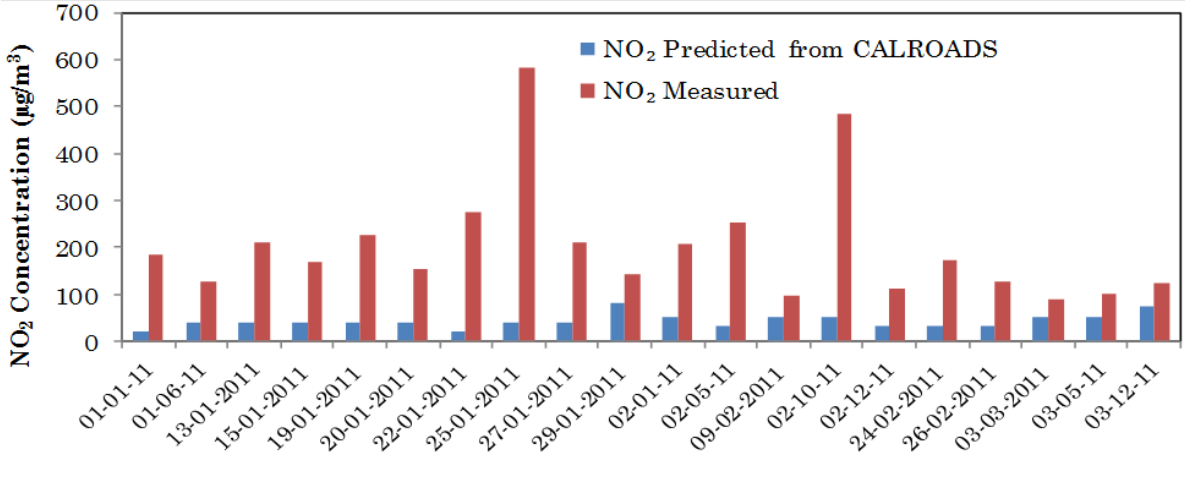


Fig. 7. Observed and Predicted NO_2 concentration at VMH on Several days.

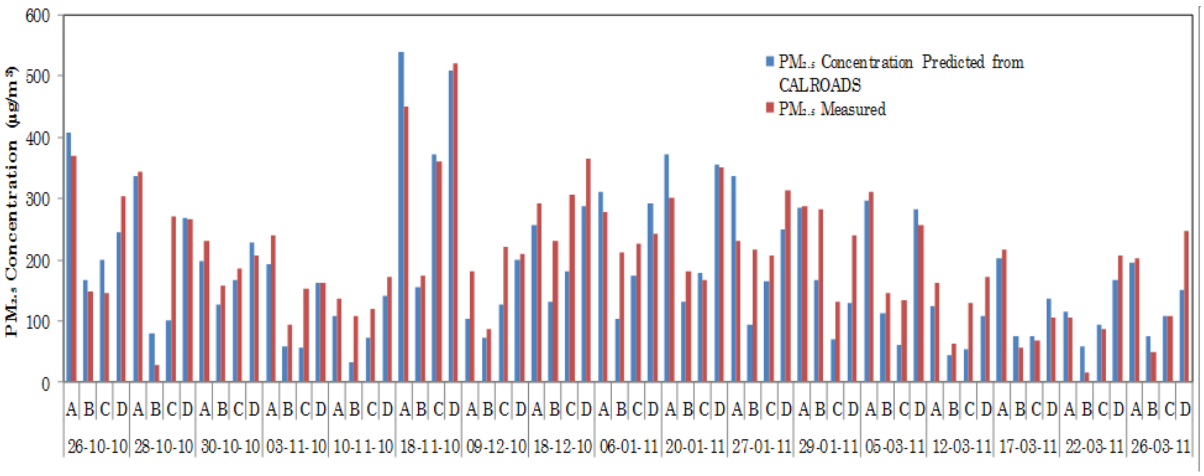


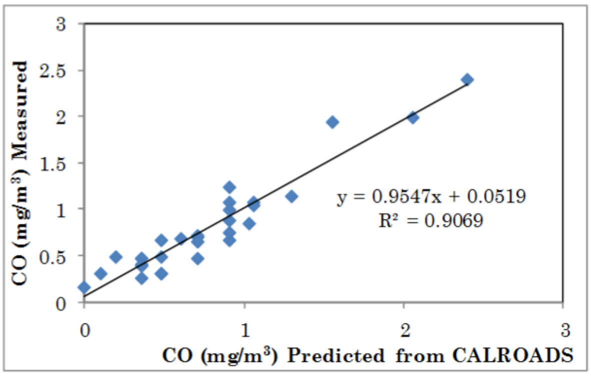
Fig. 8. Observed and Predicted $PM_{2.5}$ concentration at location A, B, C, D on Several days.

run without canyon option. CALROADS View estimates ambient pollutant concentration in ppm[16]. With the help of standard unit conversion equation, concentrations in $\mu g/m^3$ were calculated for CALROADS View predicted values.

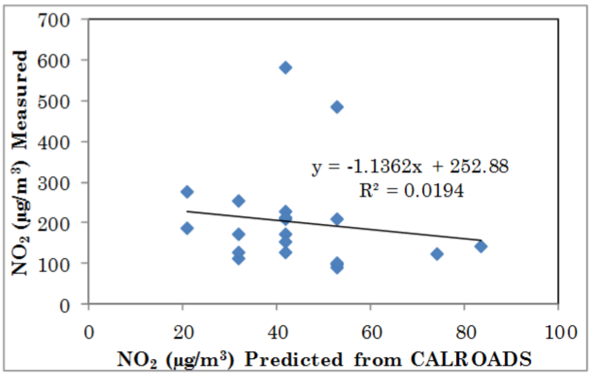
Fig. 6, 7 and 8 compare the daily observed concentrations of CO at VMH, NO_2 at VMH, and $PM_{2.5}$ at other four location (A, B, C, D) to the equivalent values (including background concentration) predicted by CALINE4 model.

CALROADS View predicted concentrations of each pollutant and their validation results with the actual measured data was shown in Table-3.

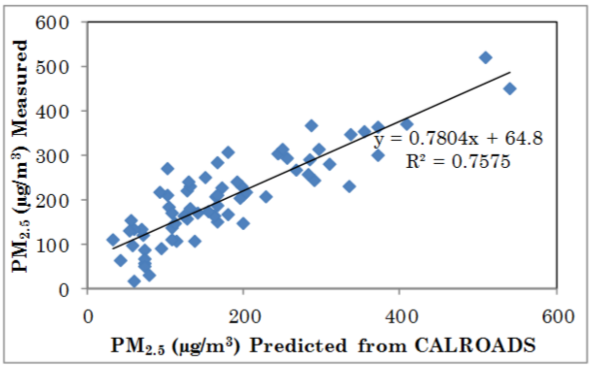
The best-fit curves for the pollutants are shown in Figure 9-(i),(ii) and (iii) for CO, NO_2, and $PM_{2.5}$, respectively.



9(i)



9(ii)



9 (iii)

Fig. 9. Best Fit Straight Line between Measured Pollutant Concentrations and CALROADS Predicted Concentrations for (i) CO, (ii) NO_2, and (iii) $PM_{2.5}$

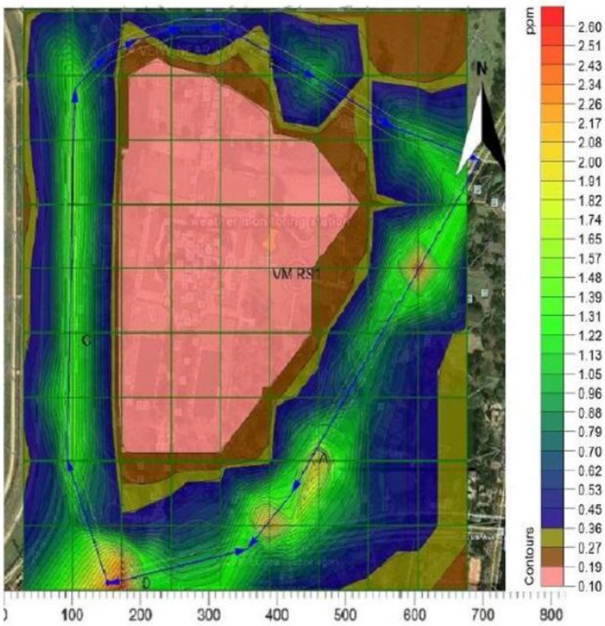
Table 3. Summary of CALROADS Model.

	CO	$PM_{2.5}$	NO_2
Calibration Equation	$C_a = 0.955C_m + 0.052$	$C_a = 0.78C_m + 64.8$	$C_a = 1.136C_m + 252.88$
Pearson's Correlation (R) (significance at 5% level)	0.95	0.87	0.14

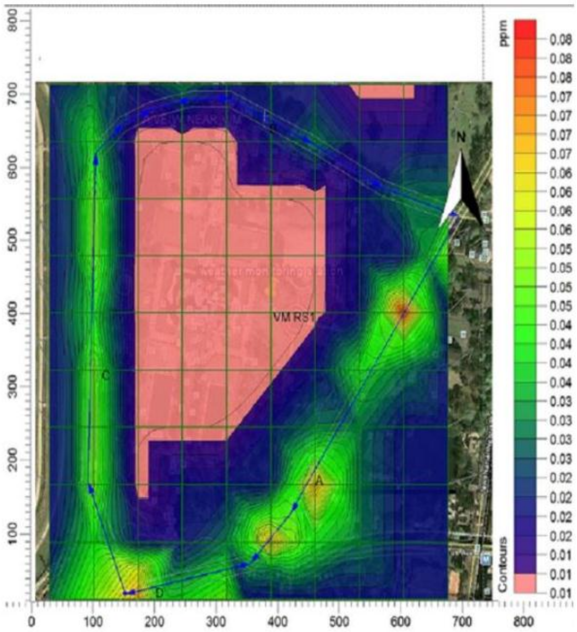
where C_a = Actual Concentration; C_m = Model Predicted Concentration

3.3. *Pollutant Contours by CALROADS View*

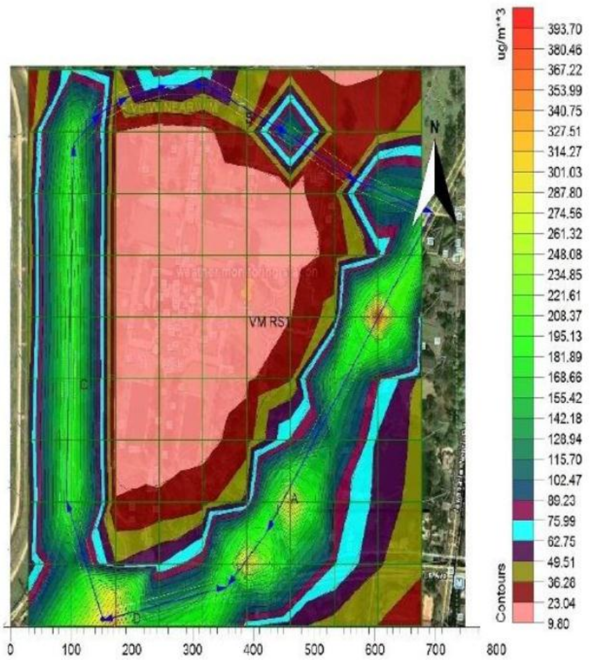
Spatial variation of pollutant concentrations or pollutant concentration contour can be developed by CALROADS View[16] if there be multiple numbers of selected receptor point.



10 (i)



10(ii)



10 (iii)

Fig. 10. Concentration Contour around VMH on 20/1/2011 for (i) CO, (ii) NO_2, and (iii) $PM_{2.5}$

To create pollutant contours for CO, NO_2, and$PM_{2.5}$, 28th monitoring day (20.1.2011) was chosen. An array of 101 receptors placed in a grid covering 727m x 1232m area (colourful rectangular area in figure 10(i), (ii) and (iii), encompassing VMH grounds selected for contour generation). The generated contour maps for CO, NO_2, and $PM_{2.5}$ are shown in figure 10(i), 10(ii) and 10(iii) respectively.

3.4. *Comparison between Regression Model and CALINE4 (CALROADS)*

The regression model was developed with the help of pollutant concentrations at VMH grounds. So it does not incorporate the dispersions of the pollutant in the atmosphere at all. So the prediction of pollutant levels is not possible with the help such type of regression models. The regression model could not be used due to several reasons, such as, i) the flexibility to define the receptor distance in the regression model, ii) the options to use the meteorological parameter, which is the guiding parameter for dispersion of the pollutants. On the other hand, CALINE4 is a well-established model, which is capable to predicted pollutant level up to 500m away from the roadway and also on a point on the roadway, as we have the flexibility to set up the receptor distance in the 500m radius. CALINE4 also gave better correlation for CO and nearly similar to the regression model for $PM_{2.5}$, but it ultimately miscalculated in the case of NO_2.Here validation of CALINE4 is conducted with a point situated within an enclosed area, hence testing its capability to predict the dispersion of the pollutants originating from multiple line sources at different distances. So it is applicable to any receptor point for which coordinates are known. Again the CALROADS View can generate a spatial variation of pollutant level in the form of contour maps. But simultaneously it is also to be noted that, CALINE4 model could not predict NO_2 level with acceptable accuracy, which may be because of its dependence on background concentration of atmospheric ozone [17]. Hence the choice of CALINE4 model should be made subject to the constraints of purpose and feasibility, the deciding factor being the choice of pollutant.

4. CONCLUSION

An approach has been presented for predicting the level of traffic-induced air pollutants namely, CO, $PM_{2.5}$, and NO_2 for a network of roadway enclosing a famous heritage monument and museum in the city of Kolkata, Victoria Memorial Hall. The study indicates the methodology to develop traffic constituent based regression model. A CALINE4 (CALROADS) model was also validated to develop CO, $PM_{2.5}$ and NO_2 level spatial variations in the form of contours in the same study area, along with suggesting the probable approaches towards decision-making in selecting between the two categories of models (regression-based and CALINE4), based on statistical and logical arguments.

During the study of CALINE4 correlation for CO was 0.952, a pretty high accuracy level, whereas correlation coefficient for $PM_{2.5}$ was 0.8703, a fairly acceptable one. But for NO_2 the model gave a correlation of 0.139, which makes it unsuitable for predicting the dispersion of NO_2 generated from on road traffic. This may be due to its dependence on background Ozone layer for prediction of NO_2 as reported in the literature. It has been found that Caline4 was unsuitable for measuring NO_2 for a background O_3 concentration less than 40ppb; whereas the background Ozone layer for Kolkata during the sampling period was much lower than that of 40ppb. So this result is very much in accordance with the actual conditions.

To keep the maximum concentration of above-mentioned pollutants below NAAQS, different alternatives can be taken. Such as increasing numbers of lanes to avoid congestion, introducing a change of process or raw materials to some extent in terms of new fuel driven vehicle, by replacing the old vehicles in different proportion, etc. All these steps involve certain amounts of costs. The reduction of pollution is evaluable in terms of profit gained. Therefore, the optimum option is required to be found out. But to know the impact of any alternative strategy over the extent of air quality improvement, the proper relationship between traffic characteristics and resulted pollutants are essentials to be evaluated. The study defines these interrelations from multiple angles to assess it from different aspects. In respect of Victoria, it may be of much use because soiling on the Victoria Memorial Hall has been quite a problem, and prediction of particulate matter concentration is essential to mitigate the existing problem. This study and its approaches thus might be helpful to the planners to develop strategies to manage automobile pollution problems as a way towards the goal of sustainable urban development.

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