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Air Quality Modeling in Street Canyons of Kolhapur City, Maharashtra, India

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Abstract:

Automobile transport has now become an inherent part of human life, and the negative aspects like air pollution are becoming more and more pronounced. Increased vehicular traffic is leading to deterioration of air quality in streets of Kolhapur city in recent years. It is very important to assess the impact of traffic related air pollution on human health, and to take administrative decisions for improving air quality. In present study, two street canyon models viz. STREET and STREET Box are applied to model the concentration of pollutants. The model results are based on traffic volumes, geometry of study area, and meteorological conditions prevailing in study area. Background values are obtained from National Ambient Air Quality Monitoring Station at Dabholkar Corner, Kolhapur. Hourly concentration of pollutants like SPM and SO_2 are computed using the models and those values are compared against the observed values in the selected street to find out best fit model for conditions existing in Kolhapur. STREET Box model was found to fairly estimate concentration of pollutants while STREET model was found to underestimate concentrations. A more accurate method is required to estimate background concentrations.

Keywords: Air quality, Street canyon model, Suspended Particulate Matter (SPM), Sulfur dioxide (SO_2)

1.0 Introduction:

Air quality in urban areas is getting deteriorated mainly due to the increased vehicular population in cities. Many of the pollutants either emitted directly or indirectly formed due to photochemical reactions taking place within the local atmosphere pose serious health hazard to humans (Vardoulakis et al. 2003). Main traffic related pollutants include: Carbon monoxide (CO), Nitrogen oxides (NO_x), Sulfur Dioxide (SO_2), hydrocarbons, and particulates. Poorly maintained vehicles gives rise to more pollution problems. These pollutants cause both acute and chronic effects on human health. CO reduces oxygen carrying capacity of blood; benzene pollutants can cause cancer whereas particulates and SO_2 can cause respiratory diseases like asthma, bronchitis (UNEP, 2009).

In urban areas where population and traffic density are relatively high, human exposure to hazardous substances is significant. Due to this concern, the street canyons are considered as hot spots for air pollution problems (A. Ghenu et al. 2007). Air quality dispersion models serve as a valuable tool for assessing the air quality against the National Ambient Air Quality Standards (NAAQS) and in decision making regarding the air pollution management. A variety of street canyon models are now available, starting from simple empirical models to complex Computational Fluid Dynamic (CFD) models (Vardoulakis et al. 2003). The pollutant concentration in street canyon mainly depends upon the traffic characteristics (type and number of vehicles), canyon geometry, urban background concentration, and meteorological parameters (wind speed and direction).

The objective of this study is to evaluate the impact of road traffic on population in nearby areas. One of the busiest streets in Kolhapur city i.e. Station Road, located in the heart of the city was chosen for the study purpose. Two empirical street canyon models are used to predict the concentrations of pollutants viz. Suspended Particulate Matter (SPM) and Sulfur Dioxide (SO_2) in the selected street. The general flow diagram of the procedure to calculate hourly concentration in street canyon based on traffic volume, canyon geometry, background concentrations and meteorological input data monitored at site is shown in fig. 1.

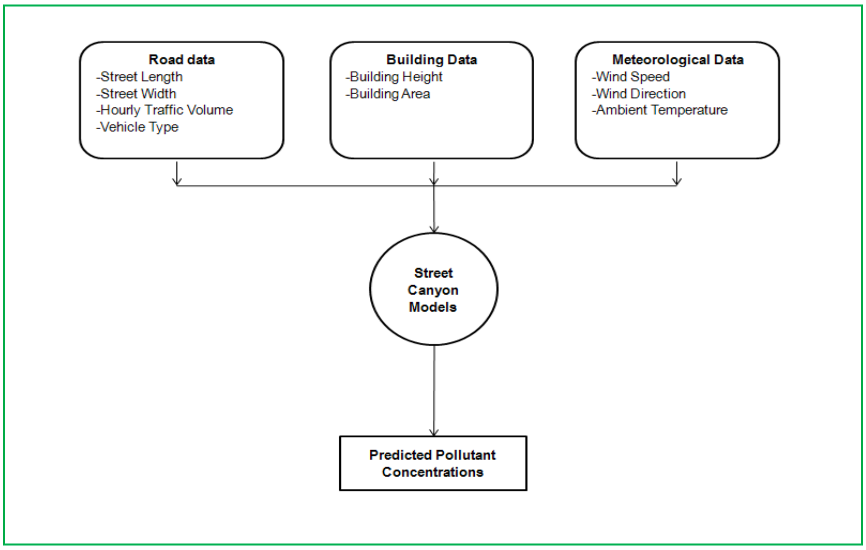

Figure 1: Flow diagram of the procedure to calculate pollutant concentrations in street canyons

2.0 Materials and Methodology:

2.1 Street Canyon Models:

A number of models have been applied in various street canyon and wind tunnel experiments. These models are very useful in traffic management, urban planning, pollution forecasting, and public health assessment, etc. This study uses two semi-empirical models viz. STREET and STREET Box models, to calculate ambient air concentrations of pollutants in street canyon. The following is the brief description of the models.

2.1.1 The STREET Box Model:

STREET Box model is developed by Mensink and Lewyckyj. This assumes a uniform concentration distribution over the street. It is very similar to Box model used for calculating the dispersion of pollutants generated from a city. The concentration in the street is determined from a mass flux balance between a horizontal convective flux, a turbulent diffusive vertical flux, and a continuous road transport emission source (C. Mensink et al. 2006).

$$C = \frac{Q}{U_{=}\left(\frac{H}{L}\right)W + \left(D + lU_{\ddagger}\right)\left(\frac{W}{H}\right)} + C_b$$

Where,

C : Calculated concentration in the street ($\mu g/m^3$)

C_b : Background concentration ($\mu g/m^3$)

Q : Emission source strength per unit length ($\mu g/m\text{-}s$)

H : Average building Height (m)

W : Width of street (m)

L : Length of the street (m)

$U_{=}$: Wind speed parallel to the street (m/s)

$U_{\ddagger}$: Wind speed perpendicular to the street (m/s)

l : Characteristic mixing length (m)

D : Diffusion coefficient at low wind speeds (m^2/s)

$U_{=}$ is the wind speed parallel to the street responsible for the ventilation of the STREET BOX, whereas $U_{\ddagger}$ (m/s) is the wind speed perpendicular to the street responsible for the vertical exchange of the pollutant.

Characteristic length l can be associated with a typical mixing length caused by turbulent eddies shedding off at roof level and is set to l = 1 m (Mensink et al. 2002). D is the diffusion coefficient at low wind speeds. Diffusion is dominant at low wind speeds. Suggested value of D is 1.5 m^2/s (C. Mensink et al.2006).

2.1.2 The STREET Model:

The STREET is the first model developed by Johnson et al. (1973). The STREET model is of empirical nature. It is based on assumptions of the initial mixing of pollutants and the vehicle induced turbulence. According to this model, pollutant concentrations in the street canyon are made up of two distinct components; one is urban background concentration and second is vehicular emissions. This model also assumes that pollutant concentrations are inversely proportional to wind velocity at the roof top. It computes pollutant concentrations on both sides of street i.e. Leeward and Windward side.

The concentration on the Leeward and Windward side can be expressed as:

$$C_L = \frac{KQ}{(U + U_0)[(x^2 + z^2)^{0.5} + h_0]} + C_b$$

$$C_W = \frac{KQ}{(U + U_0)W} + C_b$$

$$C_I = \frac{1}{2}(C_L + C_W)$$

Where,

C_L : Concentration on the leeward side ($\mu g/m^3$)

C_w : Concentration on the windward side ($\mu g/m^3$)

C_I : Intermediate Concentration ($\mu g/m^3$)

Q : Emission source strength (µg/m- s)

W : Width of the street canyon (m)

U : Wind speed at the roof level (m/s)

h_0 : Empirical constant representing some initial mixing height ($h_0 = 2$ m)

U_0 : Empirical constant representing the mechanical air movement caused by traffic ($U_0 = 0.5$ m/s)

x & z : Horizontal distance and the height of the receptor relative to the centre of the traffic lane (m)

K : Dimensionless constant determined from the best least square fit to the measured values (K = 7)

2.2 Vehicular Emissions:

In this study, vehicular emissions were calculated using the hourly traffic volume and the emission factors. The source strength was computed for each of the pollutant as:

$$Q\ (g\text{-}km^{-1}\text{-}hr^{-1}) = \sum (N_i\ (hr^{-1}) \times EF_i\ (gm\text{-}\ km^{-1})$$

Where N_i represents number of vehicles per hour of type i, EF represents emission factor for corresponding vehicle type.

The emission factors used are chosen from studies conducted by CPCB (India), T. V. Ramachandra et al. (2009). Vehicles were classified into four categories namely: two wheelers, three wheelers, four wheelers and heavy duty vehicles.

A summary of emission factors used in this study is given in table 1.

Table 1: Summary of Emission factors used in study

Type of Vehicles	Emission Factors (g/km)	
	SPM	SO_2
Two wheeler	0.05	0.013
Three wheeler	0.20	0.029
Four wheeler	0.03	0.053
Heavy Duty	0.20	1.42

2.3 Site Description:

Kolhapur city is located in south-western Maharashtra at 16°42′N 74°13′E. It has an average elevation of 545 meters (1788 ft). The geographical area of the district is 7685 Km^2. Kolhapur is situated on the banks of river Panchganga. The “station road” is one of the crowded streets in Kolhapur city. This street is surrounded by many high rise buildings. As it is one of the main commercial areas in Kolhapur, many people are directly exposed to the pollutants. The average traffic volume is over 1000 vehicles per hour.

2.4 Canyon Geometry:

The emissions were modeled over a length of 200m and average road width 30 m. Average building height in area is 13 m. There is divider of 1.25 m at the center of the road, which divides the road in two traffic lanes.

The aspect ratio of the canyon i.e. H/W ratio is 0.43 (13/30 = 0.43), hence this canyon falls in Avenue canyon category i.e. canyons having aspect ratio less than 0.5. The length to height ratio is also important in street canyon studies, and it was found to be 15.38. Such canyons are called as long canyons (L/H ratio > 7).

Figure 2: Google earth image of study area i.e. Station road

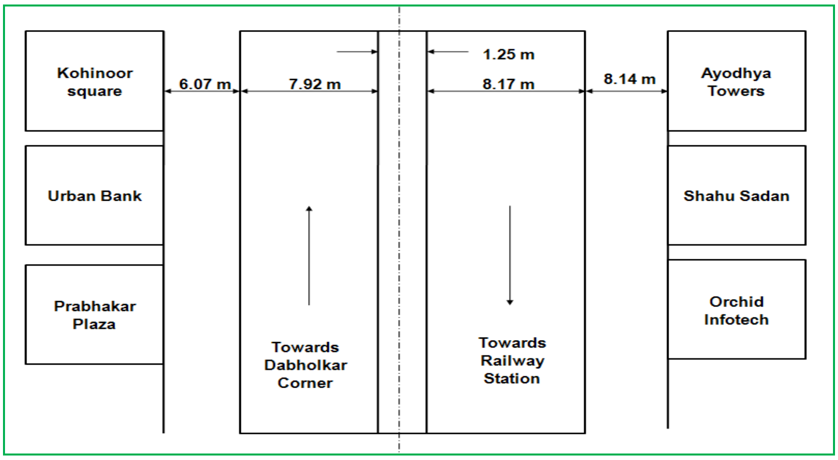

Figure 3A: Sketch of Measurement Site (Plan)

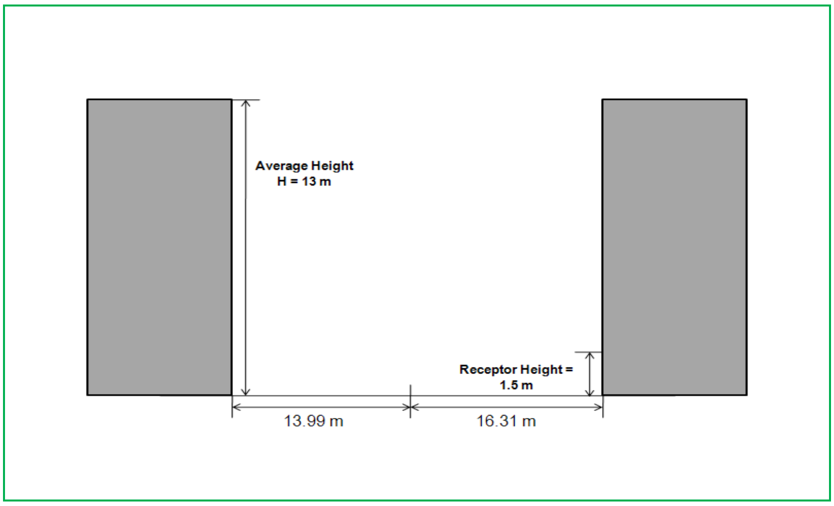

Figure 3B: Sketch of Measurement Site (Section)

2.5 Monitoring:

The hourly temperature and wind speed values were recorded at the roof top level. Temperatures were observed using a mercury thermometer and wind velocities were measured using a digital anemometer.

The concentrations of SPM were determined using Gravimetric method. A High Volume Sampler (HVS) fitted with a Whatman glass fiber filter paper (Size: 20.3 X 25.4 cm) was used for colleting Suspended Particulate Matter (SPM). Flow rate maintained through sampler was $1.3 m^3$/min. The SPM concentrations were measured gravimetrically by weighing the mass of particulates collected and knowing the total volume of air sampled.

The concentration of Sulfur dioxide was also determined using Gravimetric method. Hydrogen Peroxide (H_2O_2) was used as absorbing agent. After sampling it was made to react with Barium Chloride ($BaCl_2$) to form a precipitate of Barium Sulphate ($BaSO_4$), and then weight of SO_2 was determined from moles of $BaSO_4$. Concentration of SO_2 was determined using weight and volume of air sampled.

The monitoring was performed directly at the road side. Both the SPM and SO_2 monitoring was performed for one week i.e. from 5th March, 2012 to 11th March, 2012. The sampling was done for 8 hours a day during 10: 00 am to 4: 00 pm local time.

2.6 Background Concentrations:

A number of methods have been suggested to account for urban background concentrations. In this study, background concentrations were extracted from MPCB database, as observed at nearest air quality monitoring station established under National Ambient Air Monitoring Program. The said monitoring station is located at Ruikar trust, Dabholkar Corner, Kolhapur.

2.7 Model Performance Measures:

Performance of Street Canyon models is evaluated using following measures:

1. **Root Mean Square Error (RMSE)**

$$RMSE = exp\sqrt{\left\{\sum_{i=1}^{n}\frac{(ln\,Cp - ln\,Co)^2}{n}\right\}}$$

Where,

RMSE : Root Mean Square Error (RMSE)
C_p : Predicted Concentration
C_o : Observed Concentration

For an ideal model, RMSE value should be equal to zero.

2. **Frictional Bias (FB)**

$$FB = \frac{2\,(\overline{Cp} - \overline{Co})}{\overline{Cp} + \overline{Co}}$$

Where,

FB : Frictional Bias
C_p : Predicted Concentration
C_o : Observed Concentration

For an ideal model desired value of FB is zero.

3.0 Results and Discussions:

3.1 Traffic Flow Variation:

Variation in number of vehicles on station road is shown in figure 4. It was observed that traffic reaches a peak during morning hours between 9:30 am to 11:00 am and in the evening hours between 5:30 pm to 7:00 pm. This morning and evening rush can be attributed to office and school start and closure timings respectively. Particularly evening traffic volume was observed to be more than that of morning on most of days.

It is seen from the fig. 5, that traffic is dominated by motorcycles and light vehicles i.e. auto and cars. Two wheelers accounts for 59%, whereas percentages for three, four and heavy duty vehicles is 20, 12 and 9 % respectively.

3.2 Meteorological Parameters:

Temperature and wind speed variations are shown in figure nos. 6 - 7. Maximum average temperature was observed to be 37.6 ^{0}C on 11th March, 2012 and minimum value was observed to be 32.8 ^{0}C on same day during evening hours. Winds parallel and perpendicular to street plays a significant role in dispersion and dilution of pollutants within street. Winds parallel to street tend to disperse the pollutants whereas winds perpendicular to street tend to accumulate pollutants within street canyon. Hence later are undesirable.

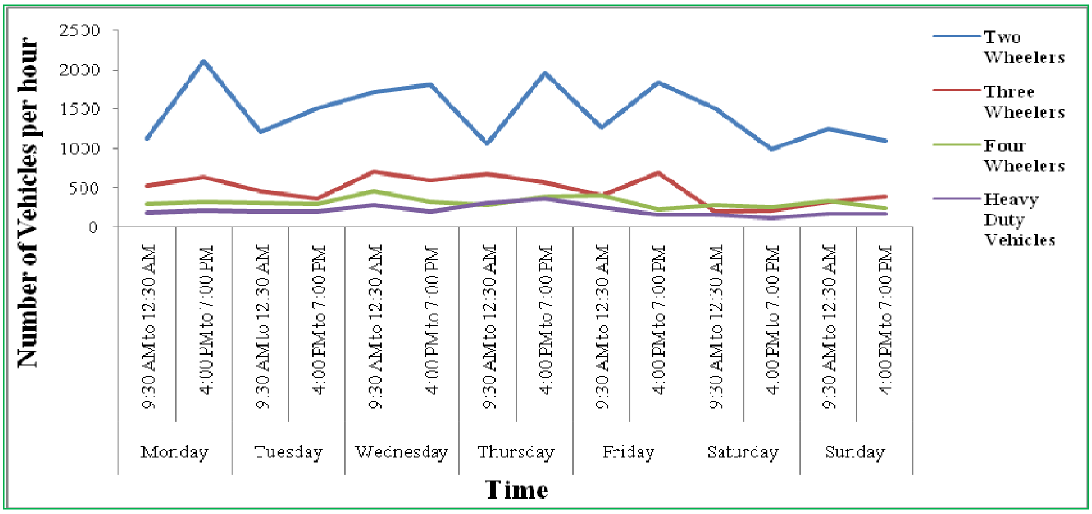

Figure 4: Traffic flow variations during study period

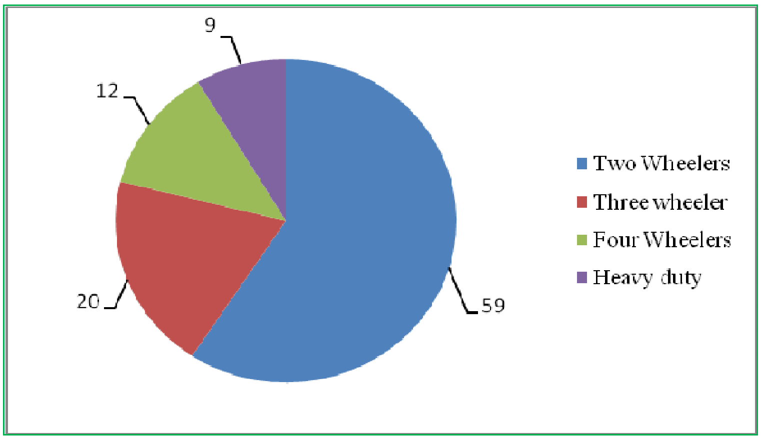

Figure 5: Scale map of traffic volumes

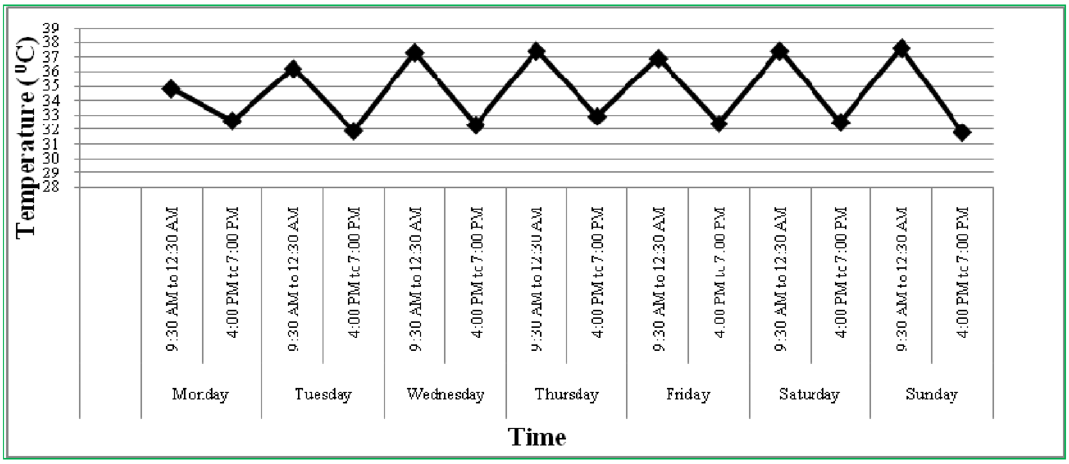

Figure 6: Temperature Variations during Study Period

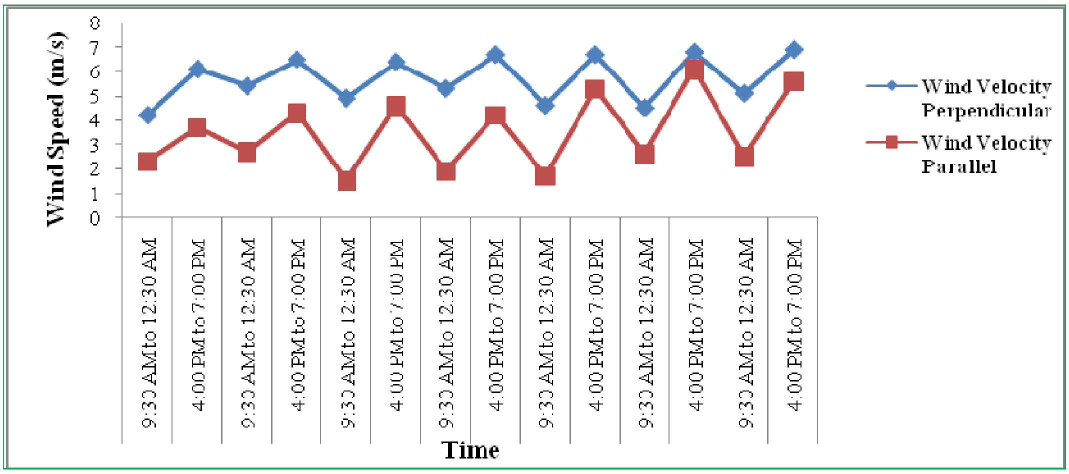

Figure 7: Hourly Average Wind Speeds Measured at Monitoring Site

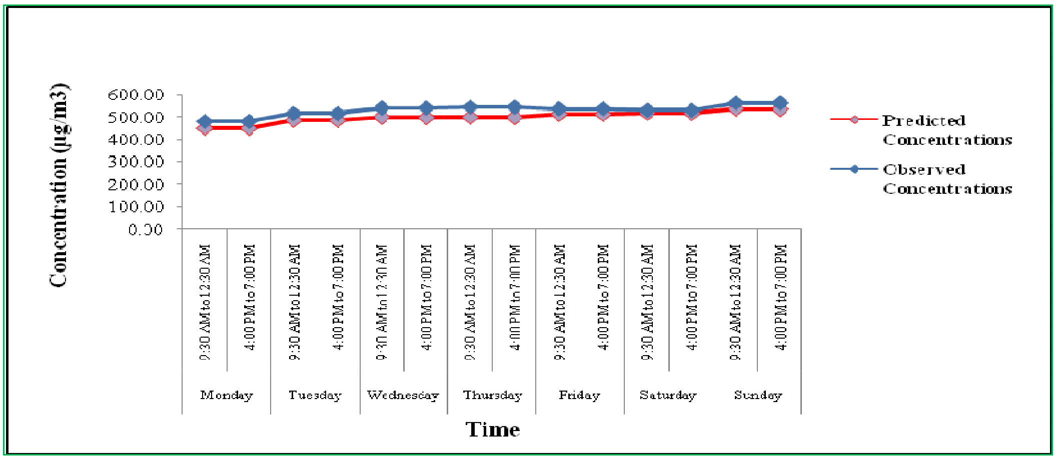

Figure 8: Predicted and Observed concentrations of SPM at Station road using STREET Box Model

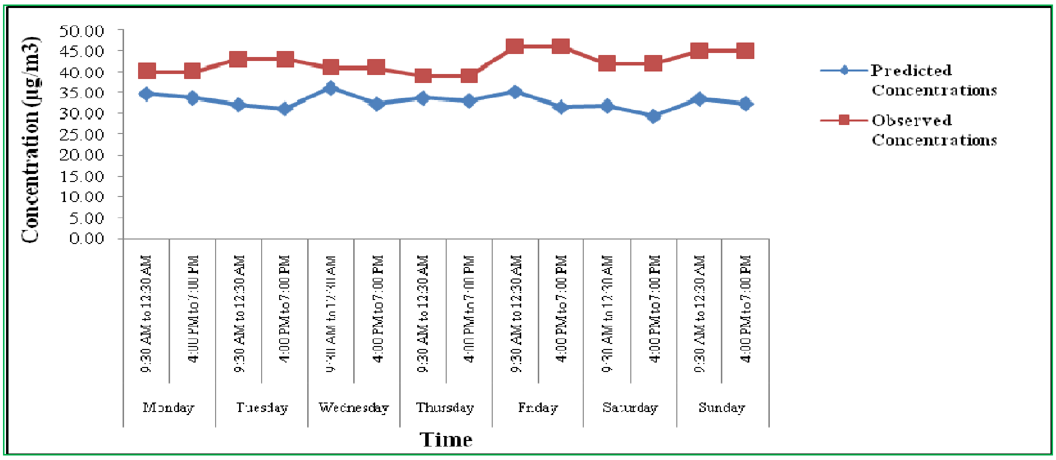

Figure 9: Predicted and Observed concentrations of SO_2 at Station road using STREET Box Model

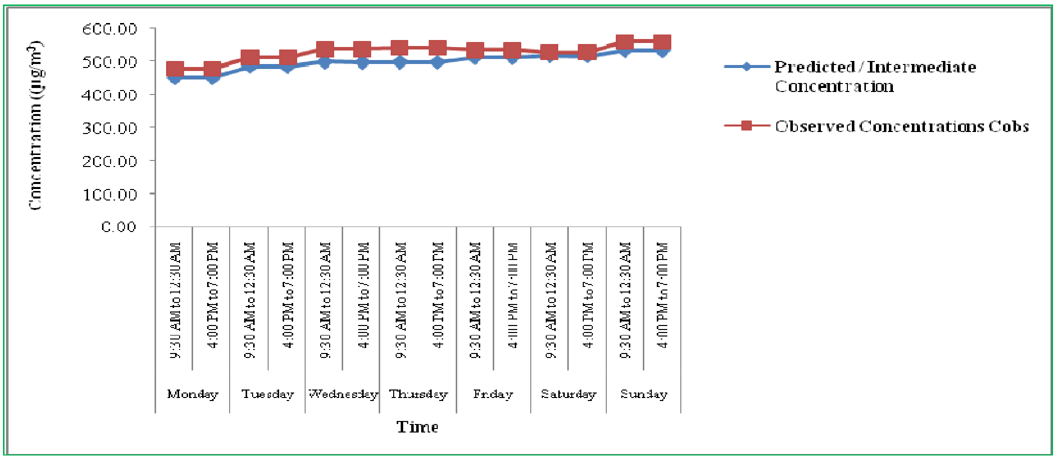

Figure 10: Predicted and Observed concentrations of SPM at Station road using STREET Model

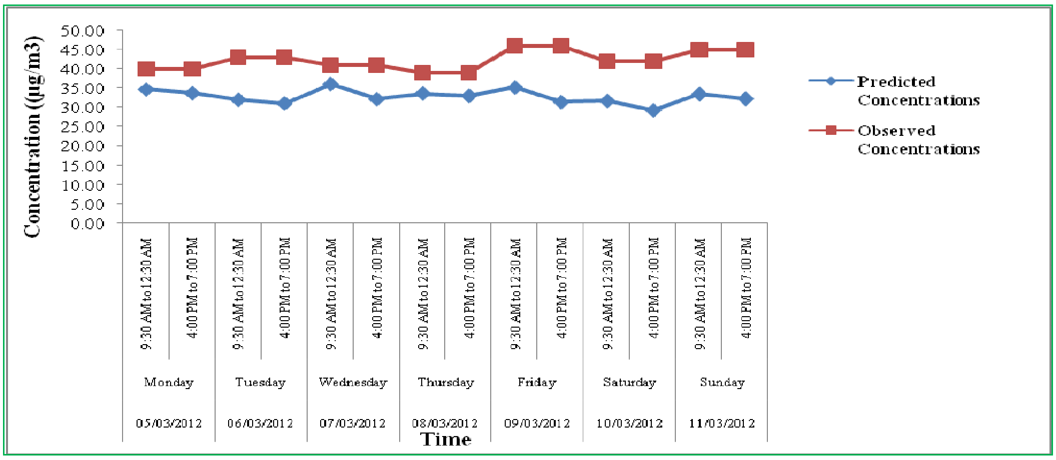

Figure 11: Predicted and Observed concentrations of SO_2 at Station road using STREET Model

3.3 Street Canyon Modeling:

The field data was input to the two street canyon models and results obtained are discussed in this section. Figure 8–11, shows the predicted and observed concentrations of SPM and SO_2 calculated using STREET Box model and STREET models. It is observed that observed concentrations are always greater than predicted concentrations. This can be attributed to other sources existing in particular location and the traffic pollution in streets surrounding station road. Both Street Box and Street models show a good correlation between predicted and observed values for SPM but results are not satisfactory for SO_2. This may be because SPM is more inert than that of SO_2 and another reason can be background concentrations used are not that accurate. Hence for success of these models an accurate estimation of background concentrations is very important.

Table 2: Weekly averages of background concentration, STREET Box model, STREET Model and Observed Concentrations

Pollutants	Background Concentration	STREET Box	STREET (Leeward)	STREET (Windward)	STREET (Intermediate)	Observed Values
SPM ($\mu g/m^3$)	496.57	499.30	500.39	498.91	499.65	526.86
SO_2 ($\mu g/m^3$)	27.71	32.92	33.82	31.46	32.64	42.29

Table 3: Model Performance Measures

Measure	Pollutant	STREET Box	STREET
RMSE	SPM	1.24	1.24
	SO_2	2.68	2.75
FB	SPM	0.00	0.00
	SO_2	- 0.01	- 0.01

Table 3 shows model performance measures for two models. From this it can be seen that RMSE values for SPM are quite satisfactory while those for SO_2 are not satisfactory. RMSE values are more due to difference between predicted and observed values. Frictional bias values for both the models are good enough.

4.0 Conclusions:

Two models viz. STREET Box and STREET were used to simulate pollutant concentrations in the street. SPM and Sulphur dioxide (SO_2) concentrations were modeled and monitored for a street canyon at Station road, Kolhapur for a period of one week. From the results obtained it is clear that pollutant concentrations are dependant upon traffic volume, wind direction and wind speeds. Winds perpendicular to street axis are undesirable and produce worst conditions while winds parallel to street axis are favorable for pollutant dilution. The results obtained are compared with observations from measurement site. It was found that STREET Box model provides a good estimation of pollutant concentration while STREET model underestimates the concentrations. This may be due to less accuracy in background concentrations. These models can provide a quick estimate of pollutant concentrations which will be very useful in urban air quality assessment and to meet National Ambient Air Quality Standards (NAAQS).

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