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Comparative Evaluation of Air Quality Dispersion Models for Predicting Particulate Matter Concentrations at a Busy Traffic Roadway in Chennai City

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COMPARATIVE EVALUATION OF AIR QUALITY DISPERSION MODELS FOR PREDICTING PARTICULATE MATTER CONCENTRATIONS AT A BUSY TRAFFIC ROADWAY IN CHENNAI CITY

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***Abstract**: Air quality models are an integral part of the regulation process aimed at protecting the urban air quality. Several, air quality dispersion models are being widely used to estimate/ predict the air pollutant concentrations emitted from various types of sources such as point (stack) , line(vehicles) and area (domestic/open burning) sources. In the present study, three Gaussian based line source models namely general finite line source model (GFLSM,* Luhar and Patil ,1989*), California line source model (CALINE-4, Benson. P, 1984 and 1889), Industrial source complex short term (ISCST-3, US.EPA, 1998) model have been used to predict the particulate matter (PM) concentrations at Sardar Patel road in the Chennai city. PM Source emission rate and meteorological parameters have been used as model inputs to predict the PM concentrations. A detailed traffic census has been conducted at study region to quantify the PM emission rate. The main metrological parameters required to run the models have been collected from the meteorological department.*
The models performance has been evaluated using the statistical parameters viz. mean of the observed and predicted concentrations ($\overline{O}$ and $\overline{P}$ *respectively) and their standard deviations (*σ_O *and* σ_P *respectively), Root mean square error (RMSE), linear regression coefficients (Slope, a and intercept, b), index of agreement (IA), and mean bias error. The results indicated that all the three models are able to predict* PM_{10} *concentration with reasonably good accuracy during traffic flow hours (morning 7 am-12 pm and 4 pm-10 pm) and poor prediction during lean traffic hours and inversion conditions.*

***Keywords**: particulate matter; emission rate; heterogeneous traffic; air quality model; statistical indicators.*

INTRODUCTION

Motor vehicles are the main sources of PM pollution in many urban centers of the world. PM emitted from vehicles are of particular concern because these are ground level sources and are having maximum impact on the people using the busy corridors (Wang et al. 2003). PM is directly link to their potential for causing health problem such as cardiovascular, pulmonary

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dieses, inflammation of the airways that may worsen existing lung disease and enhance the health risk (Hoek et al. 2002). It worsens the health conditions (respiratory morbidity, mortality and cancer) of the person having pre existing diseases such as hay fever and asthma (WHO, 2003; U.S.EPA, 2004). The inhaled PM also alters the ability of blood to clot and the circulation of red blood cells and platelets (Delfino et al. 2005). This results in cardiovascular morbidity and mortality (Pope and Dockery, 2006). In general, PM has been classified into PM_{10} (coarse), $PM_{2.5}$ and PM_1 (fine) based on aerodynamic diameters smaller than 10, 2.5 and 1 μm, respectively (40CFR51.100-91, WHO, 2003).

In the past, number of studies has been reported on PM emissions from the vehicles in urban environment (Riediker et al. 2003). Hoek et al. (2002) reported that PM originating from traffic exhibit elevated concentrations during peak traffic flow and poor dispersion (inversion) conditions. Janssen et al., (1997) concluded that time spent in traffic are critical for population exposure to high PM levels. Wijnen et al. (1995) reported that travelers are often exposed to PM levels three times higher than the background levels. Like many other parts of the world, air pollution from motor vehicles is one of the most serious and rapidly growing pollution problems in urban centers of India. The Chennai city is one among them. In recognition of the severity of the PM pollution problem Central Pollution Control Board (CPCB) has designated Chennai city as a non attainment area. Therefore the city needs an effective AQM strategy to reduce ambient PM concentrations.

Air quality prediction models have been widely used for preparing AQM strategies and decision making (Mehdizadeh and Rifai, 2004). Vehicular pollution modelling, in general, refers to carrying out air pollution prediction by simulating impact of emissions from vehicles in a given region. In general, the air quality models can be classified as point, area or line source models depending upon the source of pollutants which it models. Line source models are used to simulate the dispersion of vehicular pollutants near highways or busy roads where vehicles continuously emit pollutants. Several line source models have been formulated to predict pollutant concentration near highways or busy roads. Gaussian-based line source dispersion models are extensively used throughout the world including India, to carry out prediction of vehicular pollutant concentrations along the highways and busy roads. These models despite of several limitations and assumptions have been used successfully for regulatory purposes and for developing clean air strategies.

In the present study, three Gaussian based line source models namely general finite line source model (GFLSM), California line source model (CALINE-4), Industrial source complex short term (ISCST-3) model have been evaluated for predicting PM_{10} concentrations at Sardar Patel road, which is one of a busy road in Chennai city, India.

METHODOLOGY

Study Area

Figure 1 shows the details of study region. The study site is located in the premises of Indian Institute of Technology Madras (IITM), Chennai. The Sardar Patel road is one among the busiest road in Chennai city, which accommodates large number of vehicle during peak hours. This road stretches from Adyar to Guindy and is flanked by the Indian Institute of Technology Madras and

Cancer Institute on one side and the Central Leather Research Institute on the other side.

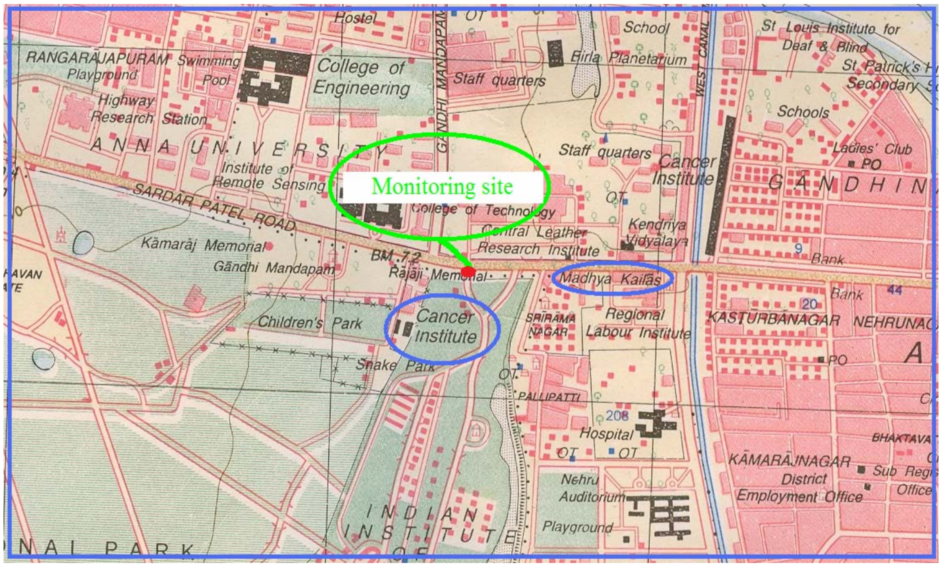


Fig. 1. Shows the sampling location and the study area.

Data

The PM_{10} mass concentration at the study site is measured using portable environmental dust monitor (GRIMM-107) for a complete one week in the month of August 2009. The Grimm dust monitor is small portable instrument designed to provide continuous number and mass size distributions of particulate matter suspended in the ambient air. The dust monitor samples air at 1.2 lit/min into a light scattering optical particle counter, with a lower cut-off at 0.25 µm. The instrument kept at a distance of about 15 meters from the centre of the SP road and the sampling inlet is placed at 1.2 m above the ground level. The PTFE-Teflon Filter, 47 mm diameter, 0.2 micron size is being used for PM sampling. During the monitoring the 1-minute average concentrations of PM_{10} are recorded on a data storage card. The hourly and 24-hour average concentrations are subsequently calculated from 1 minute readings. Meteorological parameters such as temperature, wind speed, wind direction, are downloaded from CPCB continuous ambient air quality monitoring station located at IIT Madras for the monitoring period. A continuous traffic census has also been conducted at the study region. The traffic counts have been made at 15 minutes intervals for 24-hours for a week.

DESCRIPTION OF LINE SOURCE MODELS

Numerous air pollution prediction models have been developed for both finite and infinite line sources. Gaussian plume model is one of a general mathematical model developed and widely used to describe the dispersion phenomenon. In this model, the distribution of pollutant within the plume is assumed to be Gaussian in both the vertical and horizon directions. Among the various line source models, General finite line source model (GFLSM) developed by Luhar and Patil (1989), California Line Source Model (CALINE-4) developed by Department of

Transportation, California and Industrial Source Complex Short Term (ISCST-3) models are wildly used in India for regulatory and air quality impact assessment purposes.

General Finite Line Source Model (GFLSM)
A simple general finite line source model was developed by Luhar and Patil in the year 1989, which overcomes the infinite line source constraints. It assumes co-ordinate transformation between the wind co-ordinate system (x1, y1, z1) and the line source co-ordinate system (x, y, z). The middle point of the line source can be assumed as the origin for both coordinate systems, which also have the same z-axis. The position of the receptor R in the line source coordinate system is (x, y, z) and that in wind co-ordinate system is (x1, y1, z1) as shown in Figure 2. In the line source co-ordination system all the parameters, namely, x, y, z can be obtained from the road receptor geometry. This model specifies the dispersion parameter as a function of wind-road orientation angle and distance from the source.

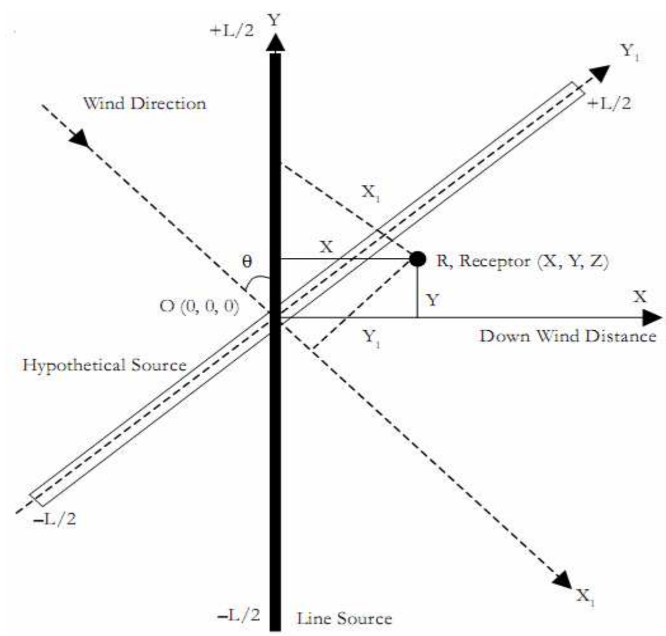


Fig.2. Relationship between wind co-ordinate system and line source co-ordinate system.

The pollutant concentration (C) in μg/m^3 is computed from the equation (1)

$$C = \sum_{i=1}^{N} \frac{w_i Q}{2\sqrt{2\pi}\sigma_z u_e} \exp\left\{ -\frac{1}{2}\left[z - \left(h_e - \frac{V_i x}{(u+u_0)(A+B\sin\theta)} \right)^2 \right] \right\}$$
$$\times \left\{ erf\left[\frac{\sin\theta(\frac{L}{2} - y) - x\cos\theta}{\sqrt{2}\sigma_y} \right] + erf\left[\frac{\sin\theta(\frac{L}{2} + y) + x\cos\theta}{\sqrt{2}\sigma_y} \right] \right\} \qquad (1)$$

where N is the number of particle size classes; Q is the emission rate in mg/m-sec; V_i is the settling velocity corresponding to the average particle size of i^{th} class; w_i is the weight fraction of particles in the i^{th} size class; σ_y and σ_z are the horizontal and vertical Gaussian dispersion parameters. The x is the downwind distance in meter; z is the receptor height in meter and the value taken as 1.5 m; L is the length of the road in meter; h_e is the effective source height in metre; θ is the angle between the wind vector and the road length in degrees; erf is the error function; u_e is the effective wind speed in m/sec; u is the wind speed due to the traffic wake in m/sec and the value taken as 0.2 m/sec; u_0 is the wind speed due to the atmospheric turbulence in m/sec. Table 1 summarizes the equations used for the estimation of key input parameters to GFLSM model.

Table 1. Estimation of key input parameters for the GFLSM model

$\sigma_y^2 = \sigma_{ya}^2 + \sigma_{y0}^2$	$\sigma_z^2 = \sigma_{za}^2 + \sigma_{z0}^2$
$\sigma_{ya}^2 = c.x^d$	$\sigma_{za} = a.x^b$
$\sigma_{y0} = 2.\sigma_{z0}$	$\sigma_{z0} = 3.57 - 0.53U_c$
$h_e = h + h_p$	$U_c = 1.85.u^{0.164}.\cos^2\theta$
$h_p = \left(\frac{F_1}{\alpha.U'^3}\right)^2.x$	$u_e = u_s.\sin\theta + u_0$
	$V_i = \left(\frac{gD_p^2\ \rho_p}{18\mu_a}\right)$
$F_1 = \frac{465.g}{380.T_s}$	

Constants	Stable (A to C)	Neutral (D)	Unstable (E to F)
U' (m/sec)	0.18	0.27	0.27
α	20.7	11.1	11.1

Note: where σ_{ya} and σ_{za} are the horizontal and vertical atmospheric dispersion parameters; σ_{y0} and σ_{z0} are the horizontal and vertical traffic induced dispersion parameters; a, b, c and d are constants and it depends on the stability class; u_s is the mean wind speed in m/sec; g is the acceleration due to gravity in cm/sec^2 (981 cm/sec^2); D_p is the aerodynamic diameter of the particle in cm; ρ_p is the density of the particle in g/cm^3 and the value taken as 1.5 g/cm^3; μ_p is the dynamic viscosity of the air in g/cm.sec and the value taken as 1.85 x 10^{-4} g/cm.sec; h is the line source height in meter and the value taken as the average tailpipe height i.e., 0.3 m; h_p is the plume rise in meter; F_1 is the buoyancy flux; U_c is the critical wind velocity in m/sec; u is the effective wind velocity in m/sec; T_s is the temperature in ° Kelvin; α and U' are the constants and depends on the stability classes.

California Line Source Model (CALINE-4)

The CALINE-4 model is widely used to predict near road vehicle emissions. It embeds the concept of mixing zone and uses modified Gaussian distributions. CALINE-4 uses a series of equivalent finite line sources to represent the road segment. It models the whole region of finite line sources as a zone with uniform emissions and turbulence. It can model roadways at-grade, depressed, and filled (elevated); bridges (flow under roadway); parking lots; and intersections. Bluffs and canyons (topographical or street) also can be simulated by the CALINE-4. It accepts composite vehicle emission factors (expressed in grams per vehicle) developed and input by the user for each roadway link. The user inputs composite emission factors by link. The required input parameters are the average number of vehicles per cycle per lane and composite idle emission factor. Additional inputs include wind direction bearing, wind speed, atmospheric stability class, mixing height, wind direction standard deviation, and temperature. The concentration (C) at a point with coordinates is calculated based on equation (2).

$$C(x, y, z) = \frac{q}{2\pi u \sigma_y \sigma_z} \times \left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2} \right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2} \right) \right] \int_{y1}^{y2} \exp\left(-\frac{y^2}{2\sigma_y^2} \right) dy \qquad (2)$$

where q is the linear source length, u is the wind speed, σ_y and σ_z are the horizontal and vertical Gaussian dispersion parameters, H is the source height, y1 and y2 are the y coordinates of finite line source end points. Among all the variables, σ_y is functions of the x coordinate of the point where the concentration is calculated and horizontal wind angle standard deviation; σ_z is modified by incorporating the effects of vehicle induced heat.

Industrial Source Complex Short Term (ISCST-3) Model

The Industrial Source Complex Short Term (ISCST) model (version 3) is developed by EPA (Environmental Protection Agency) USA. Its last version released by US EPA on December, 23, 1998. It provides options to model emissions from a wide range of sources that might be present at a typical industrial source complex. The basis of the model is the straight-line, steady-state Gaussian plume equation, which is used with some modifications to model simple point source emissions from stacks, emissions from stacks that experience the effects of aerodynamic downwash due to nearby buildings, isolated vents, multiple vents, storage piles, conveyor belts, etc. Emission sources are categorized into four basic types of sources, i.e., point sources, volume sources, area sources, and open pit sources. The volume source option and the area source option also been used to simulate line sources. The ISCST-3 model accepts hourly meteorological data records to define the conditions for plume rise, transport, diffusion, and deposition. The model estimates the concentration or deposition value for each source and receptor combination for each hour of input meteorology, and calculates user-selected short-term averages. Input data for ISCST-3 are the wind speed, mixing heights, terrain and emission sources. ISCST-3 model has been quite successful on modelling point sources over short distances (a few kilometers) because of the Gaussian assumption. The concentration at a receptor is estimated by the equation (3).

$$C(x, y, z) = \frac{2Q_L}{\sqrt{2\pi u}\ \sigma_z} \times \left[\exp\left(-\frac{(H^2)}{2\sigma_z^2} \right) \right] \qquad (3)$$

where Q_L is the line source length, u is the wind speed, σ_z are the vertical dispersion parameter and H is the source height.

RESULTS AND DISCUSSION

Performance of GFLSM

Table 2 summaries the performance statistics of the GFLS model prediction on one week data (include date and year) set of the Sardar Patel road in Chennai city. The mean value (60.26 µg/m^3) of predicted PM concentration is higher than the observed mean value (46.18 µg/m^3). The MBE value is positive indicating a tendency of the GFLSM to over predict .The standard deviation of the GFLSM prediction is higher than the observed standard deviation of the observed data set at study site. The systematic RMSE value for GFLSM is found to be higher than the unsystematic RMSE. Further the value of index of agreement for the GFLS model is 0.53, this explain that 53% of the models prediction are error free.

Table. 2. The statistics of measured and predicted PM_{10} concentrations for GFLSM.

Model	Statistics									
	$\overline{O}$	$\overline{P}$	σ_o	σ_p	MBE	$RMSE_S$	$RMSE_U$	IA	Slope (a)	Intercept (b)
GFLSM	46.18	60.26	17.32	30.28	14.08	33.51	4.75	0.53	0.478	38.15

Performance of CALINE-4

Table 3 gives the performance statistics of the CALINE-4 model prediction. The mean of predicted PM concentration is slightly lower than that of the observed mean value. The MBE value is negative indicating a tendency of the model under predict the PM_{10} concentration. The standard deviation of the CALINE-4 model prediction is lower than the observed standard deviation of the one week data set. Further the value of index of agreement for the CALINE-4 model is 0.50, indicates that 50% model predictions are error free.

Table. 3. The statistics of measured and predicted PM_{10} concentrations for CALINE-4.

Model	Statistics									
	$\overline{O}$	$\overline{P}$	σ_o	σ_p	MBE	$RMSE_S$	$RMSE_U$	IA	Slope (a)	Intercept (b)
CALINE-4	46.18	30.43	17.21	7.7	-15.75	39.93	3.19	0.5	0.009	30

Performance of ISCST-3

Table 4 gives the performance statistics of the ISCST-3 model prediction. The MBE value is negative indicating a tendency of the model to under predict the PM concentration. The mean of predicted PM concentration is moderately lower than that of the observed mean value. The value of index of agreement indicates that 43% model predictions are error free.

Table. 4. The statistics of the measured and predicted PM concentrations for ISCST-3.

Model	Statistics									
	$\overline{O}$	$\overline{P}$	σ_o	σ_p	MBE	$RMSE_S$	$RMSE_U$	IA	Slope (a)	Intercept (b)
ISCST-3	46.18	34.11	17.32	10.68	-12.08	14.130	5.52	0.43	0.038	32.35

Models Comparative Performance

Figure 3 compares the measured and predicted concentrations during one week in August 2009 at study site. From the figure it is observed that GFLSM is over predicting the PM_{10} concentrations at the study site, while CALINE 4 and ISCST3 are under predicting the PM_{10} concentrations. Table .5 summarizes the models predictions made between 6AM – 12NOON, 1PM-4PM, 5PM-10PM, and 11PM-5AM at Sardar Patel road. It is found that GFLS model Predictions are reasonably accurate (63% predictions are error free) than other two models during morning traffic (6AM – 12NOON)

The CALINE4 model is moderately predicting PM_{10} Concentrations thought the day (40 -50% predictions are error free).This model predictions are consistent irrespective of hours of the day.

ISCST3 model predictions are also reasonably accurate during morning and evening traffic hours (39 %and 41% predictions are error free resp.)

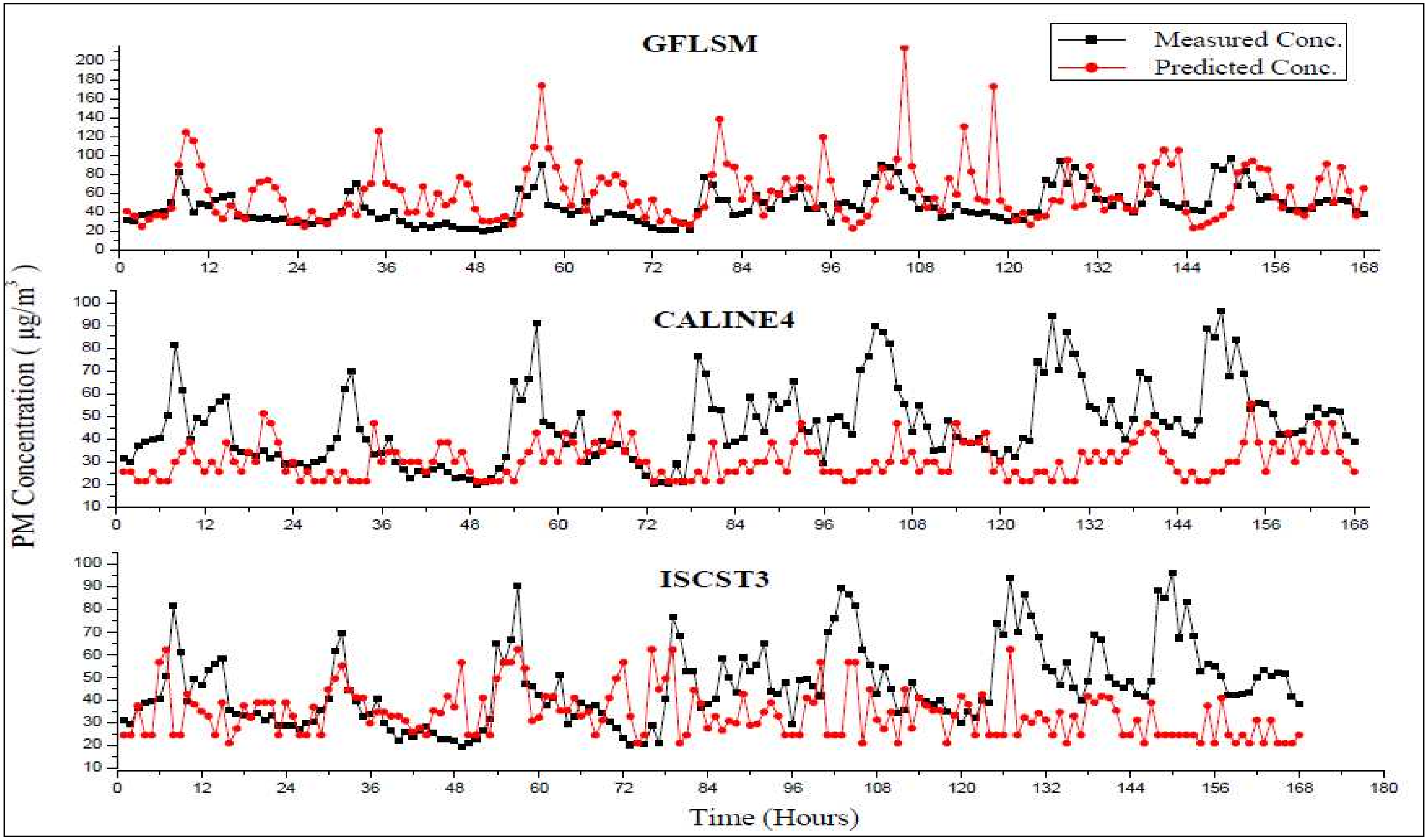
Table.5 Model predictions during different time of the day.

Model/Time	6AM-12AM	1PM-4PM	5PM-10PM	11PM-5AM
GFLSM	0.63	0.184	0.30	0.28
CALINE-4	0.40	0.42	0.50	0.41
ISCST3	0.39	0.35	0.41	0.24

CONCLUSIONS

The applicability of Gaussian based line source models namely GFLSM, CALINE-4 and ISCST-3 in predicting a PM_{10} concentration at an urban roadway has been tested on one week data collected at SP road in the month August 2009. Selected statistical indicators have been used to judge the model performance. Results reveal that GFLSM predictions are better than the CALINE4 and ISCST3 models during morning traffic flow hours. However GFLS model predictions are poor during lean traffic hours and inversion conditions. It is also observed that GFLSM model is over predicting PM_{10} concentrations, whereas CALINE4 and ISCST3 model under predicting PM_{10} concentrations at the SP road. The CALINE4 model predictions are found to be consistent throughout the hours of the day. ISCST3 model predictions are also reasonably accurate during morning and evening traffic hours (39 %and 41% predictions are error free respectively.)

redicted and measured concentrations of three models for PM_{10} prediction.



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