Emission Load Distribution and Prediction of NO\textsubscript{2} and PM\textsubscript{10} using ISCST3 and CALINE4 Line Source Modeling

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Abstract - Mysore district is one of the tourist destinations, in Karnataka, India, with a population of about 10.25 lakhs. 2-wheelers (2W) constitute more than 75% of total vehicular population. Based on the vehicle growth during the last few years, it is observed that, the vehicle growth in Mysore city is about 8 to 9% per annum. Industrial source complex short term model 3 (ISCST3) and California line source model 4 (CALINE4) were used to predict NO\textsubscript{2} and PM\textsubscript{10} concentrations emitted from line/mobile sources. PM\textsubscript{2.5} and SO\textsubscript{2} emission factors were found to be very less (0.04 and 0.002 g/km) compared to CO and NO\textsubscript{2} emission factors (1.4 and 1.7 g/km). Emission loads for CO and NO\textsubscript{2} pollutants were found to be high at link 1, 2, 5, 6, 12 and 13 due to heavy traffic densities. During winter season ISCST3 and CALINE4 model predicted NO\textsubscript{2} concentrations were found to be ranging from 9–25 μg/m\textsuperscript{3} and 10–40 μg/m\textsuperscript{3}, respectively. However, PM\textsubscript{10} concentrations were found to be 18–43 μg/m\textsuperscript{3}. Maximum concentration was found near to Receptors (R1-3), which may be due to maximum vehicular density and downwind to the pollution sources. Pollutant concentrations were found to be maximum during winter season (calm condition) followed by summer and monsoon seasons (unstable condition). NO\textsubscript{2} and PM\textsubscript{10} predictions made by ISCST3 and CALINE4 model showed a significant variation. Though, NO\textsubscript{2} and PM\textsubscript{10} concentrations were found to be within National Ambient Air Quality Standards (NAAQS) of 80 μg/m\textsuperscript{3} and 100 μg/m\textsuperscript{3}, respectively. It was also observed that, CALINE4 model was not applicable to predict pollutant with lower concentrations.

Key Words: ISCST3, CALINE4, PM\textsubscript{10}, NO\textsubscript{2}, Emission Load.

1. INTRODUCTION

Due to urbanization and rapid growth of motor vehicles, Indian cities are experiencing deteriorated air quality which is responsible for serious health, environmental and socio-economic impacts [1]. The motor vehicle population in India has increased from ~0.3 million (in 1951) to 1.15 million (in 2009), of which 2W accounted for approximately 70% of the total vehicles [2]. Line source dispersion models such as, ISCST3 and CALINE4 models can provide current and future air quality levels at any given point in the impact zone, which can be used to facilitate control and manage the vehicular/urban air pollution [3,4]. Faulkner et al. (2008) stated ISCST3 model was sensitive towards the changes in wind speed, temperature, solar radiation, mixing heights and surface roughness for predicting downwind PM\textsubscript{10} concentrations [5]. Bhankar et al. (2005) indicated that, industrial sources account for 77% and 68% of the total emissions of SO\textsubscript{2} and NO\textsubscript{2} respectively, whereas vehicular emissions contributed to about 28% of the total NO\textsubscript{2} emissions, in Jamshedpur, India [3]. Further, Kansal et al. (2011) informed that, in Delhi city vehicles contribute 58% of the total ambient air pollution, followed by Thermal Power Plants (TPPs) 30% by using ISCST3 model [6]. However, CALINE 4 model is the latest version in CALINE series and most widely used to predict air pollutant concentrations (CO, NO\textsubscript{x} and PM) emitted from mobile sources along the highway under urban and sub-urban conditions [7]. Ganguly et al. (2009) have showed that, GFLSM model prediction decreases with the increase in downwind distances as compared with CALINE4 model [8]. Dhyani et al. (2013) have used CALINE4 model on two road corridors, Kiratput (flat terrain) and Darlaghat (hilly terrain) in Himachal Pradesh to predict CO concentration from traffic emission [9]. Further, Dhyani et al. (2014) have carried out environmental impact assessment (EIA) for a highway corridor in Delhi city, India and used CALINE 4 model for the prediction of CO concentration [10]. Most of the traffic count studies revealed that, maximum traffic densities were found between 08:00 – 11:00 hours and 17:00 – 21:00 hours [9,11,12]. However, air pollutant concentrations near road intersections have observed to be varied in minutes due to the influence of traffic signals [13,14,15], which can inevitably increase the complexity of prediction of pollutants by any model. Mysore is the most popular tourist place in Karnataka. The total number of vehicles which was about 6000 in 1970 increased to 1.45 lakhs in 1996, 3.55 lakhs in 2005 and the current vehicle population is 6.5 lakhs in 2014 [16]. Hence, the aim of the present study is to collect meteorological data, prepare emission inventory and conduct traffic count studies along with segregation of category of vehicle passing and to predict NO\textsubscript{2} and PM\textsubscript{10} concentrations emitted from line/mobile sources using ISCST3 and CALINE4 models.
2. STUDY AREA

The present study investigates the status of ambient air (November, 2016 to July, 2017) along the highway passing through industrial area of Mysuru city, which connects the highway with the industries and residential areas located in northern and eastern part of the study area, respectively. The major portion of the ring road is being six lanes with service roads on the either side. The entire length of outer ring road starts from Bangalore – Mysuru road (SH-17) and circumferences Mysuru city. The selected stretch along the ring road is of 3.3 km with elevation profile varying from 746 m to 786 m. Three monitoring stations (six receptor locations) (Figure 1) with 1 km interval were selected to predict Ambient Air Quality (AAQM) using ISCST3 and CALINE4 models. The receptor points were selected as, Seshadripuram College (R1), Weigh Bridge (R2), V-LEAD Institute (R3), Prema Fuel Station (R4), Dexter Logistics (R5) and JSS Urban Haat (R6). For CALINE4 model predictions road stretch was divided into 14 links based on elevation, intersection and direction of the road. However, the highway was divided into 10 area sources and further, these area sources were converted into line sources for ISCST3 model predictions.

3. MATERIALS AND METHODS

3.1 Emission inventory

A traffic count study is a detailed examination and analysis of a transportation system supported by data collection. The data collection process was conducted using the CCTV camera at the monitoring location in an orderly manner which ensures that, data gathered is both defined and accurate. The collected data provides a baseline for further analysis. Traffic volume studies were conducted to determine the number, movements, and classifications of roadway vehicles at a given location. Automotive Research Association of India [17] emission factors were considered in the present study. These emission factors along with total number of vehicles per hour were used to calculate Weighted Emission Factor (WEF) developed by US-EPA [4,9,18].

\[
WEF = \frac{\sum (EF_i \times V_i)}{V} 
\]

Where, \(EF_i\) = Emission factor for different category of vehicles, \(V_i\) = volume of different category of vehicles. In the present study WEF in g/mile was calculated using ARAI standards. The calculated emission factors were used as inputs for ISCST3 and CALINE4 models and as well as to identify the emission load distribution over the study area.

3.2 Micro-meteorology

Meteorological parameters such as: wind speed, wind direction, temperature, relative humidity (RH), are responsible for the dispersion of air pollutants in the atmosphere. The daily variation of meteorological data were collected from www.wunderground.com [19]. Hourly meteorological data were used to plot season wise diurnal variation of temperature, wind speed and relative humidity (Figures 2a-c). Minimum temperature and wind speeds were observed during late night and early morning periods (01:00 to 07:00 h) in all the seasons and gradually increased during day time with solar radiation. On the other hand, RH was found to be maximum during 01:00 h to 10:00 h and it gradually decreased and reached the minimum at 11:00 h to 17:00 h and then started increasing. The trend was found to be similar for winter, summer and monsoon seasons.
Fig 2: Diurnal variation of Temperature, Wind speed and Relative Humidity during (a) winter, (b) summer and (c) monsoon season over Mysuru city.

However, a maximum temperature of 37°C was found in summer season followed by 30°C in winter and 29°C in monsoon season. The average temperature was varying from 22°C to 26°C. Further, RH was found to be ranging from 50-65% during winter season, 751% during summer season and 66-86% during monsoon season. A maximum and minimum wind speed of 19 km/h and 5 km/h was noticed during monsoon and winter season, respectively. The average wind speeds were varying from 6 km/h to 11 km/h in all the seasons. The wind rose plot for winter season (Figure 3a) showed predominant wind was blowing from E (90°) and ENE (68°) directions. The resultant vector of wind directions from winter season to summer season showed, wind direction was changing from E to WSW direction. However, wind rose plots for summer and monsoon seasons (Figures 3b-c) showed predominant wind was blowing from SW (225°) and WSW (248°) towards NE (45°) and ENE (68°) directions, respectively.

3.3 Ambient air quality modeling

In order to predict NO₂ and PM₁₀ concentrations emitted from line/mobile sources at selected receptor points, ISCST3 and CALINE4 models were used in the present study.
3.4 ISCST3 dispersion model

The USEPA developed ISCST3 air pollution dispersion model was used to predict NOx and PM10 concentrations at selected receptor locations [20]. The model has the capability to handle Polar or Cartesian coordinates, simulating point, area, volume, and line sources, considering wet and dry deposition, accounting for terrain adjustment, building downwash algorithm [3]. ISCST3 algorithm is based on numerical solution of three dimensional diffusion-convection equation assuming a Gaussian plume mechanism and used to compute GLCs of non-reactive pollutants [21,22,23]. ISCST3 Gaussian plume model for prediction of downwind pollutant concentrations from line sources can be described by eqn. (2).

\[
C = \frac{2Q_v}{\sqrt{2\pi\sigma_z}} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)
\]

Where, \(C\) = the downwind pollutant concentration (µg/m³), \(Q_v\) = line source emission rate (g/m²s), \(\sigma_z\) = vertical dispersion coefficients (m) based on stability class, \(u\) = average wind speed at pollutant release height (m/s), \(H\) = effective height above ground of emission source (m).

3.5 CALINE4 dispersion model

CALINE4 model is the fourth generation line source Gaussian plume dispersion model. CALINE4 predicts the concentration of carbon monoxide (CO), nitrogen dioxide (NO2) and suspended particulates (PM10) near roadways. It employs a mixing zone concept to characterize pollutant dispersion over the roadway due to vehicles plying on the road corridor [4,9]. CALINE 4 can predict the pollutant concentrations for receptors located within 500 m under given traffic and meteorological conditions [24,25]. It represents a line source as a series of finite length elements each oriented perpendicular to the wind. The length of each element is determined based on its distance from the receptor of interest. The model uses Pasquill Gifford categories to characterize the stability of the atmosphere [7].

4. RESULTS AND DISCUSSION

4.1 Traffic volume studies

To estimate the contribution of vehicular emissions to the ambient air quality, the numbers of vehicles passing through the study area were collected by installing CCTV camera at Seshadripuram College, Mysuru, India. The vehicular density /volume have been counted with the help of a compact disc having the record of 7 days x 24 hours of traffic flow in .mp4 format. The traffic volume have been categorized into five groups i.e., 2 wheelers (2W), 3 wheelers (3W), 4 wheelers (4W), Light duty vehicles (LDV) and Heavy duty vehicles (HDV) and used to conduct emission inventory studies. It was observed that, number of 2W vehicles were found to be maximum (12,775 nos./d) (Figure 4a) followed by 4W (4,464 nos./d), HDV (2,790 nos./d) and LDV (2,080 nos./d). However, Sharma et al. (2013) [4] and Dhyani et al. (2017) [11] showed that, traffic flow was dominated by 4W, followed by 2W, 3W and HDVs at a highway in Delhi city, India. During weekdays the peak traffic volumes were observed during 08:00 h – 11:00 h (morning peak hours) and 18:00 h – 21:00 h (evening peak hours). Khare et al. (2012) [26], Sharma et al. (2013) [4] and Dhyani et al. (2017) [11] have also observed peak traffic hours between 08:00 – 10:00 hours and 18:00 – 20:00 hours in Delhi, India. However, during weekends (Figure 4b) peak traffic volume was noticed only between 17:00 and 21:00, during evening peak hours. The reason for lower vehicular density in the morning hour during weekends may be due to absence of schools, colleges and offices (Holiday) and higher vehicular density in the evening hours during weekends may be due to people going out for recreational activities. A maximum number of ~23,000 vehicles were observed during weekdays and ~17,500 vehicles were counted during weekends, near to Seshadripuram College. Further, 7 days traffic variation near Seshadripuram College showed similar trend of vehicular density during peak morning and evening traffic hours as shown in Figure 4c. The Heavy duty vehicles were found to be maximum during morning hours, which may be due to supply of raw materials to the industries.
located on the highway, however, a similar observation was also made by Prakash et al. (2015 and 2016) [27,28].

Fig - 4: Traffic variations during (a) weekdays, (b) weekends and (c) daily variation, near to Seshadripuram College.

4.2 Percentage distribution of vehicles and emission factors (EF)

Traffic composition was mainly dominated by 2W during weekdays and weekends and varying from 50–56%, followed by 4W (19–28%), LDV (9–12%), HDV (6–12%) and 3W (3–4%) at the study area (Figures 5a-b). It was also observed that, during weekdays number of HDV was more, however, during weekend number of LDV was found to be more. Goud et al. (2015) reported that, traffic composition was dominated by 2W (42–43%), followed by 4W (39–40%), 3W (8–9%), LDV (5–6%) and HDV (4%) at Central Silk Board intersection, Bengaluru, India [30]. However, in the present study, maximum traffic was observed during summer season (~25,000 vehicles/day) followed by winter (~22,000 vehicles/day) and monsoon season (~20,000 vehicles/d). The maximum number of vehicles observed during summer season may be due to summer vacation/holidays. ARAI emission factors were used to identify the NO\textsubscript{2} and PM\textsubscript{10} emission factors from each category of vehicles. From the Figure 6 a-b, it was observed that, during weekdays and weekends, NO\textsubscript{2} (EFs) was mainly contributed from HDV (75–86%) followed by 2W (6–10%), LDV (5–10%), 3W and 4W (1–3%). A similar observation was made for PM\textsubscript{10} pollutant also (Figure 7a-b).
Fig – 5: Percentage contribution of traffic volume during (a) weekdays and (b) weekends.

Fig – 6: Percentage contribution of NO\textsubscript{2} Emission factors (gm/km) from different category of vehicles during (a) weekdays and (b) weekends.

Fig – 7: Percentage contribution of PM\textsubscript{10} Emission factors (gm/km) from different category of vehicles during (a) weekdays and (b) weekends.
Fig - 8: Average Hourly Emission Loads (gm) at 14 links during (a) weekdays, and (b) weekends from 9 am to 6 pm.

PM$_{10}$ was mainly contributed from HDV (87–89%) followed by 2W, LDV (5–12%) and 3W, 4W (<1–2%). It was clearly understood that, even though the number of 2W was found to be maximum, but the contribution of maximum emission loads were from HDV, LDV and 4W vehicles. Bhanarkar et al. (2005) have also reported, largest contribution of NO$_2$ (57%) among the vehicular emissions was due to heavy-duty vehicles in Jamshedpur region, India [3].

4.3 Emission load distribution along the highway

An emission inventory is accounting the amount of pollutants emitted into the atmosphere and it usually contains the total emissions for one or more air pollutants, originating from all source categories within a specified span of time. Emission inventory depends upon location, elevation, frequency and duration of emission, etc. and it provides the information about the status of air pollution in the urban fringes. Emission inventory of different pollutants in various urban cities of India have been reported by a number of researchers [3,27-38]. However, in the present study the length of the selected highway was 3.3 km, which was divided into 14 links based on elevation, intersection and direction of the road. Emission factors for CO, NOx, PM$_{10}$, PM$_{2.5}$ and SO$_2$ was considered based on ARAI (2008) [17] and Road Transport emission factor (NAEI, 2013) [39] to identify the emission load over the study area. These emission factors along with total number of vehicles per hour (VPH) were further used to calculate weighted emission factor (WEF) developed by US-EPA. CALINE4 model requires an input of WEF at each link along the identified highway stretch. Emission factor is a function of total number of vehicles. In the present study emission factors of PM$_{2.5}$ and SO$_2$ were found to be very less (0.04 and 0.002 gm/km) when compared to CO and NOx emission factors (1.4 and 1.7 gm/km). This may be due to vehicular exhaust mainly contains CO, CO$_2$ and NOx compared to PM$_{2.5}$ and SO$_2$ [40]. A similar study of calculating of emission factors was conducted by Goyal et al. (2010) [38], Goud et al. (2015) [29] and Prakash et al. (2015 and 2016) [27,28]. The
average hourly emission factors and emission loads, which are based on distance between the links, during weekdays and weekends from 09:00 am to 06:00 pm are shown in Figures 8 (a-b). Emission loads were calculated based on emission factor (gm/km) and link distance (km). From the plots it was observed that, emission load of CO and NOx was high at link 1, 2, 5, 6, 12 varying from 400 – 600 gm. The reason for higher emission loads were due to more numbers of vehicles, as the places were near to Hebbal industrial area main road (L5 – L6), J.K. Tyres (L12 – L13) and also due to the larger link distances (~ 300–400 m). However, there was a little variation of emission load for weekdays and weekends because of less difference in hourly variation of total number of vehicles over 14 links from 09:00 am to 06:00 pm.

4.4 ISCST3 and CALINE4 model predictions

ISCST3 and CALINE4 models were applied to predict NO2 and PM10 concentrations (Figures 9a-c) emitted from line sources within the study area. Highway (3.3 km length and 36 m width) passing through the Industrial area of Mysuru was considered as major area/line source of pollution, as the daily number of vehicular density varies from 20,000 to 25,000 vehicles. A standard ±5% error was also considered in model predictions. It was observed that, NOx concentration predicted by ISCST3 and CALINE4 model during winter season (Figure 9a) were found to be 9–25 μg/m³ and 10–40 μg/m³, respectively. However, ISCST3 and CALINE4 model predicted PM10 concentrations were found to be ranging from 18–43 μg/m³. Maximum concentrations were found near to R1, R2 and R3, which may be due to more number of vehicles at the receptor locations. An approximate of 10,000 to 14,000 vehicles were counted from 10:00 h – 18:00 h. The reason for difference in prediction of pollutant concentrations may be due to ISCST3 model was higher version model and also due to the limitations of CALINE4 model predictions. This may also be due to the input parameters into the CALINE4 model was very limited and it predicts the NOx concentration in ppm, which further has to convert into μg/m³. Palmgren et al. (2003) found that traffic density and diesel vehicles were important explanatory variable for particulate concentrations along the roads of Denmark [41]. As the number of vehicle increases pollutants such as, CO, NOx and PM10 concentration also increases with the vehicular exhausts [40,42,43]. However, during summer season (Figure 9b) pollutant concentrations were found to be less compared to winter due to high wind speeds and wind directions. Wind speeds were found to be more during summer season compared to winter season. NOx and PM10 concentrations during summer season were found to be 4–20 μg/m³ and 11–40 μg/m³, respectively. Benson (1992) has reported that, dispersion models do not perform well under low wind conditions [25]. It was also observed that, CALINE4 model was not applicable for the pollutant with less concentration and model accuracy was found to be upto two decimal points.

Fig 9: ISCST3 and CALINE4 model prediction for NO2 and PM10 during (a) winter, (b) summer and (c) monsoon season.
According to Sharma et al. (2013) CALINE4 model should not be used in urban environmental conditions where roadside air quality is influenced by industrial, thermal power plants and urban street canyons, which plays a vital role in determining the resultant pollutant concentrations. Further, the result of ISCST3 and CALINE4 models for monsoon season (Figure 9c) was found to be minimum because of less number of vehicles and high wind speeds (> 24 km/h) compared to winter and summer seasons. The reason for less concentration obtained during summer and monsoon seasons may be due to the receptors (R3-6) were located upwind to the source as wind was blowing from W, WSW and SW towards E, ENE and NE direction, respectively.

In the present study scatter plots of ISCST3 and CALINE4 predictions for NO$_2$ and PM$_{10}$ concentrations combined winter, summer and monsoon seasons are made shown in Figure 10. The “factor-of-two” or FAC2 plot was used to assess model performance. If 75% of the data sets fall within the FAC2 band, the model predictions are considered as good correlation with each other [7,44,45]. For the prediction of NO$_2$ (Fig. 10a), it was observed that, most of the points were within the FAC2 lines but some of the points were found to be outside of FAC2 line because of the variation in model predictions. The reason may be due to CALINE4 model is a lower version model with limited input data and ISCST3 model is a higher version model and can calculated hourly variation of pollutant concentration. However, for prediction of PM$_{10}$ (Fig. 10b), almost all points were found to be within the FAC2 line. This may be due to CALINE4 model was more applicable for particulate pollutants than gaseous pollutants.

5. CONCLUSIONS

ISCST3 and CALINE4 models were used to predict NO$_2$ and PM$_{10}$ concentrations emitted from line sources. The meteorological parameter showed an average temperature of 22°C to 26°C over the study area. Further, relative humidity was found to maximum during monsoon season (66-86%) and minimum during summer season (7-51%). A maximum wind speed of 19 km/h was noticed during monsoon season, indicating higher dispersion of air pollutants. The windrose plots indicate that, wind direction gradually changes from NE direction towards SW and WSW direction during winter to summer and monsoon seasons. Traffic count studies showed, number of 2W vehicles were maximum (12,775 nos./d) followed by 4W (4,464 nos./d), HDV (2,790 nos./d) and LDV (2,080 nos./d). The number of 2W were maximum in traffic distribution, but NOx and PM$_{10}$ (EFs) were mainly contributed from HDV (75-86%) followed by 2W (6-10 %), LDV (5-10%), 3W and 4W (1-3%). PM$_{2.5}$ and SO$_2$ emission factors were found to be very less (0.04 and 0.002 g/km) compared to CO and NOx emission factors (1.4 and 1.7 g/km). Further, emission loads for CO and NOx pollutants were found to be high at link 1, 2, 5, 6, 12 and 13 due to heavy traffic densities.

On the other hand, NOx concentrations predicted by ISCST3 and CALINE4 models during winter season were found to be ranging from 9–25 μg/m$^3$ and 10–40 μg/m$^3$, respectively. However, PM$_{10}$ concentrations were found to be 18–43 μg/m$^3$. Maximum concentrations were found near to R1, R2 and R3, which may be due to maximum vehicular density.

NO$_2$ and PM$_{10}$ predictions by ISCST3 and CALINE4 model showed a significant difference due to the input parameters into the CALINE4 model which were very limited and CALINE4 predicts NOx concentration in ppm, which further have to convert into μg/m$^3$. ISCST3 and CALINE4 model predicted NO$_2$ and PM$_{10}$ concentrations were found to be maximum during winter season due to calm atmospheric conditions (low temperature and wind speeds). However, NO$_2$ and PM$_{10}$ concentrations were found to be within NAAQS of 80 μg/m$^3$ and 100 μg/m$^3$, respectively.
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