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Vehicular pollution modeling using the operational street pollution model (OSPM) for Chembur, Mumbai (India)

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Abstract Megacities in India such as Mumbai and Delhi are among the most polluted places in the world. In the present study, the widely used operational street pollution model (OSPM) is applied for assessing pollutant loads in the street canyons of Chembur, a suburban area just outside Mumbai city. Chembur is both industrialized and highly congested with vehicles. There are six major street canyons in this area, for which modeling has been carried out for NO_x and particulate matter (PM). The vehicle emission factors for Indian cities have been developed by Automotive Research Association of India (ARAI) for PM, not specifically for PM_{10} or $PM_{2.5}$. The model has been applied for 4 days of winter season and for the whole year to see the difference of effect of meteorology. The urban background concentrations have been obtained from an air quality monitoring station. Results have been compared with measured concentrations from the routine monitoring performed in Mumbai. NO_x emissions originate mainly from vehicles which are ground-level sources and are emitting close to where people live. Therefore, those emissions are highly relevant. The modeled NO_x concentration compared satisfactorily with observed data. However, this was not the case for PM, most likely because the emission inventory did not contain emission terms due to resuspended particulate matter.

Keywords Operational street pollution model · Traffic pollution modeling · Urban air quality · NO_x · PM

Introduction

The World Health Organization (WHO 2006) has estimated that globally, air pollution is responsible for 2 million premature deaths annually. Urban pollution loads are governed by emission densities and meteorological conditions (Hertel and Goodsite 2009). Air quality monitoring is carried out to communicate air quality level in the city using recommended methods by regulatory authority. Various measurement techniques and maximum air pollution concentration levels are fixed in different countries as shown in Table 1. The filter dynamics measurement system (FDMS) and gravimetric techniques both are used for PM_{10} measurement in Europe. The maximum concentration level is fixed generally based on the health exposure. Mumbai is a megacity and one of

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Table 1 Measurement techniques and maximum admitted concentration values

	Measurement techniques		Maximum admitted values (μg/m^3)	
	NO_x	PM_{10}	NO_x	PM_{10}
India	Colorimetric	Gravimetric	40 (annual)	60 (annual)
Europe	Chemiluminescence	Gravimetric/FDMS	40 (annual)	40 (annual)

the most polluted cities in the world. Traffic emissions are known to have major influence on the local pollution levels. Two decades ago, industrial air pollution dominated the pollution loads of Mumbai. But with the growth of the city, the local authorities have forced the industry to relocate to the outskirts of the city. With the continuous growth of the city, because of the increasing need for places to live, heights of buildings in the city center have steadily increased and formed deep street canyons with even more dense traffic loads. Air pollution due to traffic is therefore a major concern in Mumbai today, and furthermore, since measurements are scarce, there is a great need for tools that may be used in assessing air pollution loads in the busiest roads. Several air quality models have been developed for assessing vehicular pollution. USEPA has developed models such as the EPA HIWAY (Zimmerman and Thompson 1975; Petersen 1980), CALINE (Benson 1992), and AERMOD (Cimorelli et al. 2004; Kumar et al. 2015, 2016) for line sources. The general finite line source model (Luhar and Patil 1989) has been formulated for line source based on the Gaussian diffusion equation. Worldwide, but especially in European countries, the operational street pollution model (OSPM) is widely used for modeling vehicular pollution for regulatory and control management purposes (Kakosimos et al. 2010). OSPM, developed at Aarhus University, is an empirical, parameterized model for urban street canyons with very short calculation times.

In this paper, the Weather Research and Forecasting (WRF) model has been used for the simulation of meteorological parameters and it provides mesoscale meteorology at surface level disregarding the influence of buildings on the microscale wind field. The WRF meteorology serves as input for the OSPM model which is able to handle the specific meteorology and dispersion conditions inside street canyons in the presence of buildings. OSPM calculates concentration of exhaust gas based on a combination of a plume model for the direct contribution and a box model for the recirculating part of the traffic pollution in a street canyon. This method has been applied on the Chembur region of Mumbai city for two periods: the winter season and the entire year. The purpose of this study was to compare average concentration of the 4 days with highest pollution in the winter season and annual average concentration with measurements. The winter season has usually critical dispersion condition that generates maximum pollution levels. Also, national ambient air quality standards are given on annual and daily basis. The annual average of ambient air quality may be complying with the prescribed limit but air quality for a limited period may be exceeding the 24-hourly standards in winter season. Winter season is much worse than the other periods of the year which has severe cause on health. In the following section, a brief general description of OSPM is given, followed by sections describing the study area and model setup. Finally, model results have been validated with available observed concentration reported in literature. The experimental data has been used only for validation of the model.

Operational street pollution model

In OSPM, concentration of exhaust gases is calculated based on plume model for the direct contribution and based on box model for the recirculating part of the pollutants in the street. The plume model for direct contribution is based on the assumption that emissions and traffic-induced turbulence are uniformly distributed in the street. The direct contribution is computed using an analytical solution of integration along the wind path inside the street canyon. The crosswind diffusion is disregarded and the wind direction at the street level is assumed to be a mirror image of the roof-level wind. The extent of the recirculation zone determines the length of the integration path (Berkowicz et al. 2006). Details concerning the various parameterizations applied in the OSPM model are described in more detail in Berkowicz (2000). Although the model is able to handle streets with openings in building facades along the street, or street buildings on only one side of the street, it is still most suited for closed street canyons that it was originally developed for, and for which it has been most extensively tested (Kakosimos et al. 2010). OSPM has been evaluated in a variety of studies where it typically has been combined with an urban background model and results have been compared with the measurements from urban streets in larger cities (Kukkonen et al. 2003). The model may be operated in batch mode on a large number of streets in the city and it has been shown to perform well in a study of Copenhagen, Denmark (Berkowicz et al. 2008). However, the OSPM model has also been applied in a variety of other cities including the city of Thessaloniki (Greece) for modeling of PM_{10}, for which the results were shown to be in good agreement with observed data when predictions were performed for all streets in the historical city center (Assael et al. 2008). The performance also has been evaluated for urban street canyons of Nantes in France (Gokhale et al. 2005). In a Finnish study, a measurement program has also been conducted in a street canyon of Helsinki, and the OSPM model was applied for modeling CO, NO_x, NO_2, and O_3 (Kukkonen et al. 2001). Also, here, predictions of pollutant levels were in good agreement with measurements. Furthermore, OSPM has been built into the Danish AirGIS system (Jensen et al. 2001; Ketzel et al. 2011), for assessing human exposure in assessment of health effects. Several studies have documented that OSPM performs well (Berkowicz et al. 2006; Hung et al. 2010; Ketzel et al. 2012).

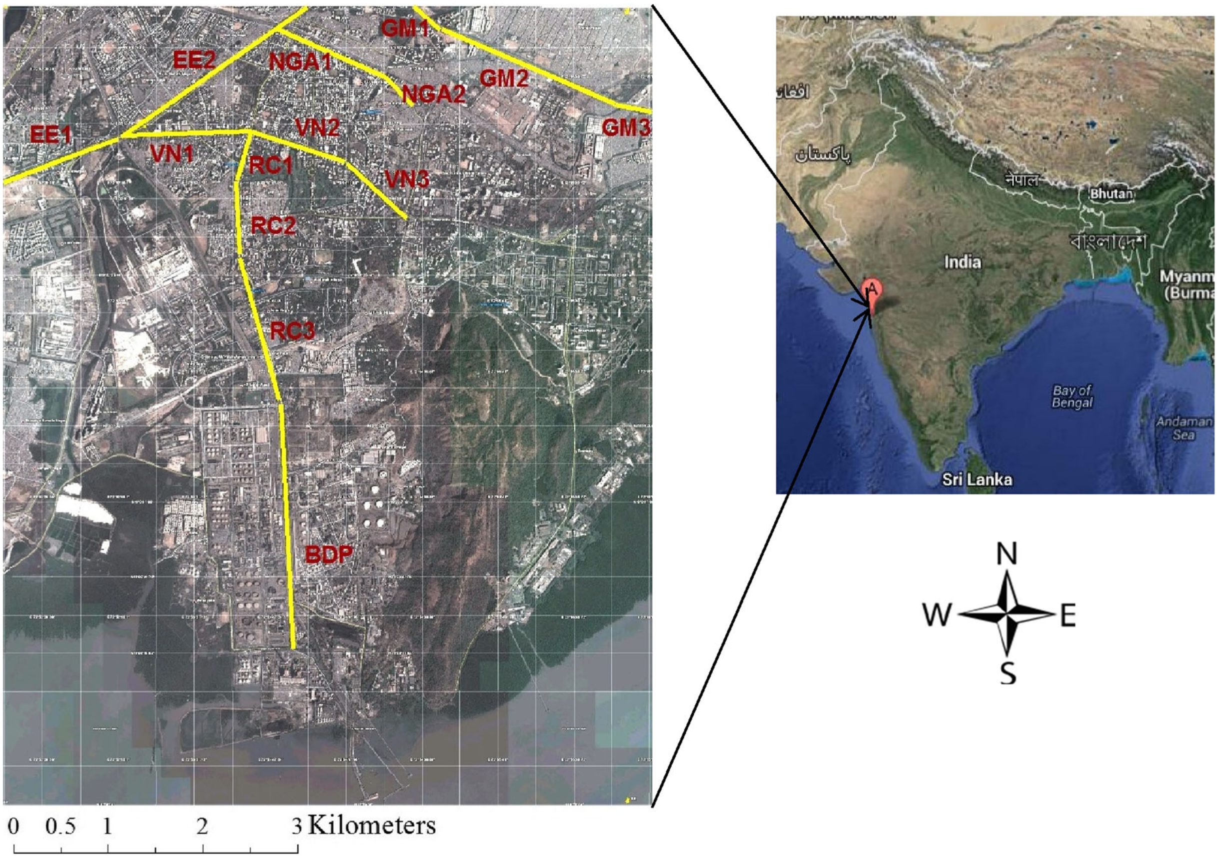


Fig. 1 Study area Chembur with the six investigated streets highlighted

Weather research and forecasting model

The meteorological parameters have been generated using advanced Weather Research and Forecasting (WRF) model for the Chembur region of Mumbai city. These parameters have been processed for further use in the OSPM. One fully revised resource for researchers and practitioners in the growing field of meteorological modeling at the mesoscale is the second edition of mesoscale meteorological (MM) model (NCAR 2012). The next-generation mesoscale numerical weather prediction system is the WRF model, which is designed to serve both atmospheric research and operational forecasting needs (Henmi et al. 2005). WRF is the most recent numerical model adopted by NOAA's National Weather Service as well as the US military and private meteorological services. The capability of this model is to simulate and forecast the meteorological profile reflecting either real data or ideal data atmospheric conditions. The WRF model has provided meteorological parameters for the Chembur region which have been used in the vehicular pollution model.

Methodology and data collection

Chembur is a suburb in eastern Mumbai, India whose longitude and latitude are 19.06° N, 72.89° E respectively. The study area is 6.5 km east to west and 8.45 km north to south. For the current study, six streets were selected for vehicular pollution modeling, and the locations of these six streets are shown in Fig. 1.

Streets are named by initial letters, where EE is Eastern Express Highway, VN is V.N. Purav road, RC is Ramakrishna Chemburkar marg, BDP is B.D. Patil marg, NGA is Narayan G. Aacharya road, GM is Ghatkopar-Mankhurd road, and 1, 2, 3 are line segment numbers.

OSPM has been applied for two time periods: firstly, for 4 days of January (winter season) in 2011, which represents the worst case in air quality because in winter season, the meteorological conditions are unfavorable. The mixing height and wind speed are low during the winter season.

Secondly, OSPM has been applied for the entire year of 2011 to study the annual behavior of air quality. For one of the roads (BD Patil road), the model had been run in the so-called single street mode because the orientation of the street with respect to North was uniform for the entire road. For the remaining streets, OSPM had been run in the so-called multistreet mode allowing for the street orientation to change between the single-street line segments.

The various necessary hourly input data for the model calculations are given including time series of meteorology, traffic, emission, and background

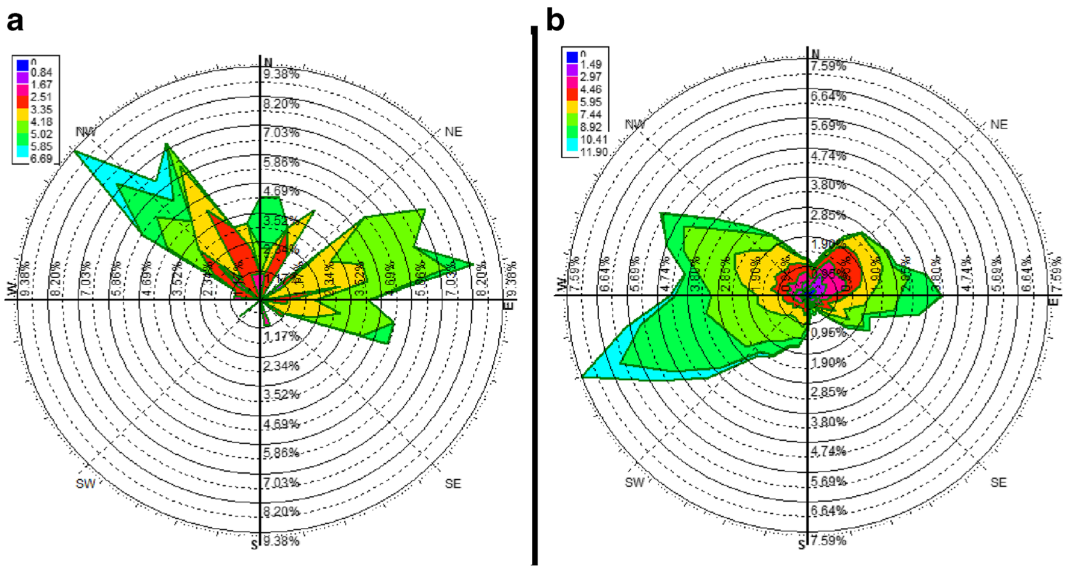


Fig. 2 Wind roses for **a** the period 1 to 4 January 2011 and (**b**) annually using predicted data by WRF

concentrations. The air quality model requires hourly meteorological parameters such as wind speed, wind direction, temperature, relative humidity, and global radiation. These meteorological data were generated using the WRF model applying a grid resolution of 25 km × 25 km and using a model domain of 10°×10° around Mumbai. Coarse-resolution meteorological data obtained from the National Center for Environmental Protection (NCEP) FNL were input to the WRF model. The wind roses for two time periods are shown in Fig. 2. These wind data were predicted by the WRF model. The first wind rose indicates that wind was blowing from the east and the northwest directions in most of the 4-day time period. However, in the annual wind rose, the most prominent wind direction is west followed by easterly directions. Temperatures were relatively constant during the 4 days of the period in the range of 20 to 30 °C. Night time temperatures were around 5 to 6° lower compared to daytime.

For each of the different roads which were part of the study domain, the number of vehicles per hour was counted in various categories of vehicles. The number of vehicles was counted for 24 h for V.N. Purav road, and for the other roads, counting was done for 8 h of the day. The count of the number of vehicles during rest of the time for all the streets was assumed to be the same as V.N. Purav road during the 16-h period. Figure 3 shows the number and types of vehicles over the day with diurnal variation for V.N. Purav road. Then, hourly emission rate was estimated using emission factors obtained from the Automotive Research Association of India (ARAI 2007). These emission factors were derived as part of a project under CPCB/MoEF.

Cars are operated by various kinds of fuels such as diesel, petrol, and gas and emission factors differ with fuel type which results to different emission rate estimates. Taxis are similar to cars but they are operated on CNG fuel. The “auto” category consists of three-wheel vehicles that should be operated by gas only as required by government policy. Light-duty diesel vehicles (LDDVs) are small goods carriers and more-than-five-seated vehicles. Heavy-duty diesel vehicles (HDDVs) are trucks, buses, and other big vehicles. Figure 3 shows peak hours for particular kinds of vehicles. These peak hours start at 8:00 and 20:00, i.e., when people travel to work and back home. Taxis have peak hours at noon time and the rest of the time, their numbers on the streets are constant except after midnight. Figure 4 represents the number of vehicles in a day on the different streets of the study area Chembur. The number of LDDVs is always high on each street and all streets contain cars, taxis, and small carrier vehicles. The number of HDDVs and two-wheelers (motorcycles) are high on mainly two streets: Ghatkopar-Mankhurd road and Eastern Express Highway road. Site-specific features such as height of building, road width, and road orientation have been included in OSPM. The building heights have been assumed to be about four stories (12 m) for Eastern Express Highway, V.N. Purav road, Ramakrishna Chemburkar Marg, BD Patil Marg, and Ghatkopar-Mankhurd road, but three stories (9 m) for Narayan G. Aacharya road. The dimensions of each road of Chembur have been given in Table 2. The orientations of streets have been given in clockwise from the north and the heights of the streets are zero as it is on ground.

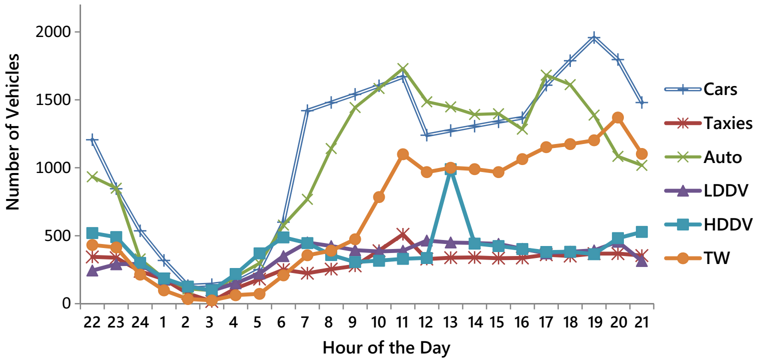


Fig. 3 Diurnal variation of number of vehicles in a day for V.N. Purav road

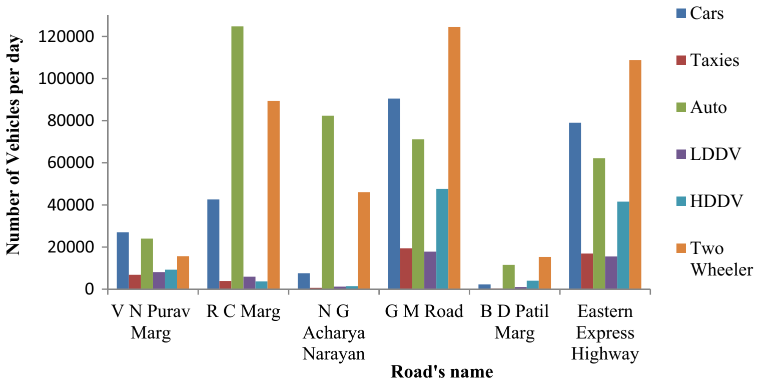


Fig. 4 Number of vehicles per day on the roads

The OSPM model requires urban background data as input for vehicular pollution modeling. This has been taken from an air quality monitoring station of Brihanmumbai Municipal Corporation (BMC) at Borivali, Mumbai as 19 $\mu g/m^3$ for NO_x and 158 $\mu g/m^3$ for PM. This monitoring station is less affected by traffic pollution because it is away from the study domain and situated on the roof. Urban background concentration data also can be estimated using on-air quality model which requires emission data without traffic contribution, but this is not available for this city. An air quality monitoring station was located on the roadside of Ramakrishna Chemburkar Marg in the study area. This measured air quality data was used in validation of OSPM model output.

Hourly emissions of NO_x and PM have been estimated based on the number of vehicles for the particular streets and using emission factors by ARAI (2007) which are the most recent emission factors applicable for Indian cities. The numbers of vehicles vary with the time of the day and it causes variation in emissions over the day. Figures 5 and 6 show the diurnal variation of the emissions at the six street canyons for NO_x and PM, respectively. Emission rate was estimated using the actual number of vehicles in unit time, emission factors and vehicle kilometer travelled (ARAI 2007) as given below.

Table 2 Dimensions of each street of Chembur

Name of Streets	Length (m)	Width (m)	Orientation of streets (degree)
EE1	1300	28	160
EE2	2250	28	145
NGA1	1050	7	20
NGA2	400	7	45
VN1	1250	21	175
VN2	1000	21	20
VN3	900	21	40
GM1	450	28	40
GM2	1700	28	25
GM3	400	28	10
RC1	550	14	110
RC2	800	21	90
RC3	1600	14	75
BDP	2500	14	85

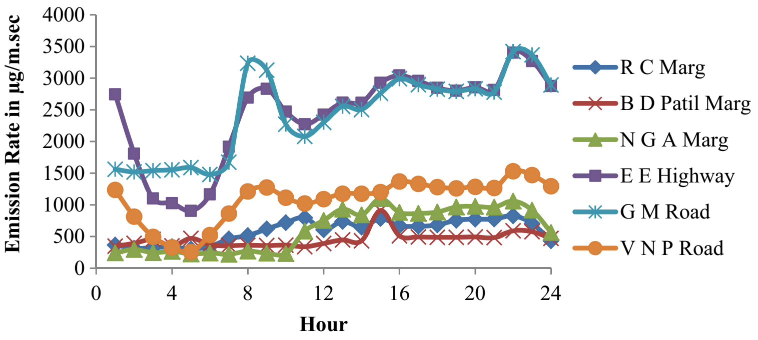


Fig. 5 Diurnal variation of NO_x emission rate (µg/m s) for the six roads

$$\text{Emission rate}\left(\mu\text{g}/\text{s}\right) = \text{emission factor}\left(\mu\text{g}/\text{km}\right) \times \text{activity}\left(\text{km}/\text{s}\right)$$

$$\text{Activity} = \text{number of vehicles}(\text{in certain period}) \times \text{length of road}(\text{km})$$

Colorimetry was used to measure the concentration of NO_x. NO_x in the ambient air is collected by bubbling air through a solution of basic sodium arsenite. The nitrite ion produced during the sampling is reacted with phosphoric acid, sulfanilamide, and N-(1-naphthyl)-ethylenediamine dihydrochloride (NEDA) to form an azo dye and then determined colorimetrically at 540 nm. Calibration curve is obtained by the colorimetric method by adding different concentrations of NO_2 solution such as 1 to 10 µg NO_2/ml, H_2O_2, and NEDA reagents at 540 nm. Absorbing reagent is prepared by dissolving 4.0 g of sodium hydroxide in distilled water and 1.0 g of sodium arsenite and dilute to 1 L with distilled water. Sulfanilamide is prepared by dissolving 20 g of sulfanilamide in 700 mL of distilled water, 50 mL of 85 % phosphoric acid, and dilute to 1 L with distilled water. NEDA is prepared by dissolving 0.5 g NEDA in 500 mL of distilled water. To prepare H_2O_2 solution, 0.2 ml of 30 % H_2O_2 is taken and diluted it with freshly prepared distelled water, make up final volume to 250 ml with distilled water. The calculation of concentration is done by Jacob and Hochheiser (1958) and CPCB (2011).

Results and discussion

The OSPM model was run for two periods: (a) 4 days of winter and (b) the entire year of 2011 to compare the worst season of winter season with annual average. OSPM performed well with meteorology of time-weighted average for both periods. Average time-weighted wind direction for the study period was considered for modeling. The air pollutant dispersion is driven by wind speed, wind direction, and temperature. In the street canyon, wind speed and wind direction cause cavities and change the meteorological scenarios. For validation purposes, the model results have been compared to available ambient air quality measurements at a kerbside

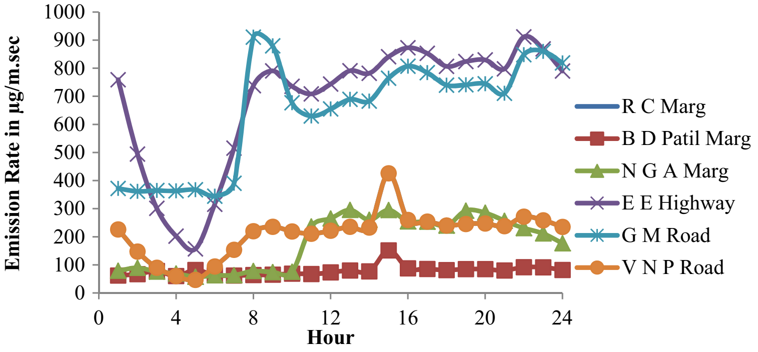


Fig. 6 Diurnal variation of the PM emission rate (µg/m s) for the six roads

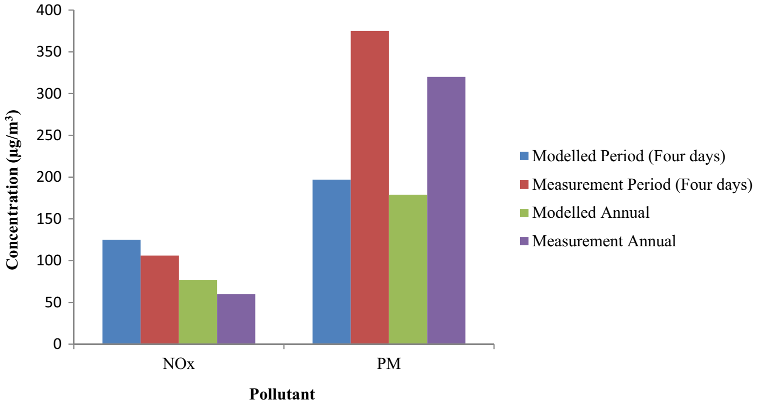


Fig. 7 Average NO_x and PM concentration (µg/m^3) of streets at Ramakrishna Chemburkar Marg 2

monitoring station (Ramakrishna Chemburkar Marg), where vehicles are the dominant source. The ambient measurements contain contributions from all sources and the influence of the vehicular source cannot easily be separated. Therefore, the background concentration has been included in OSPM as 19 µg/m^3 for NO_x and 158 µg/m^3 for PM for all the streets. These monitoring stations are operated by Brihanmumbai Municipal Corporation (BMC), Mumbai and monitors air quality parameters continuously. Air quality monitoring is done twice in a week. PM concentration is obtained by gravimetric techniques using a high-volume sampler. BMC provided SPM data only, so a factor of 0.31 was used to estimate PM_{10} concentrations from SPM concentrations based on available PM_{10} and SPM measurements (MPCB 2011). This is because vehicles do not emit particle size of more than 10 µm.

In Fig. 7, the measurement and model data are shown for NO_x and PM. Modeled NOx concentration is well-validated (23 % overestimate) with measurements which are influenced by all sources of NO_x in both, a 4-day period of winter and one full year period. The sources of emission of NO_x are industries and vehicles, with the majority of the emissions coming from street-vehicular sources. Industries have some device to control NO_x emission and these sources are not at the ground level. Due to meteorology, they have an impact at distant regions. But vehicular emissions are ground-level sources and cause more ground level concentration near the emission source. However, the model results for PM substantially underestimate the measurement (45 % underestimate) because the emission inventory of this study does not include emission of resuspended particulate matter (RSPM) mainly due to highly congested roads.

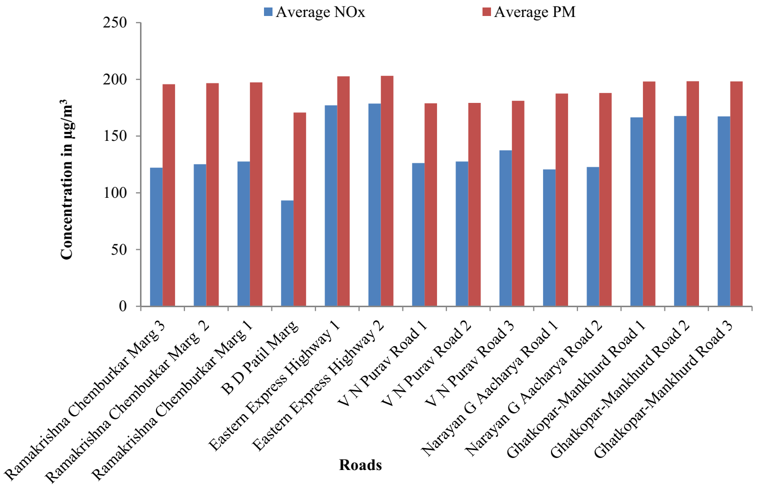
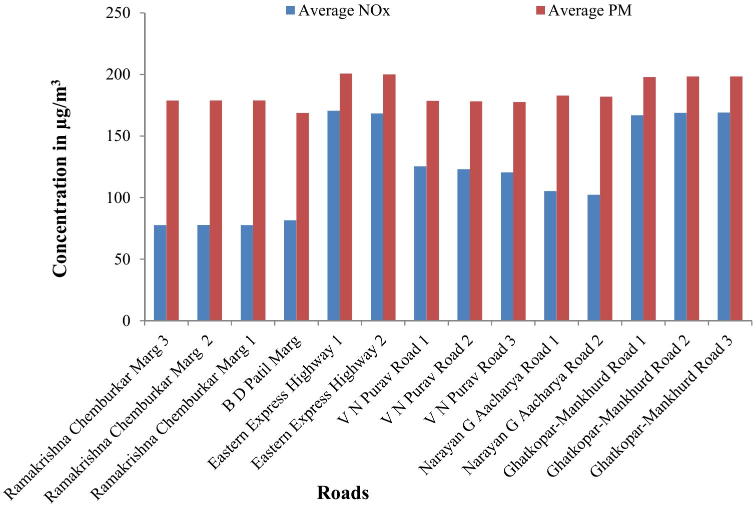


Fig. 8 Average NO_x and PM concentration (µg/m^3) of streets for 4 days period

Fig. 9 Average NO_x and PM concentration ($\mu g/m^3$) of roads for year 2011



The performance of the OSPM model with WRF meteorology was in good agreement with the observed concentration. The average pollutant concentrations in the street canyons have been generated using the OSPM for each street segment for NO_x and PM for 4 days period as shown in Fig. 8. Again, Fig. 9 shows annual concentration of NO_x and PM of each street segment in the study domain for the annual time period considered. The next objective of the modeling for two different periods viz. winter season and annual was to compare the pollution level in winter season and the entire year. In both cases, Eastern Express Highway and Ghatkopar-Mankhurd Road have high concentrations of NO_x and PM as their traffic flow and vehicular congestion is higher. The average concentration is 19 % higher than the annual average in winter for NO_x but 3 % higher for PM. The increment of PM is smaller because vehicles emit less PM and the background value for PM is high. Modeled values of Eastern Express Highway and Ghatkopar-Mankhurd Road have high concentrations, whereas equal background concentration has been considered for all the streets. So, appropriate management plans are required for these two streets.

Conclusions

OSPM has the capability to handle specific meteorology and dispersion conditions inside street canyons in the presence of buildings. It calculated concentration of exhaust gas based on a combination of a plume model for the direct contribution and a box model for the recirculating part of the traffic pollution in a street canyon. Finally, the concentration predicted by OSPM compared well with observed concentration. The present study shows that NO_x emissions dominate at the ground level. For NO_x, the model performed with a 23 % overestimate but for PM, it performed with a 45 % underestimate. Also, this study has focused on comparison of worst winter season with annual concentration by vehicles. There are 19 and 3 % increments in NO_x and PM concentration, respectively, in winter season compared to annual concentration. The winter season has less increment for PM because it has low emission. The OSPM model can be applied for peak and off-peak hour vehicle density which will give worst exposure of population. The evaluated model can be applied for rational management of any canyon of the city to improve air quality.

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