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Research article

Prediction of $PM_{2.5}$ along urban highway corridor under mixed traffic conditions using CALINE4 model

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ABSTRACT

The present study deals with spatial-temporal distribution of $PM_{2.5}$ along a highly trafficked national highway corridor (NH-2) in Delhi, India. Population residing in areas near roads and highways of high vehicular activities are exposed to high levels of $PM_{2.5}$ resulting in various health issues. The spatial extent of $PM_{2.5}$ has been assessed with the help of CALINE4 model. Various input parameters of the model were estimated and used to predict $PM_{2.5}$ concentration along the selected highway corridor. The results indicated that there are many factors involved which affects the prediction of $PM_{2.5}$ concentration by CALINE4 model. In fact, these factors either not considered by model or have little influence on model's prediction capabilities. Therefore, in the present study CALINE4 model performance was observed to be unsatisfactory for prediction of $PM_{2.5}$ concentration.

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1. Introduction

Air pollution has become a major environmental problem. Annually, 0.65 million premature deaths occur due to outdoor air pollution in India (Lelieveld et al., 2015). The health impact analysis estimates up to 49,500 deaths in 2010 and 158,500 in 2030 due to vehicular pollution in India (Guttikunda and Jawahar, 2012).

The health impacts of air pollution are significant, especially in high population density areas.

In India, the major sources of $PM_{2.5}$ and PM_{10} are windblown dust, secondary aerosol, bio and fossil fuel combustion, vehicular emissions and biomass burning (Kothai et al., 2011; Yadav et al., 2014). Kinney et al. (2011) reported that vehicular traffic is an important source of particulate pollution in developing countries. The major sources of $PM_{2.5}$ associated with vehicular traffic are exhaust emissions from diesel vehicles, together with tire wear, brake wear and road surface abrasion from all vehicles (AQEG, 2012; Ferm and Sjoberg, 2015). Further, the concentrations of particulate matter are significantly higher near the road mainly due to re-suspension of dust and emissions from automobiles exhausts (Colbeck et al., 2011).

The $PM_{2.5}$ is particularly dangerous and can cause adverse health effects (Meena et al., 2016). Studies carried out across the world have clearly established the association between health risks and proximity to the major roadway/highway (Cakmak et al., 2016). Various studies have reported that population residing near major roadways are more exposed to high pollutant concentrations than those who live farther away from roads and have increased risks of various diseases (Ingle and Wagh, 2005; Guttikunda and Jawahar, 2012; CSE, 2013).

Assessment and prediction of impacts of vehicular pollution along roads and highways are carried out with the help of highway dispersion models. These models predict future air quality along the corridors, enabling policymakers to ensure that ambient air quality does not exceed stipulated the air quality standards by formulating an effective traffic and air quality management plan. Use of highways dispersion models has increased over the years in policy support for large road infrastructure projects.

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In the present study, an attempt has been made to assess the spatial and temporal variation of $PM_{2.5}$ in Delhi along with a highway corridor with the help of CALINE4 model (Benson, 1989). The $PM_{2.5}$ predictions were carried out for a day (24-h) period during the month of June (2014) (summer) and February (2015) (winter).

2. Methodology

2.1. Site characteristics

The present study was carried out in Delhi (India). The Delhi has the high vehicular population, with nearly 6.5 million (GNCTD, 2017) registered vehicles, which constitutes nearly 4.6% of the total vehicular population of India (MoRTH, 2013). In the present study, a road corridor on NH-2 (National Highway- 2) was selected which although is part of NH but represents a typical urban road condition. Like all over India, Delhi also has mixed traffic conditions [heterogeneous/mixed traffic has been defined as, vehicles of all shapes and sizes, interact on roadway, traffic don't follow lane discipline or traffic constitutes both motorized and non-motorized vehicles or dominant mode is less that 80% of the traffic mix (Arasan and Arkatkar, 2011; Mallikarjuna and Rao, 2011)].

Delhi has a high population density of 11,297 persons/km^2 (GNCTD, 2015). More than half of Delhi's population lives within 500 m of arterial roads in Delhi (CSE, 2012; Adak, 2015). On an average, primary emissions from fossil fuel combustion (coal, diesel, and gasoline) are responsible for ~25–33% of $PM_{2.5}$ mass in Delhi (Chowdhury et al., 2007). Further, in Delhi, on an average road dust contributes ~38% to $PM_{2.5}$ concentration, amongst these motorized vehicles contribute ~20%, followed by 19% from miscellaneous sources, ~12% by domestic fuel burning and nearly 11% by the industrial point source (Sharma and Dikshit, 2016).

The site (NH-2 corridor, Sukhdev Vihar depot to Apollo hospital) is geographically located at 28° 37′ 39.99″ N and 77° 14′ 29.04″ E at 216 m above mean sea level (msl). The corridor selected for the study was a 2 km stretch of National Highway-2 (NH-2) passing through Delhi to Agra city (Fig. 1). The selected corridor caters to both inter-city and intra-city traffic and is one of the busiest roads in the city with nearly 0.2 million vehicles plying daily.

2.2. Traffic characteristics

The 24-h classified traffic volume on the selected road/highway corridor was collected through video recording using video editing software 'videopad editor' (www.nchsoftware.com/videopad) in the month of June (2014) and February (2015). The total traffic volume at the highway corridor was observed to be 1,79,394 vehicles per day (1,93,411 passenger car unit or PCU) and 1,74,519 vehicles per day (1,88,862 PCU) for June (2014) and February (2015) respectively. During June (2014) cars (4Ws) (49%) constituted the dominant vehicle category followed by two-wheelers (2Ws) (30%), three-wheelers (3Ws) (8%), light commercial vehicles (LCVs) (5%), heavy commercial vehicles (HCVs) (6%) and buses (2%). Similar traffic volume distribution was observed during February (2015) with cars dominating the vehicles category with 47% followed by 2Ws (29%), 3Ws (11%), LCVs (6%), HCVs (5%) and buses (2%).

The observed diurnal pattern of traffic flow has been shown in Fig. 2. During June (2014) and February (2015) distinct morning (0900–1000 h) and evening (1800–1900 h) peak traffic hours can easily identified. Also, the gradual increase in HCVs could be observed during night-time (between 2100 and 0600 h) (Fig. 2), thus indicating that the highway corridor had distinct diurnal variation in number and composition of the vehicular traffic.

Information on age profile (vintage) and fuel type of vehicles (petrol and diesel) were also collected from fuel station surveys carried along the study corridor through a prepared questionnaire. During the fuel station survey(s), information related to fuel type (petrol, diesel, CNG and LPG) amongst the four-wheelers (cars) and engine technology [2stroke (2S) and 4stroke (4S) in 2Ws] for different categories of vehicles along with their year of registration were collected. At the selected site, ~60% of vehicles were petrol driven, followed by CNG vehicles (~20%), diesel (~19%), and LPG (~1%). The observed age profile of vehicles plying on selected road corridor has been summarized in Table 1. Nearly 85% of all 4Ws and 70% of all HCVs, LCVs and buses (CNG) were observed to be below 10 years of age (Table 1). Further, it is mandatory in Delhi for public transport vehicles (viz., buses, taxis and 3Ws) as well as LCVs registered in the city to run on CNG fuel. Therefore, 100% 3Ws were CNG fuelled, whereas, ~77% buses were CNG fuelled and rest ~23% buses (mostly interstate or national permit tourist buses) were diesel fuelled.

It was assumed that the vehicles plying on the highway and those encountered during fuel station surveys have similar characteristics in terms of their age profile, engine technology and composition. The information collected during fuel station surveys was extrapolated to traffic plying on the selected road corridor for a realistic assessment of age profile.

Age profile obtained from fuel station surveys and traffic volume videography (e.g. percentage of 2W-2S and 2W-4S vehicles, the percentage of petrol, diesel, CNG and LPG driven vehicles in different categories of vehicles) were used to estimate weighted emission factors (WEFs) which are used as an input in CALINE4 model.

The WEF is a function of vehicle emission factor (vehicle category, type, fuel type, age profile, vintage etc.) and vehicle activity (traffic volume). For estimation of WEF (g/mile) (representative values for all categories of vehicles) emission factors for Indian vehicles were used (ARAI, 2008; Sharma et al., 2011). Due to non-availability of $PM_{2.5}$ emission factors for Indian vehicles, in the present study particulates emission factors have been used. However, all Particulate emissions in vehicle exhaust mainly fall in the $PM_{2.5}$ size range. Therefore, all PM mass emissions correspond to $PM_{2.5}$ (ARAI, 2008).

2.3. Meteorology

On-site micro-meteorological parameters such as wind speed, wind direction and relative humidity were measured continuously for 24-h in the month of June (2014) and February (2015). The hourly mixing height values were obtained from the Indian Meteorological Department (IMD) (Attri et al., 2008). Hourly P-G stability classes were estimated using wind speed, solar insolation and cloud cover (day-time and night-time) (Turner, 1994). At the selected site, the predominant wind direction was north-west during June (2014) and south-east during February (2015) (Fig. 3). Various meteorological parameters viz., wind speed, wind direction, temperature, stability class, mixing height etc. are used in CALINE4 model have been summarized in Table 2.

2.4. Emission load estimation

Hourly average emission load for $PM_{2.5}$ has been calculated for selected road corridor as a function of emission factors for different categories of vehicles w.r.t. their fuel type and age profile and vehicular activity data (Sharma et al., 2011, 2013).

2.5. CALINE4 model description

The spatial-temporal extent of $PM_{2.5}$ emitted from vehicles has

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