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Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi

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HIGHLIGHTS

- Estimation of exhaust and non-exhaust emissions from on-road vehicles in Delhi.
- Estimation of mobile source air toxics (MSATs) emissions in Delhi from 1991 to 2020.
- After 2002 the share of non-exhausts PM_{10} emissions is higher than exhausts.
- Quantitative and qualitative validation of emission with ambient air concentration.

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ABSTRACT

Analysis of emissions from on-road vehicles in an Indian megacity, Delhi, have been performed by comparing exhaust emissions of gaseous, particulate matter and mobile source air toxics (MSATs), together with volatile organic compound (VOCs) and PM_{10} (particulate matter $\leq$10 μm) from non-exhaust vehicular sources, during the past (1991–2011) and future (2011–2020) scenarios. Results indicate that emissions of most of the pollutants from private vehicles (two wheelers and cars) have increased by 2- to 18-times in 2020 over the 1991 levels. Two wheelers found to be dominating the emissions of carbon monoxide (CO, 29–51%), hydrocarbons (HC, 45–73%), acetaldehyde (46–51%) and total poly aromatic hydrocarbons (PAHs, 37–42%). Conversely, private cars were found to be responsible for the majority of the carbon dioxide (CO_2, 24–42%), 1,3-butadiene (72–89%), benzene (60–82%), formaldehyde (23–44%) and total aldehyde (27–52%) between 1991 and 2011. The heavy-duty commercial vehicles (HCVs) shows their accountability for most of the nitrogen oxide (NO_x, 18–41%) and PM_{10} (33–43%) emissions during the years 1991–2011. In terms of PM_{10} emissions, vehicular exhaust contributed by 21–55%, followed by road dust (42–73%) and brake wear (3–5%) between 1991 and 2011. After 2002, non-exhaust emissions (e.g. road dust, brake wear and tyre wear) together indicate higher accountability (66–86%) for PM_{10} emission than the exhaust emissions (14–34%). The temporal trend of emissions of NO_x and CO show reasonable agreement with available ambient air concentrations that were monitored at locations, significantly influenced by vehicular activity. Encouraging results were emerged, showing a good correlation coefficient for CO (0.94) and NO_x (0.68).

1. Introduction

High levels of urbanization and economic growth has been observed during the last decade in the Indian subcontinent. In 1951, about 17% of India's population were living in urban areas that increased to 32% in 2011; this growth is further expected to rise by 35% by the year 2021 (Singh, 2012). Similarly, significant rise in per

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capita income and gross domestic product (GDP) were noticed during the recent decades in India. The urbanization and economic development has traditionally been strongly connected with an escalation in the demand for transportation and the number of road vehicles. According to MoSPI (2014), the registered vehicle population in India were 55 million in 2001 that became 142 million, with a 61% growth, in 2011. It is important to note that 35% of these vehicles are only plying in a few selected mega (i.e. those over 10 million population) and metro (i.e. those over 1 million population) cities, which are only having the 11% of country population (Kumar et al., 2011; Singh, 2012). The excessive vehicle population in Indian cities has significantly raised the level of air pollution emission loads, resulting in severe health risk issues (Gurjar et al., 2010; Nagpure et al., 2011, 2014; Kumar et al., 2015).

Indian megacity Delhi is the second most populous and among top polluted cities of the world (WHO, 2014). It is important to know that the air pollution related deaths have increased by two-fold between 1991 and 2010 in Delhi (Nagpure et al., 2014). Many studies have found that on-road traffic emissions are the major contributory factor in the rising air pollution in Delhi as compared to other sources (e.g. industry, residential, thermal power plant, etc.) (e.g. Bose and Srinivasachary, 1997; Gurjar et al., 2004; CPCB, 2010; Sahu et al., 2011; Guttikunda and Calori, 2013; Nagpure et al., 2013; Goyal et al., 2013; Jain et al., 2014; Kumar et al., 2015). Although most of these studies have used registered vehicle population to estimate the on road-traffic emissions in Delhi, that is not the real on-road vehicle population. India is having one-time vehicle registration system, and the available vehicle data for particular year is the cumulative vehicle population from the beginning of the vehicle registration system, which could be far more than the actual on-road vehicles. Although, some studies have used the on-road vehicle population by applying some fraction-based approach, considering that certain percentage of vehicle population is plying on the road. Since the vehicle population composition are changing every year due to the retirement of old aged vehicles and the addition of the new vehicles, therefore the fraction-based approach may not be able to signify the on-road vehicles with their age and technology. Both approaches are not able to represent the on-road vehicle population therefore-vehicular emission estimated by using these data could be larger or smaller than the actual vehicular emissions. Since vehicle composition (i.e. vehicle technology, age and their emission factors, (EFs)) may vary by year to year, analyses of the vehicular emissions by considering these factors is essential for managing the emerging air pollution and suitable policy development in Delhi.

Vehicles are responsible for several types of gaseous and particulate matter (PM) emissions, including greenhouse gases (GHGs), criteria and mobile source air toxics (MSATs) pollutants. Similar to the other pollutants, the MSATs can cause wide range of serious health effects from birth defects, cancer, negative effects on the kidneys, lungs and nervous system (USEPA, 2007; Heal et al., 2012; Kumar et al., 2013a; CPCB, 2014). As per the estimates from the USEPA, on-road vehicles are responsible for about half of all cancers attributed to outdoor air pollution (Wargo et al., 2006). Despite their significant contributions, there is a substantial knowledge scarcity on the accountability of vehicles for MSATs (e.g. 1,3-butadiene, acetaldehyde, benzene, formaldehyde, total aldehyde, and total poly aromatic hydrocarbons, PAHs) emissions, especially for Indian urban areas. Like MSATs there are various non-exhaust processes (i.e. evaporitive, tyre, brake and road surface wear) emissions (PM_{10}, volatile organic compound (VOCs)), are inadequately studied for any Indian urban areas. Since the level of PM_{10} in ambient air quality is increasing day by day in Delhi (Sharma et al., 2013; Kumar et al., 2013b), and very limited knowledge is available for contribution of non-exhaust source for PM_{10} in Indian cities, clearly indicates a need to understand accountability of both exhaust and non-exhaust sources for better air quality management. This study employs Vehicular Air Pollution Inventory (VAPI) model developed by Nagpure and Gurjar (2012) for the time-series emission analysis (1991–2011) of on-road vehicles in Delhi. The objectives includes: (i) Estimation of CO_2, HC, PM_{10}, CO, NO_x and MSATs (e.g. 1,3-butadiene, acetaldehyde, benzene, formaldehyde, total aldehyde, and total PAHs) emissions from vehicle exhaust by considering vehicle characteristics (e.g. age, technology). (ii) Assessment of non-exhaust (e.g. road-dust, tyre wear, break wear and evaporative) emissions from on-road vehicles in Delhi, and (iii) Future projection (2011–2020) of exhaust and non-exhaust emissions using GDP and per capita based econometric model.

2. Methodology

The VAPI model (http://www.vapimodel.com/) is deployed to estimate the exhaust and non-exhaust emissions from on-road vehicles. The model is first of its kind in India, which is able to estimate the emission from transport sectors with best available data by considering the vehicle age and technology. India has one time vehicular registration system and thereby challenging to find out the actual on-road vehicle population, in particular, year wise vehicle age and technology profile. Keeping these points in mind, the VAPI model has been designed to calculate on-road vehicular population, their age and technology and future emission projection by using built-up econometric tool. The model uses adjusted EFs to estimates the emission from on-road vehicles activities (e.g. distance travel) using Eqs. (1) and (2):

$$E_{a.p.i} = EF_{p,i} \times C_{T,p,i} \times C_{H,p,i} \times C_{A,p,i} \quad (1)$$

$$E_{pi} = P_i \times E_{a,p,i} \times V_i \times D_{t,i} \quad (2)$$

Where p is a pollutant and i is vehicle category type, $E_{a,p,i}$ is adjusted emissions rate of a, pollutant *p* from a *i* vehicle category type with specific technology; $EF_{p,i}$ is emissions factor (g or mg km^{-1}). $C_{T,p,i}$ is temperature correction factor; $C_{H,p,i}$ is humidity correction factor; $C_{A.,p,i}$ is altitude correction factor; $E_{p,i}$ is total emissions (unit depend upon EF unit); $Dt_{,i}$ is annual traveling days of *a i* vehicle category type; P_i is on-road vehicle population (model wise); V_i is per day vehicle kilometer traveled (VKT km day^{-1}).

It was recognized by various studies (Watson et al., 1980; Heywood, 1988; Dodge et al., 1996) that emission of different pollutants (e.g. CO, NO_x, 1,3-butadiene, formaldehyde, acetaldehyde) from vehicle engine exhaust is significantly affected by the thermodynamic conditions of the intake air. The temperature and relative humidity of intake air have the dominant effects on exhaust emissions. Ambient temperature also affects the vehicle tire rolling resistance and affects the atmospheric density with increasing altitude, which impacts the aerodynamic drag of vehicle – all these factors directly affect the vehicle emission exhaust. VAPI model uses all these correction factors on EFs to calculate the adjusted EFs (Eq. (1)) for each year. Based on the correction factors, emissions from vehicles could vary by time. Use of these correction factors certainly reduces uncertainties in emissions. The more details of correction factors are available in Nagpure and Gurjar (2012) and US Environmental Protection Agency (USEPA, 2002). After calculating adjusted EFs, VAPI model uses vehicle population (SI Fig. S2) by their age (SI Table S1) and technology composition for a particular year, and average VKT (SI Table S2) to estimate the emission from each category of the vehicle using Eq. (2). For the projection of future vehicle population, VAPI uses inbuilt