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 PM₁₀ emissions is higher than exhausts
- Quantitative and qualitative validation of emission with ambient air concentration

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

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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 PM₁₀ (particulate matter ≤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 (CO₂, 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 PM₁₀ (33-43%) emissions during the years 1991-2011. In terms of PM₁₀ emissions, vehicular exhaust contributed by 21 to 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 PM₁₀ 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).

Keywords: Air Pollutants; Non-exhaust emission; Emission inventory; Transportation Policies, Toxic Pollutants

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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 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 (UNEP, 2014; 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 therefor-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., 2013; 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. evaporative, 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., 2013), and that 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, brake 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); $D_{t,i}$ 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 econometric Gompertz equation tool. Since the vehicle population and ownership depends on gross domestic product (GDP) and per capita income (PCI) of the city or the region, Gompertz equation in VAPI model uses these variables to project the future vehicle population (please see Section S3 of Supporting Information (SI)). Further details on the Gompertz equation are available elsewhere (Singh, 2006; Nagpure and Gurjar, 2012). For projecting number of road vehicles in future, shift from two-stroke two-wheeler to four-stroke two-wheelers, compressed natural gas (CNG) vehicle population growth, future technology change and VKT shift due to different metro phase have also been considered. As for the impact of metro rail on the changes in VKT, methodology and data given by Murty et al., (2007) have adopted. Further details of the future projection are discussed in Nagpure and Gurjar (2012). The inputs data for VAPI model to estimate exhaust and non-exhaust emissions were acquired from various sources. The details of input data and sources are available in SI Section S1.

3. RESULTS AND DISCUSSION

3.1. Exhaust Emissions

3.1.1. CO_2 , NO_x , PM_{10} , CO and HC

Unlike previous studies (Gurjar et al., 2004; Nagpure et al., 2013) distinguished trend in emission of CO_2 , HC , PM_{10} , CO and NO_x have been observed during 1991-2011 and 2011-2020 (Fig.1). The CO_2 , NO_x and PM_{10} were 2954 Gg, 35 Gg and 6 Gg during 1991, which increased to 5239 Gg, 62 Gg and 8 Gg in 2001, respectively. In 2011, the CO_2 , NO_x and PM_{10} were 14119 Gg, 98 Gg and 5 Gg and are expected to increase 48577 Gg, 322 Gg and 10 Gg in 2020. A substantial decrease in PM_{10} and NO_x emissions also have been observed during 1999 and 2002, when Delhi

155 government has phased out the all-old age commercial vehicles (e.g. bus, taxi, three wheelers)
156 and implemented CNG for all remaining commercial vehicles. The emissions of CO and HC
157 were 178 Gg and 61 Gg in 1991, respectively, which increased to 256 Gg and 79 Gg in 2001. In
158 2011, CO and HC emission were 275 and 80 Gg and is expected to rise 485 Gg and 199 Gg in
159 2020. Like NO_x and PM₁₀, an emission reduction in CO and HC is observed between 1999 and
160 2001 because of the CNG and phasing out program in Delhi.

161 Shifts in trends of emissions accountability were also noted during 1991-2011 and 2011-2020.
162 For instance, about one-third of the total CO₂ emissions were contributed by the HCVs between
163 1991 and 1995 while the cars overtook this trend (28-42%) from 1996 to 2011. From 1991 to
164 2001, share of HCVs population were highest (22-42%) among all vehicles for the NO_x
165 emissions, whereas from 2005 to 2010 bus population became dominated category. During 1991-
166 2011, the accountability of HCVs population was highest (33-43%) for PM₁₀, followed by LCVs
167 (light commercial vehicles) population. With respect to vehicle categorical CO emission, the
168 share of two-wheeler (44-51%) is highest among all vehicles followed by passenger car until
169 2006. After 2006, this trend reversed with car being the dominating contributor with 38-45% and
170 two wheelers emitting 28-34%. This was presumably due to phasing out of high emission rate
171 technology old age two wheelers and increasing population of less emission rate new technology
172 two wheelers. For HC, contributions of two wheelers were highest (43-73%) among all vehicles,
173 followed by car population (9-19%), during 1991-2011.

174 Over the period of 2011 and 2020, an annual growth rate of ~15% is observed in CO₂. Cars (30-
175 34%) were found to be producing the highest CO₂ emissions during 2011 to 2015, which is
176 dominated by buses with 30-32% contributions from 2016 onwards. About 2.5-times of emission

growth was observed between 2011 and 2020 for NO_x emissions, with an annual growth rate of 14%. Buses emerged as the highest contributor (38-43%) for NO_x, followed by LCVs and HCVs. About 7% of annual average growth has been observed in PM₁₀ emissions from various vehicles during 2011 to 2020. Among all vehicles, contribution of HCVs (43-47%) for PM₁₀ is highest followed by LCVs and two wheelers. An increase of 76% and 149% were noted in CO and HC, respectively, in 2020 from the 2011 levels. These increase is anticipated in line with the increase in vehicle population that increased by 116% in 2020 from the 2011 levels (Fig. S2). Two wheelers are expected to play a dominant role for HC emissions from 2011 to 2017, followed by buses from 2018 onwards. For CO, the car and two-wheeler would expect to share the highest contribution in future.

3.1.2. MSATs emissions

Emissions of acetaldehyde, formaldehyde, total aldehyde, and total PAHs share the similar trend during 1991-2011 and 2011-2020 (Fig. 2). Accountability of two wheelers (48-52%), cars (29-40%) and HCVs (6-8%) were highest among all vehicles for acetaldehyde emissions during 1991-2011. Among all vehicles, the responsibility of LCV population was much higher (36-44%) for formaldehyde between 1991 and 2001. However, car (39-43%) has replaced LCVs after 2002 due to change in technology and increasing population. Between 1991 and 2000, LCVs contributed highest percentage (32-36%) for total aldehyde, followed by cars and two wheelers. However, cars dominate (32-52%) by emitting maximum share of total aldehyde in megacity Delhi during 2001-2011. It is observed that initially from 1991 to 2001, LCVs contributed (36- 42%) the most to the total PAHs among all vehicle categories, while

contribution of two wheelers dominated (37- 42%) from 2002 onwards. For both 1,3-butadiene and benzene, the cars shared the highest percentage (70-88%;60-81%) during 1991 and 2011.

About 9.3% of average annual growth rate is expected in formaldehyde emissions from 2011 to 2020. It is predicted that contribution of two wheelers and cars would be highest among all the vehicles for both the acetaldehyde and formaldehyde during 2011-2020. For total PAHs emissions, the annual average growth rate of 8% is expected between 2011 and 2020. Two wheelers are projected to dominate for total PAHs emissions from 2011 to 2020. Results show that population of LCVs would become major contributor for 1,3-butadiene in future years. It is anticipated that cars and three wheelers are likely to become the highest emitter of benzene between 2011 and 2015 and post-2015, respectively.

The vehicle sub-categorical (i.e. with technology and fuel type) analysis shows that among two wheelers (e.g. two stroke and four stroke) two-stroke two-wheelers were the largest contributor for CO₂, NO_x, 1,3-Butadiene, acetaldehyde, benzene, formaldehyde, and total PAHs before 2004 and 2007 (year varies with pollutants). However, these contributions shifted to four-strokes two wheelers after 2004 and 2007 (year varies with pollutants) because of their increasing population and retirement of old age two-stroke two-wheelers (Fig. 2). Among population of petrol, diesel and CNG driven car, the petrol driven cars dominant for most of the CO, HC, NO_x and CO₂ emissions and diesel driven cars for PM₁₀ emissions throughout the study periods and there is no significant contribution of CNG driven cars are observed. Before CNG norms, the share for petrol driven taxis were highest for CO and acetaldehyde emissions, and diesel driven taxis for HC, NO_x, CO₂, PM₁₀, benzene, 1,3-butadiene, formaldehyde, total aldehyde and total PAHs. The share of most of pollutants shifted to CNG driven taxis after 2001, except PM₁₀ and 1,3-

butadiene. The contribution of diesel driven taxis were observed to be the highest for PM_{10} and 1,3-butadiene after 2001, because of more external taxi population with high emission rate (17- to 163-times higher than CNG taxis) technology (ARAI, 2007). Before 2001, petrol driven three wheelers, show a dominating role for most of the pollutants emission among their different fuel categories (e.g. petrol, diesel and CNG), which is overtaken by CNG driven three wheelers after CNG implementation and ban on other types of three wheelers in 2001. Before implementation of CNG in Delhi, about 90% contribution for most of the pollutants were contributed by the internal diesel operated buses; the contribution of internal buses for PM_{10} and 1,3-Butadiene reduced significantly after the implementation of CNG and became only 1-3% of total emissions from all type of buses (external and internal). Similarly, a significant reduction in PM_{10} and 1,3-butadiene emissions is observed in LCVs after implementation of CNG in 2006 for all new LCVs.

3.2. Non-Exhaust Emissions

In 1991, evaporative emissions of VOCs from vehicles were 516 Mg, and 3867 Mg in 2011 (Fig. 3a). It is expected that VOC emissions will increase up to 13144 Mg in 2020. Since two wheeler and car uses gasoline as a fuel, the contributions of these categories are the highest among all other vehicles during 1991-2010. After implementation of CNG in Delhi, the CNG driven vehicles emerged as a major contributor for VOC emissions in Delhi.

About 5 Gg, emissions of PM_{10} from all total non-exhaust sources (includes road dust suspension, tyre wear and break wear) were noticed in 1991, followed by 8 Gg in 2001 and 20 Gg in 2011 Fig. 3 (b,c,d). Among all the three sources, road dust share was the highest 91-92% during the whole study period; brake and tyre wear contributed only 7% and 2% respectively.

Projection shows that these non-exhaust PM₁₀ emissions would become 60 Gg in 2020. In case of PM₁₀ emissions from road dust suspension, the share of HCVs and buses are highest (34-35%) during the entire study period (1991-2020) due to their high dust spreading capacity. With respect to tyre wear, the share of cars is highest (47-62%) throughout the study period. In case of PM₁₀ emissions from brake wear, the contribution of cars, HCVs and buses is the highest.

SI Fig. S3 shows the PM₁₀ contribution from all sources including exhaust and non-exhaust vehicular sources in Delhi. PM₁₀ emissions from all vehicular sources were 11 Gg in 1991, 16 Gg in 2001 and 26 Gg in 2011 and these are expected to increase to 70 Gg in 2020. It is interesting to note that share of PM₁₀ from exhaust emissions would reduce in future because of technology advancement. However, there are no norms available for non-exhaust source and therefore the accountability of non-exhaust emissions would be higher in near future. Until 1999, the share of exhaust emission for PM₁₀ was about 52%, which started decreasing and expected to reach up to 14% in 2020. A significant impact of technology is observed on reducing PM₁₀ from exhaust sources, but rising share of PM₁₀ from non-exhaust sources, especially from road dust suspension needs proper attentions of policy makers.

3.3. Empirical relationships between emission and concentration of pollutants

For the validation purpose, both qualitative (e.g., trend analysis of emissions and ambient air concentrations) and quantitative (e.g., computation of correlation coefficient) techniques have been used in this section. According to Gurjar et al. (2004), transport sector is responsible for about 80% of CO and NO_x emissions in Delhi. Therefore, CO and NO_x can be considered as good indicator pollutants, which can represent degree of air pollution emitted by road transport sector. We have compared emission results of CO and NO_x with their ambient air concentrations

in Delhi. Both emission and concentration of CO and NO_x follows similar trends between 1991 and 2009 (SI Fig. S4a,c). The coefficient of determination (r^2) value of NO_x emission from all vehicles and ambient air concentration of NO_x is found to be good (~0.68) (SI Fig. S4b). The r^2 value of CO emission from all vehicles and ambient air concentration is found to be very strong (0.94) (SI Fig. S4d). Thus, a very good agreement found between CO and NO_x emissions from vehicles calculated by VAPI model and their concentration in Delhi. The details of empirical relationships between CO and NO_x emissions and concentrations of pollutants are available in SI Section 3.

3.4. Impact of Technology and norms Change on vehicle emissions

To improve the quality of air, government has implemented various norms and introduced vehicle technology time to time in Indian cities. In 1991, government has implemented the idle limits for CO and HC for new gasoline vehicles. In 1992, mass emission norms for new diesel vehicles. The significant impact of 1991 norms and technology change for CO emission were noticed in the year 2001 and 2007, about 11% and 48% decline is observed in CO emissions during 2000-2001 and 2006-2007, because of phasing out of most of the pre-1991 two-wheeler population. Similarly, the impacts of 1992 norms on diesel vehicles have been noticed between 2006 and 2007, due to ~19% decrease in CO emissions from HCVs. The reason behind this decline is the phasing out of pre-1991 vintage HCVs population in 2007 (more fraction, and old technology with high EF; 19.3g/km), and introduction of more newly HCVs (new technology with lower EF; 6 g/km). In 1996, the government has revised the mass emission norms for gasoline and diesel vehicles, the effects of these norms have been observed on taxi population in 2011 and 2012 when the most of the pre 1996 taxis have phased out from the Delhi road. About 48% decline in CO emission from three-wheelers is observed between 2001 (~6 Gg) and 2002

(~3 Gg) due to a complete shift of petrol driven four-stroke and two-stroke three wheelers to four-strokes CNG driven three-wheelers. The most important and immediate impact of vehicle fuel technology change and phasing out norms is observed between 2000 and 2003 for most of the pollutants when government of Delhi have introduced phasing out and clean fuel technology for all commercial vehicles. About 1 to 43% of emission reductions of various pollutants (e.g. PM₁₀, HC, CO, NO_x) from transport sector were noticed during 2002, because of introduction of CNG and old age vehicle phased out program. The highest change is observed in PM₁₀ emissions during this time. Based on the current study results, it is concluded that technology change and emission norms introduced by government is having significant effects on emission reduction, although because of increasing population, rising vehicle population with rapid economic growth and share of other sectors on air pollutant emissions these effects are not visible. There is a need to upgrade the emission norms and clean fuel technology to curb the steady emissions growth in Delhi (Kumar et al., 2015).

3.5.Comparison of emissions with other studies

SI Table S6 presents our estimate and transport emissions for Delhi that are taken from different emission studies. Most of these inventories (TERI, 1997; Gurjar et al., 2004; Sharma et al., 2002; CRRI, 2002; Mohan et al., 2007; Mohan et al., 2012; Goyal et al. 2013) focus on particular emissions (e.g. greenhouse gases) and a specific year. There is no study available, which estimated the emissions from transport sector for diverse (e.g. GHGs, criteria and hazardous) range of pollutants for 20 years. Estimations of our studies are lying between maximum and minimum ranges given by different studies. SI Table S6 shows diverse range in emissions and associated uncertainties. The differences are in some cases rather remarkable. For example, as stated in previous studies (Gurjar et al., 2004; Mohan et al., 2012; CRRI, 2002; Singh and

Sharma, 2012) the NO_x emissions varied within the range of 17–118 Gg/year. The range of our estimates for different years is in between this range and closer to those found by Singh and Sharma (2012). The reason behind the variation is that most of the studies have not considered external and actual on-road population and country specific EFs. This study may underestimate the CO₂ and PM₁₀ emissions because we have considered all the technological and vehicle-category specific EFs, which is not used by many of these studies. Our emission range of CO and HC are lying between most of the studies. Studies accounting for the MSATs emission in Delhi from road transport are not available.

4. Conclusions

Emission analysis of vehicular exhaust and non-exhaust sources in Delhi during 1991-2020 was investigated by considering the vehicle age, and technology. A significant rise of up to 5-fold in emissions of CO₂, HC, CO, NO_x, 1,3-butadiene, acetaldehyde, benzene, formaldehyde, total aldehyde, and total PAHs is observed between 1991 and 2011. However, a decline of about –9% is noticed for exhaust PM₁₀ emissions in 2011 from 1991 levels, which clearly shows the impact of introduction of clean fuel technology in Delhi. It is expected that emissions of CO₂, HC, CO, PM₁₀, NO_x and MSATs would increase significantly (up to 3-fold) between 2011 and 2020. In terms of contributions, private vehicles (e.g. two wheelers, car) share more of the CO₂, CO, HC and MSATs, as well as commercial vehicle share more PM, NO_x during most of the study period (1991-2020). In terms of exhaust and non-exhaust emissions, it is observed that PM₁₀ emissions from non-exhaust sources have increase significantly during the recent years.

The study indicate that although the emissions norms and technology intervention in transport sector is having significant impact on reducing the pollution but increasing vehicle population

with economic growth is the major challenge for controlling the emissions from transport sector. There is a need of introduction for more stringent norms and emission control technology to protect the air quality from increasing air pollution from transport sector. It is important to note that norms and technology improvement can only be able to curb the exhaust emissions, and there is no action are currently taken by government to reduce the non-exhaust emissions such as brake wear, road wear, tire wear and road dust resuspension. As suggested by study non-exhaust sources, emissions contributing as much as or more than the tailpipe exhaust PM₁₀ in Delhi, and their burden is destined to increase in the future. Thus, rising share of PM₁₀ from non-exhaust sources, especially from road dust suspension needs proper attentions of policy makers.

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Fig. 1. Exhaust emissions of (a) CO₂, (b) CO, (c) NO_x, (d) PM₁₀, and (e) HC in Delhi during 1991-2020

Fig. 2. Exhaust emission of (a) 1,3-Butadiene (b) Acetaldehyde, (c) Benzene, (d) Formaldehyde, (e) total Aldehyde, and (f) total PAHs

Fig. 3. Non-exhaust emissions: (a) VOCs from evaporations (b) PM₁₀ from road dust suspension (c) PM₁₀ Tyre wears, and (d) PM₁₀ from the break wears.

Fig. 1

(a)

(b)

(c)

(d)

(e)

(f)

Fig. 2

Fig. 3

Supplementary Material

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