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Evolution of on-road vehicle exhaust emissions in Delhi

Rahul Goel [a], Sarath K. Guttikunda [b, c, *]

[a] Transport Research and Injury Prevention Program, Indian Institute of Technology, New Delhi, 110016, India
[b] Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, 89512, USA
[c] Center for Climate Studies, Indian Institute of Technology, Mumbai, 400076, India

HIGHLIGHTS

- A 40-year retrospective and prospective analysis (1990–2030) of on-road emissions.
- On-road emissions for the largest urban agglomeration of India–Delhi.
- An update on vehicle and passenger travel characteristics based on primary surveys.
- Multi-pollutant emissions analysis and possible policy interventions for control.

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ABSTRACT

For a 40-year horizon (1990–2030), on-road vehicle exhaust emissions were evaluated, retrospectively and prospectively, for the largest urban agglomeration in India – the Greater Delhi region with a combined population of 22 million in 2011 (Delhi along with Ghaziabad, Noida, Greater Noida, Faridabad and Gurgaon). Emissions of particulate matter, sulfur dioxide, carbon monoxide and volatile organic compounds (VOCs) reached their peak during late 1990s through early 2000s after which they reduced significantly through year 2012. On the other hand, nitrogen oxides (NO_x) and carbon dioxide show an increasing trend. The most reduction in emissions between 1998 and 2012 occurred as a result of implementation of four sets of vehicular emission standards, removal of lead, reduction of sulfur content, mandatory retirement of older commercial vehicles, and conversion of diesel and petrol run public transport vehicles to compressed natural gas. In addition, changes in the vehicular technology have also contributed to controlling emissions especially in case of auto-rickshaws and motorized two-wheelers, which changed from two-stroke to four-stroke. The rising trend of NO_x along with the presence of VOCs indicates increasing tendency to form ground-level ozone and as a result, smog in the region. We predict that the current regime of vehicle technology, fuel standards, and high growth rate of private vehicles, is likely to nullify all the past emission reductions by the end of 2020s.

1. Introduction

The Greater Delhi region is home to a metro rail system covering 190 km, the largest bus fleet operating on compressed natural gas (CNG), one of the largest manufacturing clusters, a booming construction industry, and approximately 22 million people. In this urban environment, transport sector plays a pivotal role, moving passengers and freight, and consequently the vehicle exhaust emissions on the air quality. Between 1991 and 2011, the population of Delhi and its adjoining cities, more than doubled from approximately 10 million to 22 million and during the same period, the number of registered cars and motorized two wheelers (2Ws) increased from 1.6 million in 1990–91 to 7.0 million in 2011–12 (SoE-Delhi, 2012). Using an average area covered by a 2W and a car, this translates to an area of 1.0 km^2 in 1990–91 and 17.5 km^2 in 2012–13, used primarily for parking.

Growing vehicle exhaust emissions also lead to elevated ambient concentrations and exposure rates for travelers. In Delhi, the on-road exposure to $PM_{2.5}$ (particulate matter less than 2.5 μm in diameter) concentrations is at least 50 % more than the measured ambient concentrations (Apte et al., 2011). This has hazardous health effects for those traveling on road and for those living in close proximity to roadways (Kim et al., 2004; Tsai et al., 2008). The

* Corresponding author. Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, 89512 USA.
E-mail address: sarath.guttikunda@dri.edu (S.K. Guttikunda).

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ambient PM_{10} (particulate matter less than 10 μm in diameter) concentrations have at least doubled between 2001 and 2010 (120 μg/m^3 and 267 μg/m^3, respectively), leading to an estimated 16,000 premature deaths from air pollution in 2010, and vehicle exhaust emissions are a significant share of these observations (CPCB, 2010; Guttikunda, 2012; Guttikunda and Goel, 2013).

Among the Indian cities, Delhi has been the subject of most number of published emissions inventory, air pollution, and exposure based studies. Most studies have been cross-sectional (CPCB, 2010; Sahu et al., 2011; Guttikunda and Calori, 2013), and fewer looked at trend analysis ranging from 5 to 15 years (Sharma et al., 2002; Gurjar et al., 2004; Mohan et al., 2007; Nagpure et al., 2013). While all the studies employed same or similar emission estimation methodologies, they differed in their data inputs and geographical coverage. In this paper, we present a 40-year (1990–2030) retrospective and prospective analysis of the on-road vehicle exhaust emissions in Delhi; using data collected from primary surveys to establish the age mix, fuel economy, and vehicle usage, and updated dynamic emission factors for the fleet (Goel et al., 2015).

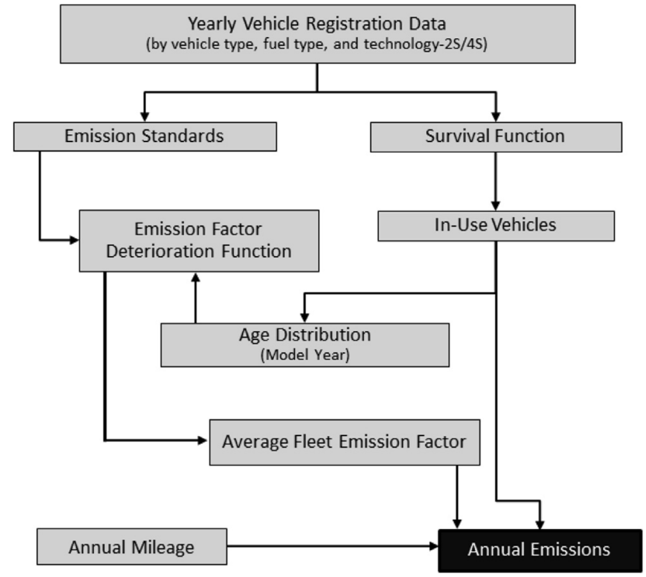

Fig. 2. Methodology for estimation of annual road-transport emissions.

2. Methods and data

The study domain is designated as the Greater Delhi region, covering the area of Delhi and the satellite cities of Ghaziabad, Noida, Greater Noida, Faridabad and Gurgaon, all within the geographical area of 80 km × 80 km (Fig. 1). The vehicle types include 4Ws (passenger cars, jeeps, and vans), 2Ws (motorcycles,

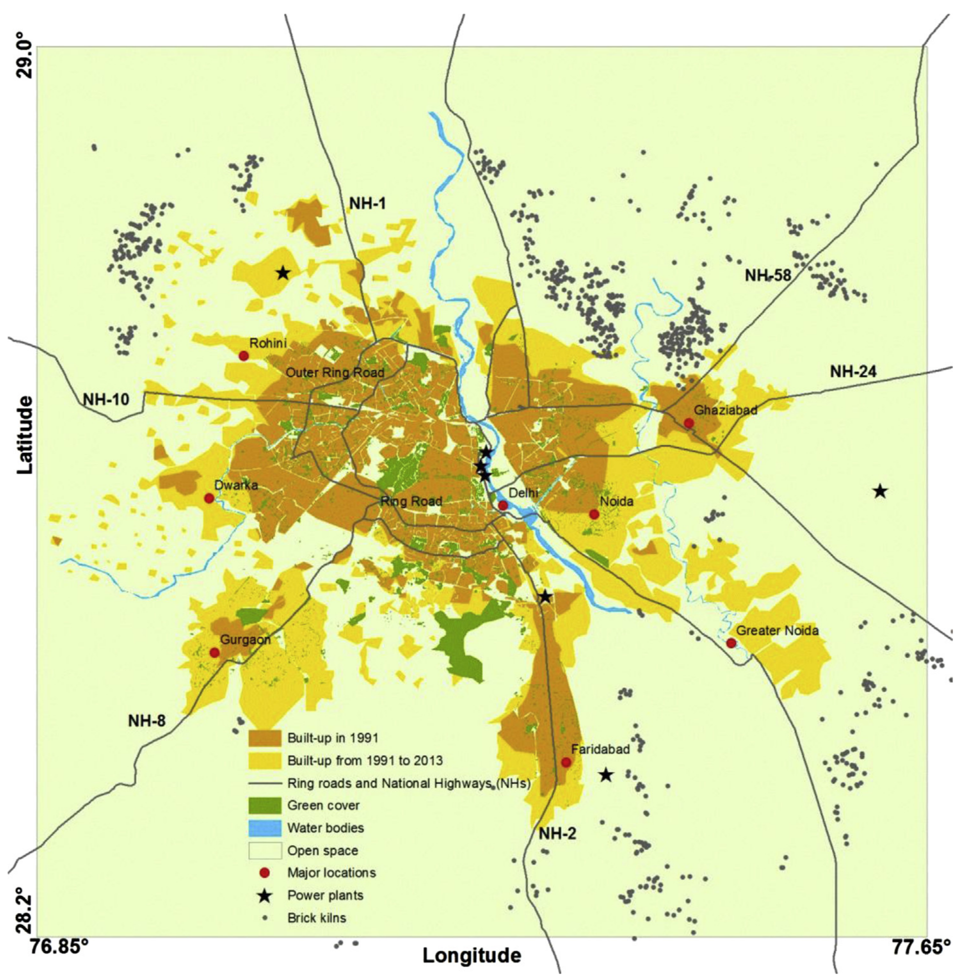

Fig. 1. Study domain over Delhi, along with location of main highways, satellite cities, brick kiln clusters, and power plants.

scooters, and mopeds), 3Ws (three-wheeled scooter rickshaws with 3 to 7seats), buses (intra- and inter-city operations), HDVs (heavy duty trucks), LDVs (light duty trucks), and others (off-road tractors and trailers).

The primary surveys and data analysis were conducted to benchmark the vehicle and passenger travel characteristics in Delhi. During the survey at the fuel stations, we asked the vehicle owner/driver the following five questions – (1) type of fuel (2) registration number (3) year of manufacture and model (4) fuel efficiency (km/liter) – reported by the owner/driver based on their experience and (5) odometer reading at the time of survey. The data analysis included analysis of "pollution under check" database, which records the vehicle characteristics, age, and emission tests. In the paper, these are referred as "fuel station survey data" and "PUC data". The details of the survey methodology, results, and discussions are presented in Goel et al. (2015).

2.1. Emissions estimation

The methodology used to estimate the annual road transport emissions is shown in Fig. 2, based on the methodologies documented in earlier studies (Schipper et al., 2000; Gurjar et al., 2004; Mohan et al., 2007; CPCB, 2010; Sahu et al., 2011; Yan et al., 2011; Guttikunda and Calori, 2013). In this study, the PM, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) emissions are estimated using

$$E_{v,f,g,p} = NV_{v,g} \times S_f \times VKT_{v,g} \times EF_{v,f,g,p} \quad (1)$$

The sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions are estimated using

$$E_{v,f,g,p} = NV_{v,g} \times S_f \times VKT_{v,g} \times FE_{v,f,g} \times PC_{f,p} \quad (2)$$

where, v = vehicle; f = fuel; g = age group; p = pollutant; E = the total emissions (tons/year) calculated by pollutant (p), vehicle type (v), fuel type (f), and by age (g); NV = the number of vehicles on-road by vehicle types (v) and by age (g); S = the share (%) of vehicles on-road for each vehicle type (v); VKT = the annual average vehicle kilometers traveled by vehicle type (v) and by age (g); EF = the fleet average emission factor (gm/km) by vehicle type (v), fuel type (f), age group (g), and by pollutant (p); FE = the fuel economy (km/lit) by vehicle type (v), fuel type (f), and age group (g); and PC = the carbon content (kg/lit of fuel) and sulfur content (ppm) of the fuel

2.2. Vehicle fleet

A summary of the in-use vehicle fleet from 1990 to 2030 is presented in Fig. 3a. The vehicle registration numbers were obtained from the Government of Delhi report (DES, 2008, 2012) and the vehicle sales numbers from the Society of Indian Automobile Manufacturers (New Delhi, India). Except for small anomalies in case of the buses and the 3Ws, the fleet has been growing continuously in size and is predicted to grow even further in the coming decades. A dip in the bus numbers between 1999 and 2002 was due to the retirement of diesel buses and introduction of CNG buses and a bump in the 3W numbers, in is due to doubling of the mandated cap on number of allowed registrations from 55,000 in 1997 to 100,000 in 2013. In September 2012, the total registered fleet in Delhi was 7.5 million and in June, 2014, the total registered fleet was 8.4 million. During 1991–2000, on an average, 50,000 cars and 100,000 2Ws were registered every year which almost doubled in the following decade (2001–2010) to 110,000 and 180,000 per year, respectively, and has increased even further to 150,000 and 300,000 per year, respectively for 2011–2013 (DES, 2012, 2013).

In case of HDVs, in addition to the registered fleet in the city, more than 50,000 trucks per day move through the city, which likely do not have Delhi as their destination. This was estimated using receipts data from 86 entry points along Delhi's border (DoUD-Delhi, 2006; EPCA, 2004). Of all the freight traffic terminating to or originating from Delhi, 86% is carried on road, 13% by rail and rest by airways (RITES, 2013). This is in part due to the extensive road connectivity, with many national highways (NHs) intersecting through the region - west by NH-10, east by NH-24, north by NH-1, north-east by NH-58, south and east by NH-2 and south-west by NH-8. These highways connect in radial directions to two ring roads (known as the inner ring road and the outer ring road). As a result of fast and convenient road-based connectivity, Delhi becomes a natural choice for bypassing truck traffic. Within the Greater Delhi region, the light duty commercial vehicles are used to cater goods during the daytime, which are registered in the region.

Delhi's public transportation system is the most discussed in India, due to its complete conversion to operate on compressed natural gas (CNG), following a Supreme Court judgment (Kathuria, 2002). The fleet has a formal (government operated) public transportation system (rail and road) in addition to demand responsive and informal para-transit modes. In the satellite cities, formal systems are largely absent, which is common for most small cities in India (Guttikunda et al., 2014). Post 1999–2001, all the road-based public transportation (buses, 3Ws, and taxis) in the Greater Delhi region runs on CNG, except for buses which carry out intercity operations.

According to Census 2011, in Delhi, there are 21% of households with at least one car and 39% households with at least one 2W. In Ghaziabad, Noida, Faridabad, and Gurgaon, combined, 23% of households own at least one car and 41% at least one 2W, which is similar to that in Delhi. Therefore, it is reasonable to assume that the number of vehicles are proportional to the population in each of

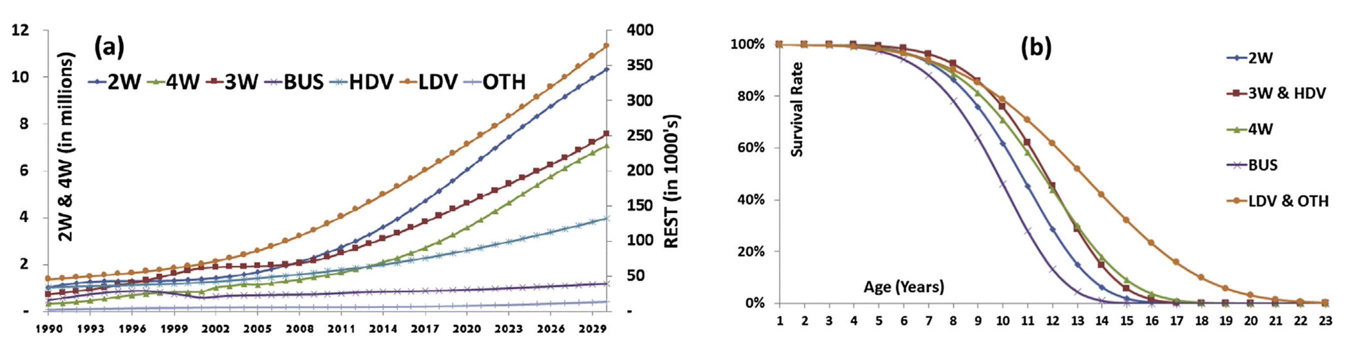

Fig. 3. (a) Estimated in-use vehicle fleet in Delhi (b) Survival functions to calculate in-use vehicle fleet in Delhi.

the cities. We utilized this information to complete the calculations for active fleet in the Greater Delhi region.

2.3. Vehicle age mix

In order to model the fleet retirements, the number of in-use vehicles, and their age distribution, we used survival function on top of the annual vehicle registration data. While the analysis refers to years 1990 through 2030, we used year-wise vehicle sales and registration data from 1960 to estimate the number of in-use vehicles and the age mix every year, instead of applying a constant retirement percentage to the fleet. A summary of the in-use vehicle age-mix between 1990 and 2030 is presented in Fig. 4. For 2012, the average age of the in-use vehicle mix is 5.4 years for 4Ws, 4.9 years for 2Ws, 5.6 years for taxi's, 4.0 years for 3Ws, 5.5 years for buses, 6.2 years for HDVs, and 6.0 years for LDVs. The intra-city bus fleet in Delhi was doubled in 2009, before the beginning of the 2010 Commonwealth Games and similarly for 3Ws in 2011; which improved their average age.

A summary of the survival functions is presented in Fig. 3b and the data is presented in the Supplementary Material. There is a mandated retirement age of 15 years for the Taxis and 3Ws, but nothing is specified for the other modes, except that the vehicles have to obtain a "pollution under check" certificate every 6 months. The vehicle survival functions were established for Delhi's fleet and calibrated to obtain age distribution of cars and 2Ws, for year 2012, using the PUC and fuel station survey databases. Similar functions were used by Baidya and Borken-Kleefeld (2009) and Yan et al. (2011) for national level fleet average assessments and Goel et al. (2015) corrected these functions for the trends observed in the in-use fleet for the city.

Table 1
Fuel efficiency of vehicles based on the fuel station surveys in Delhi.

Type of vehicle	Lower range (km/litre)	Sample size	Upper range (km/litre)	Sample size
Diesel Cars (all engine sizes)	14.0 ± 0.3	528	15.3 ± 0.5	235
Diesel Cars (<=1600 cc)	16.1 ± 0.3	322	17.4 ± 0.5	145
Diesel Cars (>1600 cc)	10.8 ± 0.3	206	11.9 ± 0.5	90
Petrol Cars	15.3 ± 0.1	1672	16.2 ± 0.2	664
2Ws	48.5 ± 0.5	1565	52.3 ± 0.8	704

Age distribution of cars and 2Ws in Delhi shows that nearly 60% of the vehicles are <5 years old and almost all the vehicles are within 15 years of age. The age distribution of vehicular fleet is in complete contrast with those observed in Europe or the United States. For instance, average age of cars in Europe is 8.2 years for year 2008 (ACEA, 2010) and in the United States is 11.1 years for year 2011 (Polk, 2012). According to 2008 data, 35% and 37% of the cars in Europe and the United States were more than 10 years old. Combined with the highest per capita income and one of the highest car ownerships in the country, propensity for early replacement of vehicles is also likely to be the highest in Delhi. Hence, the observed travel and owner behavior in Delhi would therefore be different. Given the observed trends, the survival

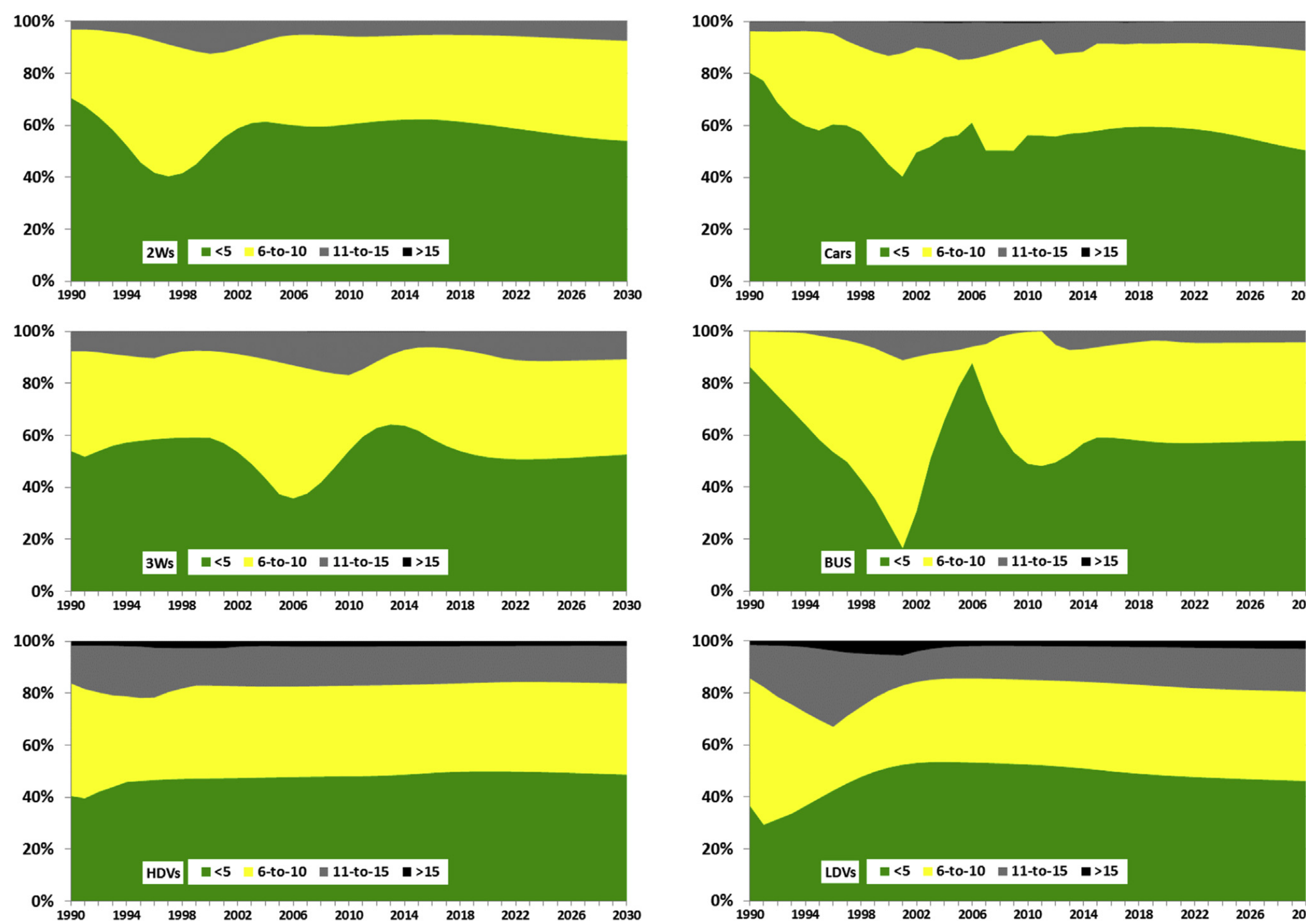

Fig. 4. Age-mix of the In-use vehicle fleet in Delhi.

functions in Fig. 3b are applicable only for Delhi and do not represent other Indian cities or India as a whole. There is a need for similar exercises in other cities, to ensure consistency among the distribution parameters.

2.4. Fuel efficiency

The fuel efficiency values for the past and the future fleet, were estimated using fuel efficiency standards of new vehicles introduced every year, overlaid with deterioration rates to reflect the reduction in fuel efficiency by age. The fuel efficiency of in-use fleet for year 2012 is summarized in Table 1, which is based on in-city primary surveys and secondary sources (Goel et al., 2015). The upper and lower bounds correspond to the maximum and minimum values reported by vehicle owners and drivers, which was one of the questions during the surveys. It was assumed that the owners and drivers keep track of their fuel usage for various reasons; and they were willing to report, sometimes, a number they estimates and sometimes a range based on their operations, such as, with and without running air conditioner. In Table 2 and Table 3, we summarized the fuel efficiency values of 2Ws and cars, used by previous studies for emission and energy estimates in India. The numbers in Table 1 clearly indicates a substantial improvement over time, which occurred in the absence of any fuel efficiency standards and can largely be attributed to improvement in vehicle technology and prevalence of small cars. In India, 70% of the cars were in the small size segment compared to ~25% for global fleet (IEA, 2011) and ~60% of cars are with engine displacement < 1200 cm^3 and average weight less than a ton, which leads to a better fleet average fuel economy than their counterparts in other countries (Goel et al., 2015).

While the four largest automobile markets – the United States, the European Union, China and Japan, adopted more stringent fuel efficiency standards to promote fuel-efficient vehicles (ICET, 2011), India has only started the process recently (PIB, 2009). The government of India has notified fuel efficiency standards for passenger cars, vans and utility vehicles to be implemented from 2016 (DieselNet, 2014). The technology and standards improvement is expected to improve the overall fuel efficiency of the fleet in the coming years, with increments varying from 20 to 30 % for cars and 2Ws and 10–25 % for other vehicle types. The fuel efficiency standards corresponding to each model year is presented in the Supplementary Material.

2.5. Vehicle mileage

The fuel stations survey data and the secondary data resources described in Goel et al. (2015), were utilized to estimate the annual mileage driven by different vehicle types for year 2012. For cars and 2Ws, we estimated an annual mileage of 12,500 km. For city buses and 3Ws, we estimated an annual mileage of 72,000 km and 55,000 km, respectively. In case of buses, the mileage of intra-city buses and that of inter-city buses were differentiated. While the former has an average daily mileage of 190 km, the latter category of buses travel much lesser distance within the city, as their journey in the city includes only the distance from the border of the domain to bus terminals. For these, an average daily mileage of 40 km (annual mileage of 14,600 km) is assumed, considering the distance between the regional border and major inter-state bus stations. The annual mileage values for LDVs and HDVs are also distinguished. This is because, LDVs are used more often for transporting goods within the city limits and HDVs are used largely for inter-city, long-distance operations. For instance, HDVs bring freight to wholesale markets, and thereafter, circulation of goods is carried out by LDVs. We considered an average annual mileage of 40,000 km for LDVs and inter-city buses and assumed a daily mileage of 40 km for HDVs. Note that 40 km in case of inter-city buses and long-distance trucks refer to the distance which the said vehicle types travel within the study domain. Their total mileage values are much higher due to their inter-city operations.

In 1990, Delhi's population as well as built-up area were almost half of those in 2011 (Mehta, 2011), therefore, one could hypothesize that annual mileage for that period was less than that in 2012. Goel et al. (2015), estimated an annual mileage of 12,000–13,000 km for cars and 2Ws in Delhi. The survey data

Table 2
Fuel efficiency values reported for 2Ws.

Fuel efficiency (km/liters)	Vehicle type	Year	Study
44.1	All 2Ws	1985	Bose and Srinivasachary (1997)
40	All 2Ws	1990	de la Rue du Can et al. (2009)
38.8–42.1	50 cm^3 engine size	1995	Chan et al. (1995)
35	All 2Ws	1997	Mohan et al. (1996)
38.5	2S	2000	Bose and Nesamani (2000)
53.7	4S	2000	Bose and Nesamani (2000)
44.4	All 2Ws	–	Padam and Singh (2001)
67.5	All 2Ws	2005	de la Rue du Can et al. (2009)
48.5–52.5	All 2Ws	2013	This study

Table 3
Fuel efficiency values reported for the 4Ws.

Fuel efficiency (km/liters)	Vehicle type	Year	Study
6.5–11	All cars	1983	Gandhi et al. (1983)
8.9	All cars	1990	de la Rue du Can et al. (2009)
11	All cars	1980s	Bose and Srinivasachary (1997)
9.4	Petrol	Pre-1984	Bose (1999)
14.2	Petrol	Post-1984	Bose (1999)
8.9	Diesel		Bose (1999)
8	All cars	1997	Mohan et al. (1996)
10.9	All cars		Padam and Singh (2001)
13.6	Petrol	2000	Bose and Nesamani (2000)
20	Diesel	2000	Bose and Nesamani (2000)
12.8	Petrol	2005	de la Rue du Can et al. (2009).
14	Diesel	2005	de la Rue du Can et al. (2009)
12.1	Petrol-hatchback	2002–2006	Chugh et al. (2011)
9.6	Petrol-sedan	2002–2006	Chugh et al. (2011)
13	Diesel-hatchback	2002–2006	Chugh et al. (2011)
12.3	Diesel-sedan	2002–2006	Chugh et al. (2011)
15.3–16.2	Petrol	2013	This study
14–15.3	Diesel	2013	This study

Table 4
Fleet average annual vehicle kilometers traveled for years 1990, 2000, and 2012.

Vehicle type	1990	2000	2012
4W	8500	10,000	11,000
2W	8500	10,700	12,000
3W	38,000	46,500	54,700
BUS	30,400	37,200	43,800
HDV	12,900	17,100	21,900
LDV	14,500	21,000	29,700

questionnaire recorded the odometer readings, which also helped understand the vehicle usage trends by age. Using these relationships, the range of annual mileage for pre-2012 was adjusted and the results for 1990, 2000, and 2012 by vehicle type are summarized in Table 4. For estimating mileage numbers retrospectively, we assumed an increment rate to estimate future mileage. The fleet average annual VKT by year are summarized in the Supplementary Material.

The VKT is different from the modal shares in the city, which represents the true form of passenger movement in the city, plus the movement of the freight vehicles. Personal transportation in Delhi is dominated by 4Ws and 2Ws. With increasing access to private vehicles, the modal shares have changed considerably between 1994 and 2007 (Fig. 5) – travel surveys show a 100% increase in modal share of cars and 66% reduction for buses (Tiwari, 2003; RITES, 2008). Most importantly, the share of non-motorized transport (NMT – walking and cycling) also increased in the city; which is often underestimated and underrepresented during the energy and emissions calculations.

2.6. Emission factors

As part of the particulate pollution source apportionment study, the Ministry of Environment and Forests conducted a limited number vehicle exhaust emission factor tests on a chassis dynamometer and utilized the same for establishing an emissions inventory for 2006 for Pune, Chennai, Mumbai, Delhi, Kanpur, and Bengaluru (CPCB, 2010). With this as base measurements for comparison and using the methodology developed in COPERT III (Ntziachristos et al., 2009), the fleet average emission factors for different vehicle types by year (1990–2030) were established for this study; utilizing the emission standards applicable for newer fleet by year, corrections applicable for engine deterioration based on fleet age-mix, and changing idling conditions on the roads. These corrections were necessary to reflect the changes in vehicle technology, driving, and on-road conditions.

A summary of the fleet average emission factors for 2012 are summarized in Table 5. A summary of the fleet average emission factors for 1990, 2010, 2020, and 2030 is presented in the Supplementary Material. The variation in the emission factors represents the standard deviation among the factors by vehicle model year. For example, for $PM_{2.5}$ emissions 0.071 gm/km represents the fleet average emission rate for 2W2S, and 0.031 represents the deviation of rates for vehicles introduced in 2012, 2011, 2010, and so on; after applying the corresponding deterioration rates for the model years.

For HDVs, we assumed emission standards at the national level, which is one standard behind that of Delhi and its satellite cities. This is because of dual fuel standards in India (Guttikunda and Mohan, 2014). For instance, while Delhi (and 16 other major cities) had access to Bharat Stage (BS)-II fuel starting from 2000 to 01, BS-III from 2005, BS-IV from 2010, rest of the country had access to BS-I, BS-II and BS-III, respectively. Therefore, currently, long distance trucks continue to use BS-III diesel, with a sulfur content of 350 ppm compared to 50 ppm in BS-IV, given the formers universal availability in India. Also the trucks with BS-IV engines registered in Delhi end up filling tanks with BS-III diesel, thus negating any benefits of new standards. Since a large fraction of freight traffic moving in Delhi is registered outside Delhi and carries out country-wide operations, the emission norms followed by such vehicles are not in compliance to those implemented in Delhi.

Table 5
Fleet average emission factors (±standard deviation) for year 2012 in the Greater Delhi region.

Mode	$PM_{2.5}$ (gm/km)	NO_x (gm/km)	CO (gm/km)	VOC (gm/km)	FE (km/lit)
Petrol					
4W1	0.050 ± 0.228	0.243 ± 1.308	3.595 ± 15.37	0.469 ± 2.898	15.3 ± 3.2
4W2	0.101 ± 0.257	0.376 ± 0.401	8.552 ± 28.33	0.867 ± 4.171	14.9 ± 3.3
2W2S	0.071 ± 0.310	0.086 ± 0.023	2.027 ± 4.678	2.049 ± 3.739	50.8 ± 8.0
2W4S	0.025 ± 0.051	0.392 ± 0.190	2.861 ± 1.883	0.455 ± 0.789	57.0 ± 10.
3W2S	0.108 ± 0.130	0.329 ± 0.407	2.958 ± 8.213	5.137 ± 11.93	19.0 ± 4.0
3W4S	0.024 ± 0.174	0.692 ± 0.969	2.916 ± 8.236	1.858 ± 4.329	21.8 ± 4.7
TAXI	0.103 ± 0.294	0.241 ± 0.144	8.467 ± 31.59	0.800 ± 4.642	12.3 ± 2.8
LDV	0.261 ± 0.589	1.451 ± 0.675	22.22 ± 63.18	2.456 ± 9.284	5.56 ± 1.0
Diesel					
4W1	0.162 ± 1.186	0.657 ± 0.567	2.244 ± 19.34	0.547 ± 4.610	17.6 ± 3.7
4W2	0.333 ± 1.365	1.162 ± 0.628	5.530 ± 36.23	1.026 ± 6.161	14.9 ± 2.7
3W2S	0.412 ± 0.777	1.453 ± 2.368	3.112 ± 8.217	0.954 ± 20.30	21.8 ± 4.7
3W4S	0.412 ± 0.777	1.743 ± 2.842	3.112 ± 8.217	0.952 ± 6.859	25.1 ± 5.4
TAXI	0.328 ± 1.558	1.209 ± 0.722	5.234 ± 40.30	0.981 ± 6.859	14.1 ± 3.2
BUS	2.672 ± 7.586	21.38 ± 37.59	11.92 ± 49.01	3.311 ± 17.20	3.08 ± 0.6
HDV	3.975 ± 7.586	28.31 ± 37.59	17.39 ± 49.01	4.428 ± 17.20	2.95 ± 0.6
LDV	2.228 ± 3.793	16.30 ± 18.31	10.33 ± 19.36	2.385 ± 7.594	5.56 ± 1.0
OTH	4.457 ± 7.586	30.80 ± 37.59	19.76 ± 49.01	4.928 ± 17.20	2.90 ± 0.6
Gas					
4W1	0.016 ± 0.118	0.198 ± 1.329	3.595 ± 15.37	0.469 ± 2.898	15.3 ± 3.2
4W2	0.033 ± 0.136	1.162 ± 0.628	8.552 ± 28.33	0.867 ± 4.171	14.9 ± 3.3
3W2S	0.041 ± 0.077	2.906 ± 4.737	2.958 ± 8.213	5.137 ± 11.93	19.0 ± 4.0
3W4S	0.041 ± 0.077	4.359 ± 7.106	2.916 ± 8.236	1.858 ± 4.329	21.8 ± 4.7
TAXI	0.032 ± 0.155	1.209 ± 0.722	8.467 ± 31.59	0.800 ± 4.642	12.3 ± 2.8
BUS	0.184 ± 0.502	25.66 ± 45.11	11.92 ± 49.01	3.311 ± 17.20	3.08 ± 0.6
LDV	0.243 ± 0.376	24.45 ± 27.47	10.33 ± 19.36	2.385 ± 7.594	5.56 ± 1.0

4W1 include all cars; 4W2 include jeeps, vans, and sports utility vehicles; 3W include all 3-wheeler para-transit vehicles; HDV includes heavy duty commercial trucks; LDV includes all light duty commercial vehicles; OTH includes tractors and trailers; 2S = 2-stroke engines; 4S = 4-stroke engines; The standard deviation represents the variation among the factors by vehicle model year.

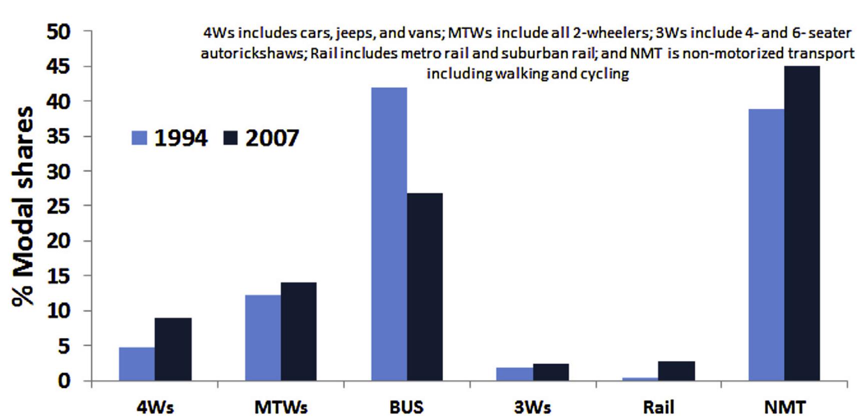

Fig. 5. Road transport modal shares in Delhi.

Table 6
Speed distribution of on-road vehicles in Delhi and its satellite cities.

Speed bins (km/h)	Percent time spent in each speed bin			
	Buses	3Ws	Cars	2Ws
0–4	37	18	24	21
5–15	22	15	16	14
16–30	23	30	25	23
>30	18	37	35	42

2.6.1. Correction for deterioration

The variation in the emission factors and fuel efficiency is due to the deterioration of engine performance and emission control equipment, which was determined from the emission tests conducted under the PUC program. An analysis of the PUC data archives showed that the trends in the CO measurements during the tests between the newer and the older vehicles, provides an overview of the emission factor deterioration rates. The data details and the deterioration functions are explained in Goel et al. (2015).

2.6.2. Correction for idling emissions

Grieshop et al. (2012) showed that the Indian driving cycle is not adequate to capture the new driving trends in a growing mega-city like Delhi. The on-road vehicle speeds play a vital role in estimating the total emissions, for which we collected the vehicle speed information (Table 6) using global positioning system (GPS) units, for buses, 4Ws, 2Ws and 3Ws, in order to estimate average speed and idling proportions of total travel time (Goel et al., 2015). For Delhi, 24%, 18%, 21%, and 37% of the driving time was measured as idling (time spent under 4 km/h) for 4Ws, 3Ws, 2Ws, and buses, respectively. In case of buses, the idling time includes the time spent at the bus stops. For each vehicle type, fuel used during idling was calculated using average daily time of idling and amount of fuel used per unit time of idling.

2.7. Fuel and technology share

Delhi has a dynamic vehicular fleet. In order to incorporate the changing share of fuels and technology types over the years, we used fuel classification for 4Ws (using petrol, diesel and CNG), 3Ws (petrol and CNG), buses (diesel and CNG) and LDVs (diesel and CNG) and in-case of 3Ws and 2Ws, a classification by engine technology (2-stroke (2S) and 4-stroke (4S)) was also used. In this study, due to limited information, the emissions model does not explicitly account for differences in the age of vehicles, which arise as a result of difference in the uptake of fuel or technology type. For instance, due to more recent uptake of 4S technology of 2Ws, 4S vehicles are younger than their 2S counterparts.

Delhi's car fleet has been experiencing rapid changes in its fuel shares of petrol, diesel and CNG. According to the 'Pollution under Control' (PUC) program database, in 2009, both diesel as well as CNG cars had a share of 14% each and by 2013, this increased to 30% for CNG and only 17% for diesel. We used trend of fuel share from 2009 through 2013 and assumed that there were almost no CNG cars before 1998. We interpolated fuel share of CNG cars before 2009 and added the reduced share from CNG to petrol cars. Pre-1998, we used linear extrapolation of share of petrol and diesel cars.

For 2Ws, we used sales proportions of scooters, mopeds and motorcycles given in Iyer (2012) from 1994 through 2010, and proportions of 2S and 4S from Muralikrishna (2007) from 1997 through 2005. The 2S to 4S shift was a rare instance when emission regulations proved beneficial for manufacturers (conforming to standards), as well as its users (increasing fuel efficiency). As a result, sales of 2S-2Ws dropped from 80% in late 1990s to 6% by year 2004, and mostly restricted to 50–60 cm^3 engine size (Muralikrishna, 2007; Iyer, 2012). According to the PUC database, 95% of in-use 2Ws in 2012 are 4S-based.

For 3Ws, we used uptake of fleet classified by 2S and 4S (petrol, diesel, and CNG), using published information (Gumber, 2004; IGL, 2005; Purwaha, 2006; TERI, 2006). The chronology of number of buses converted to CNG is estimated from Ravindra et al. (2006). The number of inter-city buses in the city is obtained from (DoUD-Delhi, 2006). The estimated shares of three fuel types and technology types are shown in Supplementary Material.

3. Results

3.1. Total emissions

The estimated total on-road vehicle emissions in the Greater Delhi region are presented in Fig. 6 for the period of 1990–2030. The temporal trends reflect a series of interventions introduced between 1990 and 2013 (Fig. 7). These interventions ranged from improvement of fuel and emission standards to judiciary mandates such as conversion of bus and 3Ws fleet to operate on CNG. Table 8 summarizes contribution of different vehicle types to total vehicular fleet and emissions of different pollutants, for year 2012. A summary of year-by-year emissions inventory from 1990 to 2030 is presented in the Supplementary Material, which includes (for each year), share of the vehicles and total emissions by vehicle type and fuel type.

3.1.1. $PM_{2.5}$ emissions

The total particulate emissions peaked during the late-1990s and reduced thereafter, in spite of a steady increase in the total number of the registered vehicles. Total annual $PM_{2.5}$ emissions increased from 17,100 tons in 1991 to a peak of 25,300 tons in 1999 and reduced to 12,700 tons in 2012. From 1999 to 2012, up to 90% of the reduction in PM emissions was contributed by buses, 4Ws, and 2Ws, with their respective shares of 52%, 24%, and 15%. Over the same period, $PM_{2.5}$ emissions from 4Ws to 2Ws also reduced by a factor of two, even though the number of in-use cars and 2Ws have increased by more than two times-from 0.8 million and 1.3 million, respectively to 1.8 million and 3.0 million, respectively. While the reduction in emissions from 4Ws to 2Ws occurred more gradually, a large part of the reduction from buses occurred over a shorter

Table 7
Share of emissions by passenger (2Ws, 3Ws, 4Ws and buses) and freight modes (LDVs and HDVs) for year 2012.

	2W	4W	3W	BUS	HDV	LDV	Total	Passenger modes	Freight modes	Total
Vehicles	59%	35%	2%	1%	1%	3%	100%	96%	4%	100%
PM2.5	8%	19%	1%	5%	38%	29%	100%	33%	67%	100%
SO_2	15%	23%	0%	1%	56%	6%	100%	39%	61%	100%
NO_x	7%	6%	9%	16%	19%	43%	100%	38%	62%	100%
CO	35%	33%	6%	5%	8%	13%	100%	79%	21%	100%
VOC	33%	19%	23%	5%	7%	12%	100%	80%	20%	100%
CO_2	17%	37%	7%	10%	11%	18%	100%	71%	29%	100%

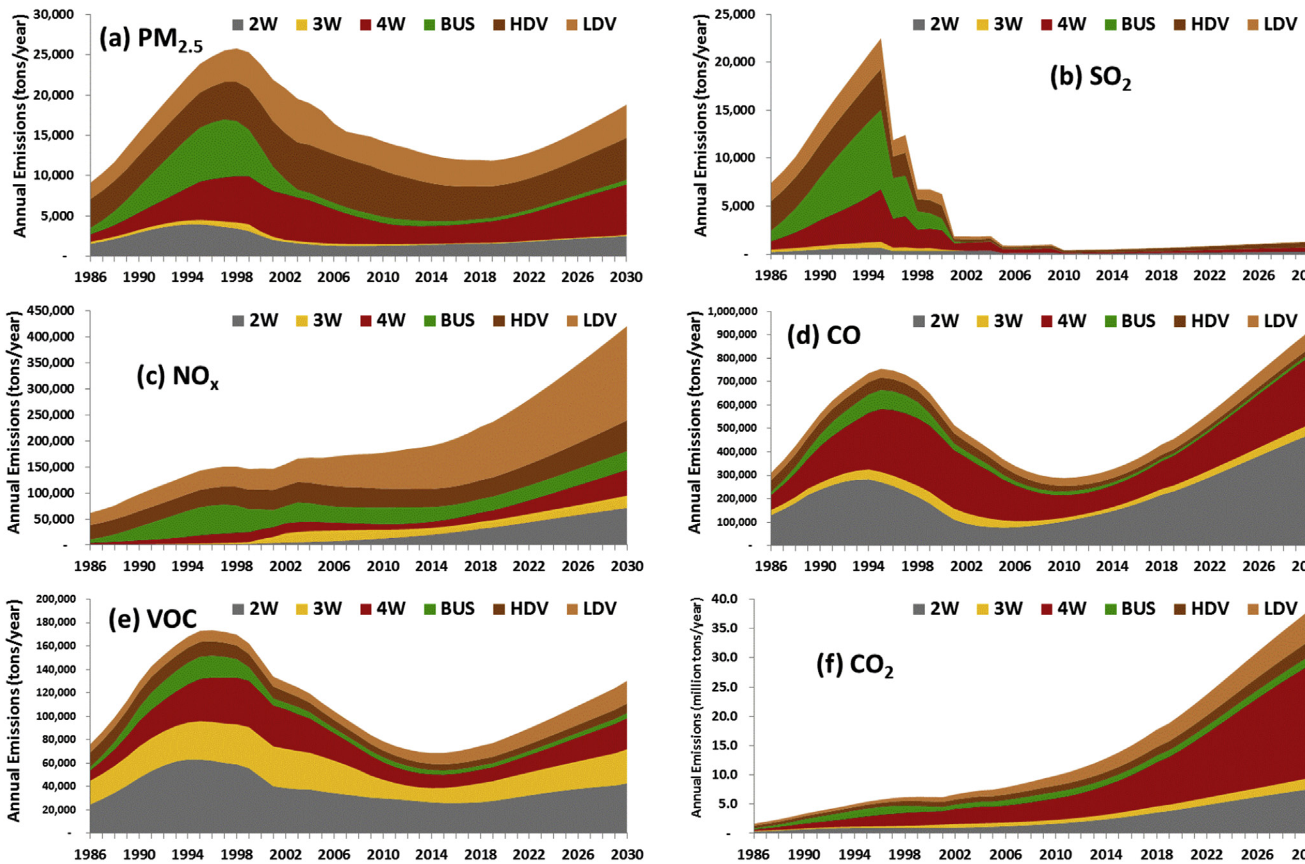

Fig. 6. Estimated annual on-road vehicle exhaust emissions in the Greater Delhi region between 1986 and 2030 (a) $PM_{2.5}$ (b) SO_2 (c) NO_x (d) CO (e) HC and (f) CO_2.

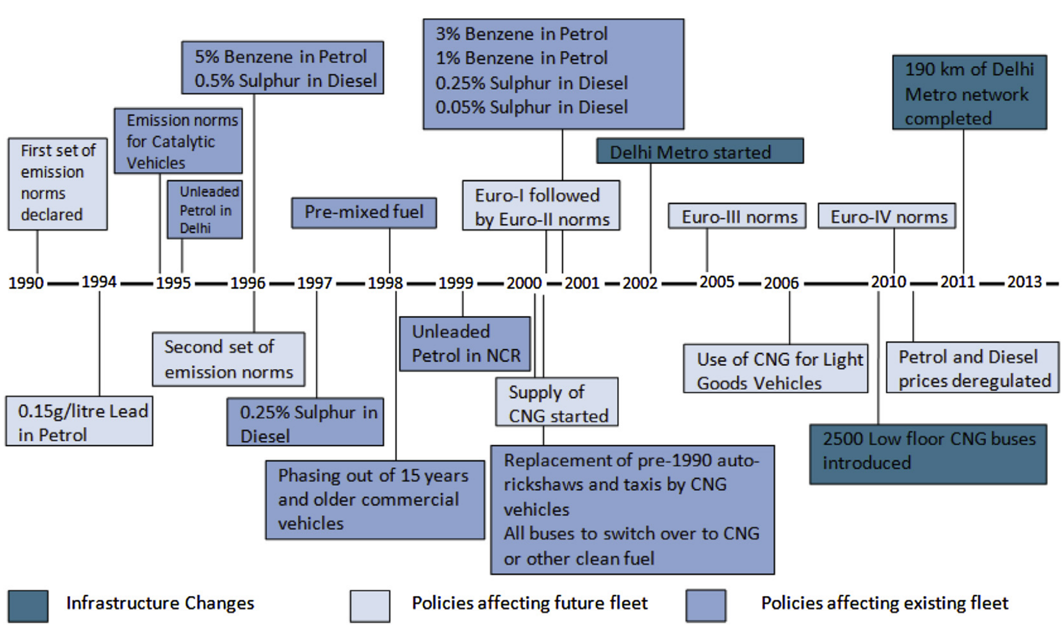

Fig. 7. Timeline of transport policies and infrastructure development in Delhi.

period. This is because reduction in emissions of 4Ws and 2Ws occurred as a result of four sets of emission standards, however, in case of buses, reduction in emissions was the result of retirement of older bus fleet and a rapid conversion of the fleet from diesel to CNG (Fig. 7). In less than 7 years from 1997 to 2003, $PM_{2.5}$ emissions from the buses reduced from a peak of 7200 tons to 950 tons, while their share in total $PM_{2.5}$ emissions reduced from 27% to 6%.

In 2012, the share of the LDVs and HDVs was the highest (67%), followed by 4Ws (20%) and 2Ws (8%). The HDVs are mostly diesel-based, and the LDVs are a mix of CNG and diesel. When classified by

Table 8
Contribution of vehicles ≥10 years old to fleet size and total on-road emissions in 2012.

	4W	2W	3W	BUS	HDV	LDV	Other
Vehicles	18%	9%	12%	5%	16%	15%	24%
PM2.5	24%	15%	30%	18%	30%	41%	28%
SO_2	24%	8%	30%	10%	16%	23%	15%
NO_x	13%	13%	–	16%	27%	36%	25%
CO	21%	13%	27%	16%	27%	36%	25%
VOC	20%	13%	27%	16%	27%	36%	25%
CO_2	21%	8%	27%	10%	16%	23%	15%

passenger modes (2Ws, 3Ws, 4Ws and buses) and freight modes (LDVs and HDVs), their share of $PM_{2.5}$ emissions is 33% and 67%, respectively which is highly disproportionate to their share in vehicular fleet.

In this analysis, we did not include the fugitive emissions on the road, due to the re-suspension of dust from constant movement of vehicles on the road. This is a major problem for most of the Indian cities (CPCB, 2010) and linked more to the urban infrastructure, than the vehicle engine characteristics.

3.1.2. SO_2 emissions

Since the SO_2 emissions are directly related to the amount of sulfur in the fuel, these emissions have reduced significantly, as a step function, as soon as the new fuel is available for use (Fig. 7). The annual SO_2 emissions increased linearly up to 1995 peaking at 22,500 tons and then reduced to 6500 tons in 1998, 4000 tons in 2001, 1100 tons in 2005, and 620 tons in 2012. In Delhi (and all the Indian cities), consequence of availability of low-sulfur diesel is also reflected in the ambient SO_2 concentrations, which is the only pollutant to often comply with the national ambient air quality standards (Guttikunda et al., 2014). These emissions could be further lower; however, due to the bifurcated fuel norms in the city and that available outside the city (at a lower price), the HDVs often use the lower quality fuel (Guttikunda and Mohan, 2014).

3.1.3. CO and VOC emissions

CO and VOC emissions follow the temporal trend similar to $PM_{2.5}$. The annual VOC emissions increased from 142,500 tons in 1991, peaked at 173,000 tons in 1996, and thereafter reduced to 71,600 tons in 2012. However, unlike PM, most reductions in VOC emissions (75%) came from the 2Ws (30%), followed by 4Ws (25%) and 3Ws (21%). VOC emissions from 2Ws reduced from their peak of 63,100 tons in 1996 to less than half in 2012 (28,400 tons). During the same period, CO emissions also reduced gradually, with 84% reduction coming from 2Ws (25%), cars (44%), and buses (15%). For CO and VOC, 2Ws are the largest contributor, followed by 4Ws in case of CO, and 3Ws in case of VOCs. For year 2012, 2Ws contribute to one-third of total CO and VOC, 4Ws contribute to one-third of CO, and one-fifth of VOC, and 3Ws contribute to only 6% of CO while they contribute 23% of VOC (Table 8).

3.1.4. NO_x emissions

Overall NO_x emissions have been continuously increasing, unlike PM, SO_2, CO, and VOC emissions. In 1991, an estimated total of 76,000 tons of NO_x was released by in-use vehicles, which increased to 120,500 tons in 2001, and 184,000 tons in 2012. From 1991 to 2012, 92% of the increase in NO_x emissions is contributed by HDVs and LDVs (60%), 3Ws (17%), and 2Ws (14%). In 2003, NO_x emissions from cars reached a peak of 13,200 tons and reduced to 10,400 tons in 2012. The most drastic increase in NO_x emissions occurred in the case of 3Ws-from 3000 tons in 1998 to 15,000 tons in 2012. This is because of fuel as well as technology conversion of 3Ws-from petrol and diesel with 2S engines to CNG with 4S engines.

3.1.5. CO_2 emissions

CO_2 emissions are directly related to the amount of fuel burnt. With a gradual increase in the total number of in-use vehicles, the total fuel burnt and the CO_2 emissions also increased; in spite of the improvement in the fuel efficiency of the individual vehicles. The estimated annual total CO_2 emissions from the in-use vehicles were 3.8 million tons in 1991 which increased to 6.2 million tons in 2001, and 11.2 million in 2012, approximately a threefold increase. As shown in Table 7, for year 2012, CO_2 emissions, only in case of 4Ws, are proportional to their share in total vehicular fleet and highly disproportionate for all other vehicle types.

3.2. Emissions by vehicle age mix

The emission totals presented in Fig. 6 are presented in Fig. 8 as percentage contributions for four age groups – vehicles <5 years, 6–10 years, 11–15 years, and >15 years. In case of Delhi, there are stricter retirement regulations than the rest of the country, especially for the commercial sector – 3Ws and taxis. All of them have a retirement age of 15 years, at which time their registration is not renewed for commercial activity. Often, past 15 years, vehicles move out of the city limits and continue their operations in the rural areas, and some continue operations off-road.

In the emission totals, the share of $PM_{2.5}$, NO_x, CO, and VOC emissions from vehicles aged ≥10 years increased from 15%, 16%, 10%, and 10% in 1991 to 33 %, 23%, 19%, and 23% in 2012, respectively. The contributions in 2012 by vehicle type and pollutant are summarized in Table 7. The usage of older vehicles is traditionally less in Delhi, compared to the rest of the country, which is also reflected in the average age of the fleet. Most of the bus fleet is new, following the entry of low floor buses during the 2010 Commonwealth Games as well as retirement age restriction of commercial vehicles. For the remaining vehicle types, on average 30–40 % of the emissions are from the vehicles older than 10 years. In case of HDVs and LDVs, 37% and 38% of their $PM_{2.5}$ emissions are coming from 16% to 15% of their respective in-use fleet.

3.3. Emissions by vehicle fuel mix

Diesel is still the dominant fuel to total emissions in Delhi. Most changes in the contribution of different fuel types to emissions occurred in case of NO_x, CO, VOC, and CO_2 starting from year 1998. The contribution of fuel mix to the total emissions is summarized in the year-to-year sheets in the Supplementary Material.

In case of $PM_{2.5}$, the change in the total emissions was significant during the late 1990s and early 2000s due to the introduction of CNG for buses and 3Ws. The drop in the total emissions during this period is ~20%. However, NO_x emissions from CNG increased from near zero in late 1990s to more than 50% in 2007, while those from diesel vehicles reduced from 95% to less than 50%. Since CNG replacement occurred from diesel-based buses, increase in NO_x emissions from CNG occurred with a reduction from diesel. For CO emissions, share of diesel has remained constant around 50%, share of petrol reduced to half from 46% in late 1990s to 25% in 2010, while that of CNG increased from zero to 25% during this time.

Trend of VOC is similar to that of CO; however, the mechanisms of change are different. While the variation in the share of CO emissions among different fuels occurred due to changing fuel standards and vehicle technology, changes in VOC emissions were primarily due to fuel switch for 3Ws. As a result, unlike CO, reduction in VOC emissions occurred at a much faster rate during the early 2000s.

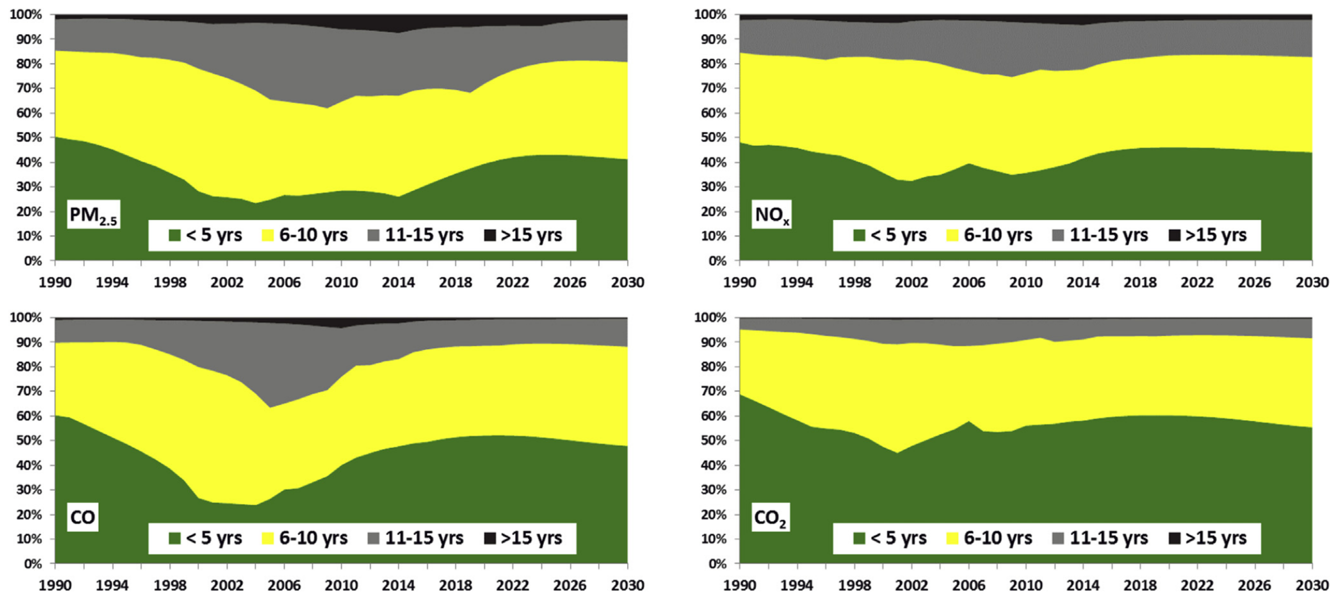

Fig. 8. Estimated annual on-road emissions in the Greater Delhi region by age group for (a) $PM_{2.5}$ (b) NO_x (c) CO and (d) CO_2.

The share of diesel cars in the new sales have almost doubled - from 27% during 2002–06 (Chugh et al., 2011) to 55% in 2013 (ICRA, 2013). In addition, dieselization in India has occurred largely with cars having large engine sizes. According to CSE (2012b), for year 2011–12, of all the diesel cars sold, 52% of them have an engine displacement between 1200 and 1500 cm^3 and 40% of them have above 1500 cm^3, while in case of petrol, only 13% of the cars sold are above 1200 cm^3. The fuel station survey data (Goel et al., 2015) shows that the diesel cars with an engine size less than 1600 cm^3 have 50% higher fuel efficiency than those with an engine size greater than 1600 cm^3 (16.1 and 10.8 km/lit, respectively). As a result, an overall average of all the diesel cars is even lesser than their petrol counterparts (14.0 and 15.3 km/lit, respectively). Thus, the dieselization of cars in India is likely to reduce the overall fuel efficiency of the fleet. This is similar to China where penetration of heavy diesel cars offset the fuel efficiency gains achieved due to fuel efficiency standards implemented in early 2000s (Wagner et al., 2009). Similar to India, preferential tax treatment for diesel led to dieselization in Europe. As a result, share of diesel cars in the total vehicle stock in EU-15 countries (consisting of UK, Germany, France, Netherlands and others) increased from 3.3% in 1980 to 32 % in 2007. By year 2009, one in every two cars sold in EU-15 was diesel (Ajanovic, 2011).

3.4. Comparison with previous studies

A summary of published inventory of no-road vehicle exhaust emissions in Delhi is presented in Fig. 9; along with the results from this study corresponding to each year for which results from previous work were available. The major differences and improvements in the emissions estimates are due to the following reasons.

- Unlike the published results, this study covers a period of 40 years from 1990 to 2030, which was modeled in an integrated and dynamic framework, where the fleet of each year is considered in continuity of the fleet from the previous year. This led to better representation of deterioration of emission factors, as well as fuel efficiency, and a better comparison of emissions over different years
- Out of the 16 studies reviewed, only two carried inventory of $PM_{2.5}$ emissions (Sahu et al., 2011; Guttikunda and Calori, 2013). Given the established link between $PM_{2.5}$ and health effects in terms of morbidity and mortality, estimation of $PM_{2.5}$ emissions is an important step in understanding the contribution of road transport sector
- The summary shows that there is some variance in the emission estimates between the studies. All the previous studies have Delhi as their study domain, while this study considered the Greater Delhi region as the study domain, which includes Delhi and its five satellite cities. This led to the estimates being on the higher side. However, for pre-1998 results, this variance is small, partly due to smaller interactions between Delhi and its satellite cities, which increased post-2000
- Most of the previous studies employed average emission factors, vehicle usage numbers, and fuel efficiencies. In this study, these parameters were benchmarked for Delhi, based on primary surveys conducted at the fuel stations and data collected from the emission testing labs, to establish the age mix, fuel economy, vehicle usage, and updated dynamic emission factors for the fleet (Goel et al., 2015)
- Most studies used registered number of vehicles as the fleet size. This leads to overestimation of private vehicular fleet by a factor of more than 2 for 2Ws and 1.5 for cars (Goel et al., 2015) and underestimate the HDVs and buses, by not including the volume of inter-city vehicles. These were corrected in the vehicle fleet assessments
- This inventory includes all the criteria pollutants $PM_{2.5}$, SO_2, NO_x, CO, and VOC; and sub-components to PM – black carbon and organic carbon, suitable for atmospheric chemical transport modeling

4. Implications

The transport sector plays an integral role in the movement of passengers and freight through the city. The contribution of vehicle exhaust emissions to the ambient pollution is substantial and needs more positive interventions for future emission control. A source apportionment study conducted by MoEF, concluded that the

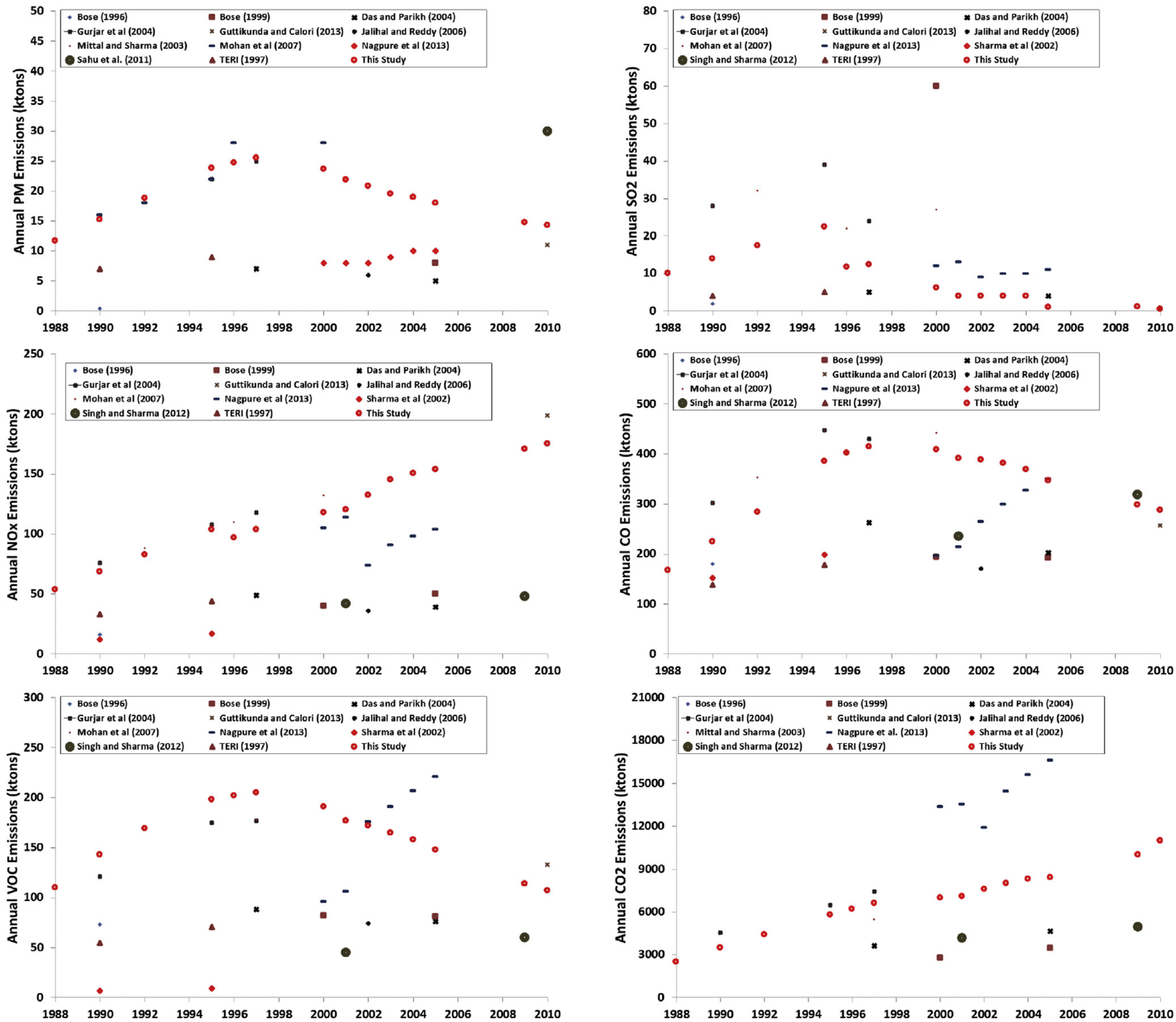

Fig. 9. Comparison of emission estimates from this study and estimates from published literature from 1988 to 2010.

vehicle exhaust emissions are responsible for up to 21% of the ambient PM_{10} pollution in the city (CPCB, 2010), with the residential and commercial sections of the city experiencing up to 50% of PM from transport sector, on a daily basis (Guttikunda and Goel, 2013).

4.1. Emissions outlook through 2030

The total emissions for all the criteria pollutants are projected to 2030, under the business as usual (BAU) scenario. These are included in Fig. 6. Under BAU, no change in the emission and fuel standards is assumed past 2014. The sales for 2014 to 2030 were estimated using annual growth rates, projected by the Society of Indian Automobile Manufacturers (New Delhi, India) (Guttikunda and Mohan, 2014). The decade from 2021 to 2030, is estimated to add 430,000 2Ws and 350,000 4Ws per year to the in-use fleet, as opposed to 350,000 2Ws and 200,000 4Ws during the preceding decade – 2011 to 2020. The total in-use fleet will grow 3 times from a total of 6.0 million in 2014 to 16.0 million in 2030 (Fig. 3a).

Since 1990, only two interventions have had significant impact of the overall emissions in Delhi – (a) periodic change in the emission and fuel standards and (b) introduction of CNG. While the benefits of the later are nullified due to a rapid increase in the overall vehicle fleet, the former is still the main proponent for controlling the emissions in the city. Because of this, for all the pollutants, the lowest emission totals are estimated for 2012–14; which will rise if left unchecked. With no changes in the standards, the 4Ws will dominate the PM, SO_2, CO, and CO_2 emissions. While the total SO_2 emissions are small, the increase in the 4W sector is coming from the increasing sales of diesel vehicles. With expected increase in the commercial activity in the region and the existing restrictions on the movement of HDVs, the LDV sector is expected contribute more to the on-road emissions through 2030.

While we did not assume any change in the emission and fuel standards for the projections, the fleet average emission rates do change annually, due to the changes in the mix of the vehicles - gradual retirement of the older vehicles and constant introduction of newer vehicles, which invariably betters the overall fleet average emission rate. This is further accelerated if the newer standards are introduced. A summary of the estimated fleet average emission rates for year 2030 is presented in the Supplementary Material, which can be compared to the emission rates for year 2012 in Table 5.

4.2. Potential to reduce on-road vehicle emissions

According to Equation (1), the overall emissions can be reduced only if we reduce the number of in-use vehicles or we reduce the annual mileage of the in-use vehicles, or we reduce the fleet average emission factors. To date, the number of vehicles and the annual mileage has only increased and the decreasing emission trends for various pollutants are due to changes in the emission factors. The potential for reducing the emissions and the contribution of the transport sector to the ambient pollution lies with the international experiences and the ability to implement the same effectively in Delhi.

Among Asian countries, India is lagging behind other countries in settings fuel standards with low sulfur content of diesel. For instance, Hong Kong, Japan, Singapore, South Korea, and Thailand have already implemented nationwide use of diesel with sulfur content of 50 ppm or less. Further, European Union has adopted Ultra Low Sulfur Diesel (with sulfur content < 10 ppm) and USA has mandated sulfur content of 15 ppm. One of the major barriers for India to adopt more stringent emission standards (Euro V or higher) is the high sulfur content in the diesel as well as petrol which is 350 ppm and 150 ppm, respectively. This is because high sulfur content of fuel gives rise to other technological constraints for reducing vehicular emissions. At such levels, sulfur inhibits the proper functioning of advanced after-treatment technologies, ranging from diesel particulate filters to lean NO_x traps that could reduce vehicle emissions by more than 90% (ICCT, 2013). It is essential to implement and enforce Bharat-5 (equivalent of Euro-5) or higher standards nationwide, as soon as possible, in order to maintain a balance between the energy demand and growing emissions (Guttikunda and Mohan, 2014). Any delay in implementation or staggered implementation (as is the case currently) of the standards, will result in a delayed response for improving air quality in Delhi.

In Delhi, buses, 3Ws, and taxis were converted to operate on CNG and a steady supply of fuel coupled with lower prices is encouraging private car owners also to switch. The number of CNG outlets in Delhi increased from 30 in year 2000 to 300 in 2013. The public transport system also benefitted from Jawaharlal Nehru National Urban Renewal Mission (JNNURM) program to better and increase the fleet (MoUD, 2012). The implementation of dedicated bus corridors, known as "bus rapid transport (BRT) system" is also among the priorities. Due to public opposition and lack of political will, the current corridor of ~6 km has not been extended further because of which the full benefits of the corridor have not been achieved. If and when fully implemented, BRT could result higher on-road vehicle speeds and consequently reduction in the emission rates and congestion times; and a favorable shift from cars and motorcycles to buses resulting in reduction of annual VKTs.

Some economic measures are also designed to force the use of public transport. One such measure is the congestion pricing, which was successfully implemented in Singapore, London, and Stockholm (Eliasson, 2009; Menon and Guttikunda, 2010; Litman, 2011), with significant changes in the ambient pollution levels and an estimated reduction in eCO_2 emissions between 10 and 20%, along with health benefits along the major corridors. A major reason for its success in Singapore, London, and Stockholm was the availability of widely accessible public transport system (road and rail) which can support the shift to a car-free environment. If implemented, there will be immediate benefits in Delhi. However, the public transport system is still not at par with those in Singapore, London, and Stockholm for effective implementation of this option.

While congestion pricing policies are difficult to replicate in the Indian context, at least for the foreseeable future, there is an important lesson to be learned. With increasing costs for private vehicles linked with their usage (fuel and other operational expenses), it is possible to achieve a shift to public transport, if combined with the provision of an adequate, reliable, and safe public transportation. One such measure is the increased parking cost, based on the activity levels in the commercial and residential centers. Currently, parking in most cities is either free or priced very low (Barter, 2012; CSE, 2012a). Increased parking cost, if coupled with the parking locations so that they are as far as bus and rail stops, will make public transportation an attractive option.

In Delhi, a majority share of trips is by walk and cycle. This is because of traditional mixed-use design of the city, which leads to shorter access to work, school, and other activities. However, according to MoUD (2008) an expanding city leads to a decrease in the share of non-motorized transport (NMT). Higher population density and absence of dedicated NMT infrastructure, motorized vehicles also pose serious risk of injury, because of which, people owning two-wheelers and cars are encouraged to use their vehicles, even for walkable distances. In the context of growing cities, the measures to improve air quality should include NMT policies as an integral part.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.01.045.

References

ACEA, 2010. The Automobile Industry Pocket Guide 2010. European Automobile Manufacturers' Association, Brussels.
Ajanovic, A., 2011. The Effects of Dieselization of the European Passenger Car Fleet on Energy Consumption and CO2 Emissions. Energy Economics Group, Vienna University of Technology, Gusshaustr.
Apte, J.S., Kirchstetter, T.W., Reich, A.H., Deshpande, S.J., Kaushik, G., Chel, A., Marshall, J.D., Nazaroff, W.W., 2011. Concentrations of fine, ultrafine, and black carbon particles in auto-rickshaws in New Delhi, India. Atmos. Environ. 45, 4470–4480.
Baidya, S., Borken-Kleefeld, J., 2009. Atmospheric emissions from road transportation in India. Energy Policy 37 (10), 3812–3822.
Barter, P.A., 2012. Off-street parking policy surprises in Asian cities. Cities 29, 23–31.
Bose, R.K., Nesamani, K., 2000. Urban Transport, Energy and Environment: a Case of Delhi.
Bose, R.K., 1996. Energy demand and environmental implications in urban transport—Case of Delhi. Atmos. Environ. 30, 403–412.
Bose, R.K., 1999. Towards better urban transport planning-problems and policies, case of Delhi. In: Workshop on-Challenges and Opportunities for Concerted Action between Asia and Europe in Urban Transport. Centre for Renewable Energy Resources, the Greek National Centre for Renewable Energy Sources, Athens, Greece (15–18 September, 1999).
Bose, R.K., Srinivasachary, V., 1997. Policies to reduce energy use and environmental emissions in the transport sector: a case of Delhi city. Energy Policy 25, 1137–1150.
Chan, C.-C., Nien, C.-K., Tsai, C.-Y., Her, G.-R., 1995. Comparison of tail-pipe emissions from motorcycles and passenger cars. J. Air & Waste Manag. Assoc. 45, 116–124.
Chugh, R., Cropper, M., Narain, U., 2011. The cost of fuel economy in the Indian passenger vehicle market. Energy Policy 39 (11), 7174–7183.
CPCB, 2010. Air Quality Monitoring, Emission Inventory and Source Apportionment Study for Indian Cities. Central Pollution Control Board, the Government of India, New Delhi, India.
CSE, 2012a. Parking Policy: Getting the Principles Right, Policy Brief. Center for Science and Environment, New Delhi, India.
CSE, 2012b. Proposal for Additional Excise Duty on Diesel Cars to Reduce Public

Revenue Losses and Public Health Costs. Centre for Science and Environment, New Delhi.
Das, A., Parikh, J., 2004. Transport scenarios in two metropolitan cities in India: Delhi and Mumbai. Energy Convers. Manag. 45 (15), 2603–2625.
de la Rue du Can, S., Michael, M., Sathaye, J., 2009. India Energy Outlook: End Use Demand in India to 2020. Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, USA.
DES, 2008. Delhi Statistical Handbook 2008. Directorate of Economics and Statistics, the Government of National Capital Territory of Delhi, New Delhi, India.
DES, 2012. Delhi Statistical Handbook 2012. Directorate of Economics and Statistics, the Government of National Capital Territory of Delhi, New Delhi, India.
DES, 2013. Delhi Statistical Handbook 2013. Directorate of Economics and Statistics, the Government of National Capital Territory of Delhi, New Delhi, India.
DieselNet, 2014. Fuel Economy Standards for Light-duty Passenger Vehicles. Accessed online from. http://www.dieselnet.com/standards/in/fe.php.
DoUD-Delhi, 2006. City Development Plan Delhi. Department of Urban Development, Government of Delhi.
Eliasson, J., 2009. A cost–benefit analysis of the Stockholm congestion charging system. Transp. Res. A Policy Pract. 43, 468–480.
EPCA, 2004. Special Report on the Non-destined Transit Trucks Using Delhi. Environment Pollution (Prevention & Control) Authority for the National Capital Region, New Delhi, India. Report No. 12.
Gandhi, K., Zvonow, V., Singh, H., 1983. Development of a driving cycle for fuel economy in a developing country. Transp. Res. A Gen. 17, 1–11.
Goel, R., Guttikunda, S.K., Mohan, D., Tiwari, G., 2015. Benchmarking vehicle and passenger travel characteristics in Delhi for on-road emissions analysis. Travel Behav. Soc. http://dx.doi.org/10.1016/j.tbs.2014.10.001.
Grieshop, A.P., Boland, D., Reynolds, C.C., Gouge, B., Apte, J.S., Rogak, S.N., Kandlikar, M., 2012. Modeling air pollutant emissions from Indian autorickshaws: model development and implications for fleet emission rate estimates. Atmos. Environ. 50, 148–156.
Gumber, A.K., 2004. CNG Infrastructure in India, Latest Development and a Success Story of Delhi. GAIL India, Delhi.
Gurjar, B., Van Aardenne, J., Lelieveld, J., Mohan, M., 2004. Emission estimates and trends (1990–2000) for megacity Delhi and implications. Atmos. Environ. 38, 5663–5681.
Guttikunda, S., 2012. Air pollution in Delhi. Econ. Polit. Wkly. 47, 24–27.
Guttikunda, S.K., Calori, G., 2013. A GIS based emissions inventory at 1 km× 1 km spatial resolution for air pollution analysis in Delhi, India. Atmos. Environ. 67, 101–111.
Guttikunda, S.K., Goel, R., 2013. Health impacts of particulate pollution in a megacity—Delhi, India. Environ. Dev. 6, 8–20.
Guttikunda, S.K., Goel, R., Pant, P., 2014. Nature of air pollution, emission sources, and management in the Indian cities. Atmos. Environ. 95, 501–510.
Guttikunda, S.K., Mohan, D., 2014. Re-fueling road transport for better air quality in India. Energy Policy 68, 556–561.
ICCT, 2013. Policy Summary: India's Vehicle Emissions Control Program, Briefing. The International Council on Clean Transportation.
ICET, 2011. Global Overview on Fuel Efficiency and Motor Vehicle Emission Standards: Policy Options and Perspectives for International Cooperation. The Innovations Center for Energy and Transportation. United Nations Background Paper, (3).
ICRA, 2013. Indian Passenger Vehicle Industry-Proportion of Diesel Cars in Industry Sales Mix Likely to Decline in Next Two Year. ICRA Research Services.
IEA, 2011. International Comparison of Light-duty Vehicle Fuel Economy and Related Characteristics. Global Fuel Economy Initiative, International Energy Agency, Paris, France. Working Paper 5/10.
IGL, 2005. Annual Report 2004–05. Indraprastha Gas Limited, Delhi.
Iyer, N., 2012. A Technical Assessment of Emissions and Fuel Consumption Reduction Potential from Two and Three Wheelers in India. The International Council on Clean Transportation, San Francisco, USA.
Jalihal, S.A., Reddy, T., 2006. CNG: an alternative fuel for public transport. J. Sci. Ind. Res. 65, 426.
Kathuria, V., 2002. Vehicular pollution control in Delhi. Transp. Res. D Transp. Environ. 7 (5), 373–387.
Kim, J.J., Smorodinsky, S., Lipsett, M., Singer, B.C., Hodgson, A.T., Ostro, B., 2004. Traffic-related air pollution near busy roads: the East Bay Children's respiratory health study. Am. J. Respir. Crit. care Med. 170, 520–526.
Litman, T., 2011. London congestion Pricing: Implications for Other Cities. Victoria Transport Policy Institute.
Mehta, R.K., 2011. Land Use Land Cover Change Detection Using Remote Sensing Datas and GIS Tools: a Case Study of Delhi State. Sikkim Manipal University, Gangtok, Sikkim. Master of Science.
Menon, G., Guttikunda, S.K., 2010. Electronic road pricing: experience & lessons from Singapore. In: UrbanEmissions. Info (Ed.), SIM-air Working Paper Series, 36–2011, (New Delhi, India).
Mohan, D., Tiwari, G., Saraf, R., Kale, S., Deshmukh, S.G., Wadhwa, S., Soumitri, G., 1996. Delhi on the move: future traffic management scenarios. In: Transportation Research and Injury Prevention Programme. Indian Institute of Technology, Delhi.
Mohan, M., Dagar, L., Gurjar, B., 2007. Preparation and validation of gridded emission inventory of criteria air pollutants and identification of emission hotspots for megacity Delhi. Environ. Monit. Assess. 130, 323–339.
MoUD, 2008. Study of Traffic and Transportation Polices and Strategies in Urban Areas in India. Ministry of Urban Development, the Government of India, New Delhi, India.
MoUD, 2012. Transforming City Bus Transport in India through Financial Assistance for Bus Procurement under JnNURM. Ministry of Urban Development, the Government of India, New Delhi, India.
Muralikrishna, M.N., 2007. Indian two wheelers. In: Presentation, PCRA International Seminar on Fuel Efficiency, Chennai.
Nagpure, A.S., Sharma, K., Gurjar, B.R., 2013. Traffic induced emission estimates and trends (2000–2005) in megacity Delhi. Urban Clim. 4, 61–73.
Ntziachristos, L., Gkatzoflias, D., Kouridis, C., Samaras, Z., 2009. COPERT: a European Road Transport Emission Inventory Model, Information Technologies in Environmental Engineering. Springer, pp. 491–504.
Padam, S., Singh, S., 2001. Urbanization and urban transport in India: the sketch for a policy. In: Transport Asia Project Workshop, Pune, India (Full Text).
PIB, 2009. Mandatory Fuel Efficiency Standard to be Implemented in two Years. Press Information Bureau, Government of India. Release ID: 52216, Accessed online from. http://pib.nic.in/newsite/erelease.aspx?relid=52216.
Polk, 2012. Average Age of Vehicles Reaches Record High, According to Polk. Polk, Southfield, Michigan, US. Accessed online from. http://www.polk.com/company/news/average_age_of_vehicles_reaches_record_high_according_to_polk.
Purwaha, A.K., 2006. CNG developments – an Indian experience. In: 23rd World Gas Conference, Amsterdam.
Ravindra, K., Wauters, E., Tyagi, S.K., Mor, S., Van Grieken, R., 2006. Assessment of air quality after the implementation of compressed natural gas (CNG) as fuel in public transport in Delhi, India. Environ. Monit. Assess. 115 (1–3), 405–417.
RITES, 2008. Travel Characteristics, Household Interview Survey Report – December 2008. In: Transport Demand Forecast Study and Development of an Integrated Road cum Multi-modal Public Transport Network for NCT of Delhi. RITES Ltd, New Delhi, India.
RITES, 2013. Total Transport System System Study on Traffic Flows and Modal Costs (Highways, Railways, Airways and Coastal Shipping). In: A Study Report for the Planning Commission. The Government of India, New Delhi, India.
Sahu, S.K., Beig, G., Parkhi, N.S., 2011. Emissions inventory of anthropogenic PM2.5 and PM10 in Delhi during Commonwealth Games 2010. Atmos. Environ. 45, 6180–6190.
Schipper, L., Marie-Lilliu, C., Gorham, R., 2000. Flexing the Link between Transport and Greenhouse Gas Emissions: a Path for the World Bank. International Energy Agency, Paris, France.
Sharma, C., Dasgupta, A., Mitra, A., 2002. Inventory of GHGs and other urban pollutants from transport sector in Delhi and Calcutta. In: Proceedings of Workshop of IGES/APN Mega-city Project, pp. 23–25.
Singh, R., Sharma, C., 2012. Assessment of emissions from transport sector in Delhi. J. Sci. Ind. Res. 71, 155–160.
SoE-Delhi, 2012. State of the Environment Report for the National Capital Region of Delhi. The Government of Delhi, New Delhi, India.
TERI, 2006. Energy Book 2005–06. The Energy and Research Institute, Delhi.
Tiwari, G., 2003. Transport and land-use policies in Delhi. Bull. World Health Organ. 81, 444–450.
Tsai, D.-H., Wu, Y.-H., Chan, C.-C., 2008. Comparisons of commuter's exposure to particulate matters while using different transportation modes. Sci. Total Environ. 405, 71–77.
Wagner, D.V., An, F., Wang, C., 2009. Structure and impacts of fuel economy standards for passenger cars in China. Energy Policy 37 (10), 3803–3811.
Yan, F., Winijkul, E., Jung, S., Bond, T.C., Streets, D.G., 2011. Global emission projections of particulate matter (PM): I. Exhaust emissions from on-road vehicles. Atmos. Environ. 45, 4830–4844.