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Benchmarking vehicle and passenger travel characteristics in Delhi for on-road emissions analysis

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ABSTRACT

In a mega-city like Delhi, vehicle exhaust emissions play a central role for urban air quality management, and measuring these on-road emissions in an environment with mixed fuels, mixed engine sizes, mixed technologies, and mixed usage patterns, is a challenging task, which means a better understanding of the vehicle and the passenger characteristics in the city is necessary. In this paper, we present a series of survey methods – vehicle owners' interviews at fuel stations, on-road observational studies, and use of data resources like vehicle registrations and pollution under check program, which can be utilized to benchmark parameters linked to an emissions inventory methodology (Activity–Share–Intensity–Factor – ASIF). We present estimates for fuel efficiency, age profiles, annual mileage, and number of in-use vehicles for cars, motorized two-wheelers (2Ws), three-wheeled scooter rickshaws (3Ws), and buses and modeled survival functions for cars and 2Ws using log-logistic distribution function. In addition, using GPS data logging, we evaluated speed distribution of buses, cars, 2Ws and 3Ws, which resulted in evaluating the modal idling times, all of which were utilized to develop a robust vehicle exhaust emissions inventory for Delhi – segregated by vehicle type, fuel type, and age group. The survey methods and analytical techniques are simple and fast to implement, which when replicated, can provide a useful data source to estimate on-road transport emissions in urban areas.

1. Introduction

As India's capital, Delhi has grown across all sectors - industry, transport, and housing, all of which have contributed to an increase in city's air pollution problems (Narain and Bell, 2006; Goswami and Baruah, 2008; Firdaus and Ahmad, 2011; Sahu et al., 2011; Guttikunda, 2012; Guttikunda and Gurjar, 2012; Ahmad et al., 2013; Guttikunda and Calori, 2013; Guttikunda and Goel, 2013). For the period of 2008 and 2011, the ambient concentrations in the city, averaged over nine monitoring stations, ranged $123 \pm 87\ \mu g/m^3$ for $PM_{2.5}$ and $208 \pm 137\ \mu g/m^3$ for PM_{10}. The variation is one standard deviation of daily average concentrations over the period. The national annual standard for $PM_{2.5}$ is $40\ \mu g/m^3$ and for PM_{10} is $60\ \mu g/m^3$. The Central Pollution Control Board (CPCB) of India and the Ministry of Environment and Forests (MoEF) studied the source contributions to ambient particulate matter (PM) pollution in Delhi and concluded that the vehicle exhaust is a major contributor to the overall PM_{10} (PM with aerodynamic diameter less than 10 μm) and $PM_{2.5}$ (PM with aerodynamic diameter <2.5 μm) pollution in Delhi (CPCB, 2010).

The city of Delhi has one of the highest vehicle ownership levels in India, with a total registered fleet of 2.5 million cars and 4.5 million 2-wheelers (2Ws), in 2012. 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). Fig. 1 shows the time series of cumulative vehicle registration numbers of cars and 2Ws in Delhi. With only 21% of the households owning cars and 38% of the households owning 2Ws (Census-India, 2012), there is a large proportion of population without access to private vehicles.

Earlier studies have documented the methods to estimate total emissions and the impact of growing transport emissions in Delhi (Gurjar et al., 2004; Mohan et al., 2007; CPCB, 2010; Sahu et al., 2011; Guttikunda and Calori, 2013). Since the studies focusing on the measurement of tail pipe emissions of on-road vehicles in Delhi are limited, we have to rely on such bottom-up emission inventory estimates. Typically, the ASIF (Activity–Share–Intensity–Factor) methodology was applied to calculate the vehicle exhaust emissions (Schipper et al., 2000; Yan et al., 2011), in

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which, the parameters are defined as total travel activity (A), modal shares (S), fuel intensity (I), and appropriate emission factor (F) as mass pollutant emitted per vehicle-km travelled. For the vehicle exhaust emissions in a city like Delhi, all types of vehicles are used, equally, to move people and freight, under varying loads. This and a vibrant age mix of the fleet presents a challenging task in understanding how each of the ASIF parameters behave to estimate the total emissions.

For PM, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs), the ASIF methodology translates to

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

For sulphur dioxide (SO_2) and carbon dioxide (CO_2) emissions, the ASIF methodology translates to

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

where, $E_{v,f,g,p}$ is the total emissions by pollutant, calculated by vehicle type, fuel type, and by age; $NV_{v,g}$ is the total number of vehicles on-road by vehicle types and by age; S_v is the share of vehicles on-road for each vehicle type; $VKT_{v,g}$ is the annual average vehicle kilometers traveled by vehicle type and by age; $EF_{v,f,g,p}$ is the fleet average emission factor by vehicle type, fuel type, age group, and by pollutant; $FE_{v,f,g}$ is the fuel economy by vehicle type, fuel type, age group; $PC_{f,p}$ is the pollutant content (for example, carbon and sulfur content of the fuel) v = vehicle; f = fuel; g = age group; p = pollutant.

Each of the parameters tell us (a) how people travel in the city and what is the average VKT for each mode (b) how old or how young is the vehicle fleet and what are their compliance levels (c) given the road and driving conditions, what is the likely wear and tear of the engine (d) how fast or how slow is the movement of vehicles in the city and (e) what are the idling rates in the city, all of which determine the overall vehicle exhaust emission rate for the city. A clear understanding of how each of these parameters is essential in establishing a credible emissions inventory for a city.

In India, few studies have been carried out to investigate vehicular characteristics such as fuel efficiency, annual mileage, and size of in-use fleet. Traditionally, information on the total number of vehicles in the city is available from the regional transport offices (RTOs), as the vehicles are registered every year. A major drawback linked to these databases is an overestimate of the actual number of vehicles on-road and in-use (Auto-Fuel-Policy, 2002; Mohan et al., 2009). This is the primary concern for the private vehicles as the owners are required to pay a lifetime tax at the time of purchase. The vehicles are often not de-registered when they are retired or sold to a second or third party. This is common for many low-income countries. In contrast, in high-income countries, such as the United States, the United Kingdom, France, Australia, and Japan, national authorities carry out field surveys of drivers for estimating fuel efficiency and annual mileage (Schipper, 2008).

The vehicular characteristics were developed for the city of Pune using video camera recording of traffic, to determine the type of vehicles on road (Barth et al., 2007). The study team also conducted parking lot surveys (visual inspection only) for odometer readings, engine size, and model year and on-board GPS recording to determine vehicle speeds. Huo et al. (2009) also utilized similar methods to establish vehicular characteristics in Beijing. Both the studies did not report real-world fuel efficiency values, which needs interviewing the driver or the owner. In addition, surveys involving visual inspection are unable to record other information, such as fuel type in case a car is retrofitted with Compressed Natural Gas (CNG), and odometer readings for cars and 2Ws with digital display.

The fuel-efficiency values of a vehicular fleet can be largely classified into two categories. Firstly, fuel efficiency of new vehicles, which are being added to the existing fleet, which depends on the availability of latest technology in the market and prevailing consumer preference. These numbers are often declared by the manufacturers based on controlled tests and not on-road measurements under real driving conditions (Iyer, 2012). Secondly, average fuel-efficiency of in-use fleet, is a more complex estimate as it is dependent on characteristics of vehicle models sold in the past and also needs to account for the degradation in fuel-efficiency over time. Unlike the former category, information for in-use fleet is much more difficult and needs to be estimated using driver/owner surveys. There are few examples of online portals which provide estimates of on-road values of fuel efficiency. For Chinese vehicles, Huo et al. (2011) reported an online portal in which Chinese drivers voluntarily post fuel efficiency of their cars. In the case of US, in 2005, the Department of Energy's fuel economy information website (<http://www.fueleconomy.gov>) began allowing users to voluntarily share fuel economy estimates. Further, the "spritmonitor" website (<http://www.spritmonitor.de/en/>) has a fuel consumption database of more than 250,000 vehicles. A similar system is not in place for Indian cities.

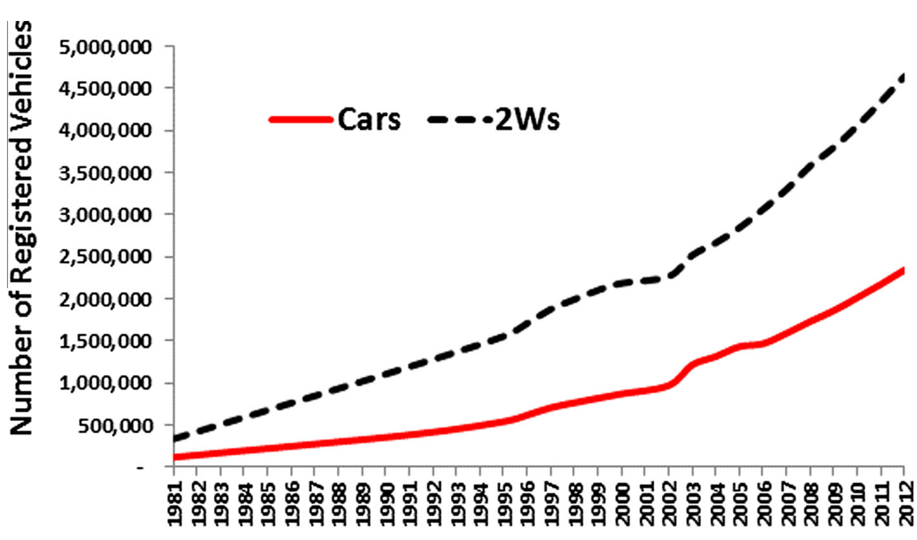

Fig. 1. Time series of vehicle registration in Delhi.

In Delhi, a series of surveys were conducted to determine the ASIF emissions inventory parameters. In this paper, we present the survey methods developed and implemented; analysis results of these surveys; a discussion on the data sources available to support benchmarking these parameters (and replication thereof); and their implications to overall emissions inventory for the city.

2. Data and methods

We collated information from primary surveys, secondary sources, and databases available in the public domain from various ministerial and regulatory groups in the city.

2.1. Pollution check centers

In India, vehicles more than one year old are required to undergo a pollution check every three months as part of the pollution under control (PUC) program. There are approximately 500 PUC centers in Delhi and are largely located at fueling stations and some located along the major corridors and highways for passenger convenience. For every vehicle tested at these centers, the operator records the (a) make and model of the vehicle (b) fuel type – petrol/diesel/compressed natural gas (CNG) (c) category of the vehicle (two-wheeler, three-wheeler, four-wheeler, bus, and truck) (d) vehicle manufacturing date (e) vehicle emission test date (f) tailpipe emission rates for CO and VOCs measured at engine idle speed and at high idle speed of engine at 2000 rpm (lambda testing) for petrol and CNG vehicles and mean Hartridge Smoke Units (HSU) measured using free acceleration test for diesel vehicles.

The PUC test data of all the vehicles is maintained by the Transport Department of Delhi (<http://delhitransportpuc.in>).We utilized this database (referred to as PUC data) from 300 centers for the year 2010 for 700,000 vehicles including passenger cars, 2Ws, buses, three-wheeled scooter rickshaws (3Ws) and freight vehicles running on a mix of petrol, diesel and CNG.

2.2. Fuel station surveys

For this survey, between May and August, 2012, we randomly selected three fueling stations from a total of 150 stations – one in south Delhi (near Hyatt hotel, closer to the ring road – surveyed 731 cars and 1048 2Ws), one in north Delhi (in Ashok Vihar – surveyed 636 cars and 491 2Ws), and one in north-western Delhi (near Rani Bagh, Pitampura – surveyed 861 cars and 35 2Ws). The three stations were located in different land-use types – along a major road, residential, and mixed-use, respectively. Through the survey, 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/L) – reported by the owner/driver based on their experience and (5) odometer reading (total km traveled) at the time of survey. The first two questions were observed and noted by the surveyor and the last three took on average 1–3 min per driver/owner. The response rate for cars and 2 W drivers was more than 95%, primarily due to the fact that only three questions were asked, which was recorded in less than the time it took for their refueling.

We carried out statistical tests to compare the age distribution of vehicles interviewed at the stations. *F*-Test was carried out in order to test the variance of age distribution over the three stations. It shows that the locations have no statistically significant difference in the age distribution of sampled cars. For this, we assumed that age distribution of the fleet explains most fleet characteristics, such as, vehicle model and fuel-efficiency. Therefore, we assumed that the data from these stations is representative of the fleet in Delhi and hence further data collection was discontinued.

2.3. Vehicle speeds

The on-road movement characteristics are different in different parts of the city and the vehicle speeds play a vital role in estimating the total emissions and in determining the temporal and spatial variation of these emissions in the city (Hansen et al., 1995; Jensen, 1995; Sturm et al., 1996; Ntziachristos and Samaras, 2000; Tong et al., 2000; Kean et al., 2003; Smit et al., 2008; Barth and Boriboonsomsin, 2009). Since, the speed distribution is dependent on the road characteristics and travel behavior, this could not be based on the point surveys. We collected the vehicle speed information across the city using instantaneous speed data from global positioning system (GPS) units, for buses, cars, 2Ws and 3Ws.

For buses, we collected GPS logs for two days (1–2, November, 2012) from 941 state-run public transportation buses, covering most of the road network in Delhi. The data was logged using u-blox-5 ROM-based GPS receivers, at a frequency of 0.1 Hz and at a position accuracy of 2.5 m. The device was attached to the dashboard of the bus facing the windshield close to the driver. The total data logged for 18,000 h includes information on latitude and longitude of the bus location, date and time stamp, speed, and the bus registration number. All the GPS data from the buses is archived and maintained by Delhi Integrated Multi-Modal Transit System (DIMTS) Ltd.

A similar centralized system is not in place for other vehicular modes. For passenger cars, 2Ws, and 3 Ws we carried out the data collection using floating car method. A mix of 10 professional car drivers, 20 professional 3W drivers at various locations, and 3 research scholars with 2 Ws, drove around the city, with a GPS device on the dashboard (for cars and 3Ws) and strapped on a backpack (for 2W), between 6AM and midnight for multiple days between January 2012 and January 2013. The data is collected using AMOD GPS data logger with SiRF III technology based receiver, with a logging frequency of 1 Hz and a positional accuracy of 10 meters. The total distance covered during this exercise was 2160 km for cars, 1210 km for 3Ws and 650 km for 2Ws, covering residential areas, highways, main roads, and arterial roads in the city.

2.4. Used car sales data

The used car market is limited and mostly conducted via word-of-mouth. Recently, a few websites have started offering used cars exchange service. We collected the information on the reported odometer readings and year of manufacture from http://www.carwale.com. For Delhi, data includes odometer readings of 2996 cars. This data is from one website only, under the assumption that owners and dealers are likely to post their advertisement on multiple sites. In the current analysis, we did not use this resource for further analysis, since we cannot verify the representative nature of these data. However, this information can be used as a secondary (proxy) database for verification of annual VKTs in the city.

3. Results

3.1. Age profile of vehicles

Vehicle age distribution was determined using PUC data as well as fuel station surveys. In Table 1, we present age distribution for eight different passenger and commercial vehicle types, derived from the PUC data. The age of a vehicle was estimated as the difference between date of manufacture and date of vehicle testing. In

Table 1
Age profile of vehicles based on the data collected during the PUC testing in Delhi.

Age bins (years)	Percentage of vehicles in each age group							
	Passenger vehicles					Freight vehicles		
	2Ws (petrol)	Cars (diesel)	Cars (petrol/CNG)	Buses (CNG)	Auto rickshaws (CNG)	Light-duty* (CNG)	Tempos* (diesel)	Trucks (diesel)
0–5	67.0	68.8	51.8	22.2	39	84	53.8	48.5
6–10	24.8	27.3	32.1	69.6	56	13	31.0	35.1
11–15	6.6	3.6	14.2	8.2	5	3	15.1	17.0
15+	1.6	0.3	1.8	0.1	0	0	0.04	0.4
All age	100	100	100	100	100	100	100	100
Total observations	330,693	18,775	294,717	8645	42,633	24,187	9598	3945

* Vehicles with gross vehicle weight = 6140 kg.

Table 2
Age profile of cars and 2Ws based on the fuel station surveys in Delhi.

Age bins (years)	Percentage of vehicles in each age group			
	Sample data		Weibull distribution (smoothing)	
	2Ws	Cars	2Ws	Cars
0–5	73	68	71	68
6–10	23	26	21	24
11–15	3	6	6	6
15+	1	1	2	2
All age	100	100	100	100
Total observations	1570	2231		

Table 2, we present the age distribution for cars and 2Ws based on the fuel station survey - since we know only the model year, we assumed that equal number of cars are bought each month according to which the average date (month and year) of registration of cars corresponding to each model year can be expressed as [Model Year $+ (6.5 \div 12)$]. The 6.5 refers to the average age in months of all cars bought in a particular year by the end of that year.

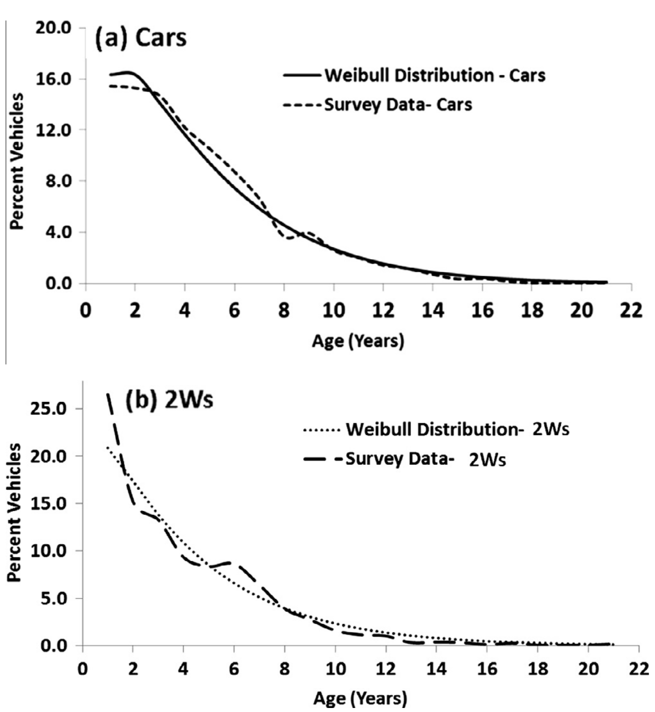

Fig. 2. Age distribution of (a) cars and (b) 2Ws, based on fuel station surveys in Delhi in 2012.

Year-wise distribution of age profile shows that the distribution needs smoothing before we could make any inferences (Fig. 2). We fitted various continuous parametric probability distributions using SPSS statistical package. Among them, Weibull distribution showed the best fit. Its cumulative probability function is expressed as:

$$F(k) = 1 - e^{-\left(\frac{k}{\beta}\right)^{\alpha}} \quad (3)$$

where, k is the age of vehicles and α and β are shape and scale parameters respectively. For cars, α and β are 1.15 and 4.49, respectively and for 2Ws the two values are 1.04 and 4.03, respectively.

Using Weibull distribution, the average age of 2Ws and cars came to 4.4 and 4.7 years, respectively. Both samples show that at least 68% of the vehicles are less than 5 years old and only 2% are more than 15 years old. PUC data also shows that almost all the vehicles are 15 years or younger – this could be an anomaly in the data set, since it is also possible that cars and 2Ws older than 15 years are less likely to undergo an emissions test at a PUC center.

Comparing the age distribution of cars from PUC data and fuel station surveys, we observed that the two differ in the proportion of cars 5 years or younger (52% and 68%, respectively) and older than 10 years (16% and 8%, respectively). The vehicles going for PUC tests are older than the actual fleet. Vehicles within one year of their registration are not required to get the PUC certification. Therefore, age distribution from PUC database should ideally be older than the actual fleet. In order to test this hypothesis, we utilized the registration numbers of cars and 2Ws, which were recorded during fuel station survey. In the online database of PUC centers, the registration numbers were entered to study their PUC certification history. From this, we determined whether a vehicle has undergone a PUC certification or not. Among the vehicles tested, only 73% of the cars and 50% of the 2Ws had their PUC test done at least once in the past year. Table 3 shows compliance rate of cars for different age categories. Younger cars have much lower compliance than older ones. This may be the reason for older fleet from PUC data than those from the fuel station surveys. Thus

Table 3
Age profile of cars based on the fuel station surveys, by vehicles PUC certificate compliance.

Age bins (years)	Percent without PUC	Total observations in age category
0–2	50	165
3–5	28	355
6–10	16	255
11–15	9	76
15+	0	7
All age	100	858

the age distribution estimated from fuel station surveys appears to be a more reliable than PUC database.

We ascertained the proportion of vehicles with PUC certification using another survey, where registration numbers of 100 cars and 100 2Ws were randomly noted at an intersection of two major arterials in south Delhi. Only 70% of cars and 51% of 2Ws had their PUC test done at least once in 2011, which is similar to those from the fuel station surveys. This also shows that vehicles surveyed at fuel stations are representative of the on-road fleet.

3.2. Estimation of in-use vehicle fleet

3.2.1. From PUC data

From PUC database we have total number of cars and 2Ws which were tested at different centers in Delhi. Since vehicles are required to undergo pollution check four times in a year, total number of tested vehicles is more than the number of unique vehicles which had undergone pollution check. Using the average number of times each vehicle undergoes pollution check in a year, we can estimate the number of unique vehicles tested at PUC centers as:

$$\mathrm{N}_{i,\mathrm{test,unique}} = \frac{\mathrm{N}_{i,\mathrm{test,all}}}{\mathrm{f}_{i,\mathrm{test}}} \tag{4}$$

where, f_i, test is the average number of times a vehicle of type i (cars/2Ws) goes for pollution check per year, N_i, test, all is the total number of vehicle type i tested and N_i, test, unique is the total number of unique vehicles tested in the reference year.

From the fuel station survey, using the registration numbers of a sample of 858 cars and 437 2Ws, we checked their PUC certification history from online portal of PUC database. Among the passenger cars, only 16% appeared for tests 4 times per year (as per the requirement), while the rest appeared fewer than 4 times. The overall average is 2.1 times per year. Among 2Ws, only 14% appeared 4 times a year, with an overall average of 2.4 times per year. In 2011, a total of 2,068,500 cars were tested at different PUC centers in Delhi. Assuming that number of times vehicles visit pollution check centers remains same for 2011 and 2012 (year when survey was conducted), for an average frequency of 2.1 times per car, total number of unique cars tested at PUC centers is 985,000. We established from the surveys that only 73% of the total on-road cars go for pollution check at-least once in a year. Using this, total number of in-use vehicles can be expressed as:

$$\mathrm{N}_{i,\mathrm{in-use}} = \frac{\mathrm{N}_{i,\mathrm{test,unique}}}{\phi_{i,\mathrm{compliance}}} \tag{5}$$

And the proportion of total registered vehicles on-road and in-use can be expressed as:

$$\alpha_{i,\mathrm{in-use}} = \frac{\mathrm{N}_{i,\mathrm{in-use}}}{\mathrm{N}_{i,\mathrm{total}}} \tag{6}$$

where, N_i, in – use as the total number of in-use vehicles in the reference year, Φ_i, compliance (73%) is the proportion of total on-road vehicles with at least one PUC certificate each year and $\mathrm{N}_{\mathrm{total}}$ is the total number registered vehicles up to the reference year.

According to the official number provided by the Transport Department of Delhi, the total number of cars and 2Ws registered in Delhi at the end of year 2011 is 2,300,000 and 4,600,000, respectively. This resulted in 59% of the registered cars and 42% of the registered 2Ws as on-road and in-use in 2011.

For all the cars undergoing the PUC tests, the database by month also provides classification by three fuel types – petrol, non-petrol (CNG/LPG), and diesel. We extracted this information from 2009 to 2012 and four year average fuel mix is 63%-petrol, 15%-diesel, and 22%-CNG/LPG cars. The fraction of LPG vehicles is less than 0.5%. For this analysis, we assumed that the fuel mix of cars from the PUC data is a representation of the fuel mix for overall car fleet in the city. This is possible if the compliance rate of PUC test does not vary by fuel of the vehicle.

3.2.2. Using age-profile from fuel station surveys

Using the number of vehicles registered in the last five years (2007 through 2012) and the proportion of vehicles within 5 years of age, total number of in-use vehicles can be expressed as:

$$\mathrm{N}_{i,\mathrm{in-use}} = \frac{\sum_{k=2007}^{2012} \mathrm{VehReg}_{i,k}}{\mathrm{f}_{i,5}} \tag{7}$$

where $\mathrm{VehReg}_{i,k}$ is the number of vehicle type i registered in year k and $\mathrm{f}_{i,5}$ the proportion of vehicles within 5 years of age. An important piece of information required, besides the age profile from the surveys (Table 2), is the number of the vehicles registered on an annual basis and we assume that all the vehicles younger than 5 years are in-use.

From the fuel station surveys, we estimate 68% ($\mathrm{f}_{\mathrm{car},5}$ of cars are 5 years or younger. Now, total number of vehicles registered in the previous 5 years (2007 through 2012) is 826,500 ($\sum_{k=2007}^{2012}\mathrm{VehReg}_{i,k}$). This indicates that the total number of in-use cars is 1,215,500 ($\mathrm{N}_{\mathrm{car,in-use}}$), which is 51% ($\alpha_{\mathrm{car,in-use}}$) of the total registered cars in 2012. From the fuel station surveys, there are 71% ($\mathrm{f}_{2\mathrm{W},5}$) of the 2Ws within an age of 5 years and total registered 2Ws in the previous 5 years – 1,479,000. Thus, total in-use 2Ws are estimated to be 45% ($\alpha_{2\mathrm{W,in-use}}$) of the total registered 2Ws. Note that the number of in-use vehicles using this method may be an overestimate as it assumes that all the vehicles registered within previous 5 years are in-use which may not be the case.

3.3. Vehicle survival function

For modeling the survival rates, we use the Weibull distribution based survival function as described by Baidya and Borken-Kleefeld (2009) for modeling age distribution of vehicles in India, based on their likely retirement. The survival function is given as:

$$S_{i,k} = exp\left[-\left(\frac{k+\mathrm{a}_i}{T_i}\right)^{\mathrm{b}_i}\right] \tag{8}$$

where, k is the age of the vehicles, S_k is the probability of survival of vehicle type i at age k, T_i is the characteristic service life of the vehicle and a/b are the failure steepness. The model was introduced by Zachariadis et al. (1995, 2001) for European settings. We utilized the data from the PUC centers and the fuel station surveys to estimate these parameters (b and T). We found that using this survival function, no combination of parameters was able to obtain age distribution as well as the proportion of in-use vehicles. Therefore, we used log–logistic survival function for which the survival function is given as:

$$S_{i,k} = \left[1+\left(\frac{k}{\mathrm{a}_i}\right)^{\mathrm{b}_i}\right]^{-1} \tag{9}$$

where a_i and b_i are the parameters of the distribution for vehicle type i. In order to estimate the parameters, we calculated in-use vehicles for each model year from the fuel station survey and compared it with the in-use vehicles estimated by the survival function. Number of in-use vehicles of type i from the survey sample for model year k ($n_{i,k,observed}$) is calculated as:

$$n_{i,k,observed} = \alpha_{i,\mathrm{in-use}} \times \mathrm{f}_{i,k} \times \mathrm{N}_{i,\mathrm{total}} \tag{10}$$

where subscript *observed* is used for survey data, f_i, k the proportion of vehicles from the survey sample for model year k, $\alpha_{\mathrm{in-use}}$ the proportion for in-use vehicles and N_i, total is the total number of registered vehicles till year 2012 and using survival function, number of vehicles for each model year is

$$n_{i,k,model} = S_{i,k} \times VehReg_k \tag{11}$$

where, $n_{i,k,model}$ is the number of in-use vehicles and $VehReg_k$ is the number of vehicles registered in age category k and subscript 2012 indicates the reference year for age of vehicles. In order to estimate the parameters for the distribution, we used Solver application of Microsoft Excel with an objective function to minimize the square of difference between the observed and modeled number of in-use vehicles as:

$$\mathrm{Min}\sum_{k=1}^{T}\left(n_{i,k,observed} - n_{i,k,model}\right)^2 \tag{12}$$

Using this, we obtained $a_{car} = 8.38$ and $b_{car} = 3.76$ for cars $a_{2W} = 7.50$ and $b_{2W} = 3.20$ for 2Ws and the corresponding plots of the survival functions are shown in Fig. 3. Using the modeled in-use vehicle estimates for each year, we can estimate total number of in-use vehicles as:

$$N_{i,2012} = \sum_{k=1}^{n}(n_{i,k,model}) \tag{13}$$

and the age distribution of vehicles as:

$$f_k = \frac{n_{k,2012}}{N_{i,2012}} \tag{14}$$

where, f_k is the proportion of number of in-use vehicles in age category k. The age distribution of cars after applying the survival function with obtained parameters is 64% (0–5 years), 28% (6–10) and 8% (>10) with an average age of 4.99 years. The similar method for 2Ws gives an age distribution of 70% (0–5 years), 24% (6–10) and 6% (>10) with an average age of 4.5 years. An example calculation of in-use 2Ws using the estimated parameters of log–logistic survival function is presented in the Supplementary material.

3.4. On-road vehicle mileage

The on-road vehicle activity is defined as the vehicle kilometers traveled on a daily or on an annual basis. In Fig. 4, we present the variation in the annual mileage based on the odometer readings collected from the fuel station survey for cars and 2Ws, along with the lower and upper bounds for 95% confidence intervals (CI). The overall average for cars is 12,200 ± 450 km and for 2Ws is 12,800 ± 350 km. Segregating by fuel use, diesel cars have an annual mileage of 15,400 km and petrol cars have an annual mileage of 11,600 km.

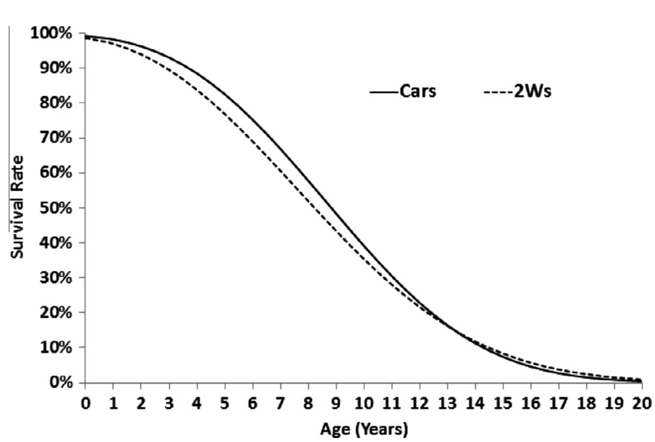

Fig. 3. Vehicle on-road survival functions for cars and 2Ws using log-logistic distribution for Delhi.

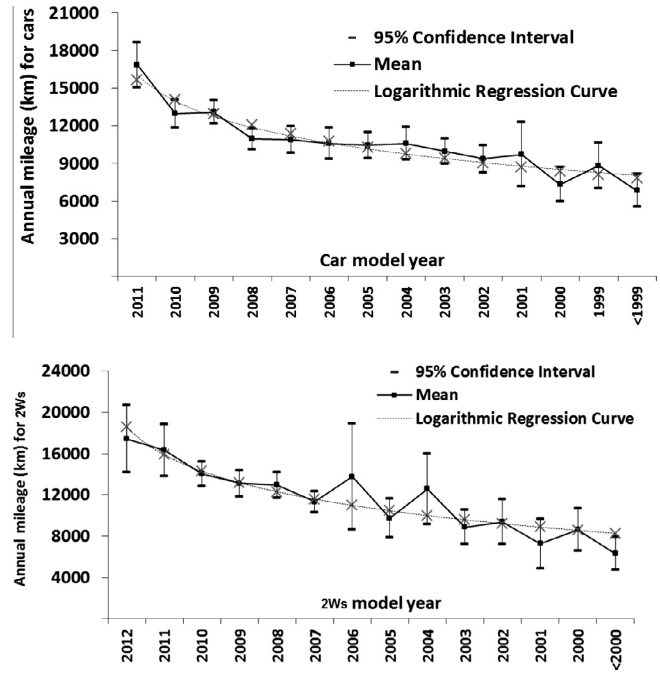

Fig. 4. Annual mileage of cars ($n = 2220$) and 2Ws ($n = 1565$) based on the fuel station surveys in Delhi.

In order to model the relationship between the total mileage and the age of vehicle, we fitted various non-linear curves. For cars and 2Ws, we found that a log–log relationship suits best. Since the variance explained by such models is very low given the spread of values for each model year, we fitted a logarithmic function for the average values of annual mileage corresponding to each model year. As shown in Fig. 4, the model also helps in smoothing the data. The models for cars and 2Ws explain a variance of ~90% and ~83%, respectively and are given as:

$$MAnnualAvg_{Cars,k} = -3873\ln(k) + 18315 \tag{15}$$

$$MAnnuaAvg_{2Ws,k} = -3915\ln(k) + 18602 \tag{16}$$

where $MAnnualAvg_{Cars,k}$ and $MAnnualAvg_{2Ws,k}$ are annual average mileage (in km) of cars and 2Ws, respectively and k = (2012-Model year +1). For both cars as well as 2Ws, annual mileage reduces by 27%, 42% and 52% after 5 years, 10 years and 15 years, respectively with a reference model year of 2011. Using odometer readings of second hand cars reported for sale on the internet, overall average (excluding 2012 models) is 10,750 ± 200 km. Also, the drop in annual mileage with increasing age is a linear trend with steep slope compared to non-linear form for cars in fuel-station surveys.

In the fuel station surveys, we did not interview bus and 3W drivers. The information for buses from the GPS units, in terms of speed and hours of operation, can be used to calculate daily and annual average VKT. The average operating speed for the buses was 15 km/h and the buses operate on average 13 h a day (excluding time spent at terminals and depots), which translates into an average of 195 km per day (71,175 km per annum).

For 3Ws, we interviewed 200 drivers and recorded average distance travelled per day. While some of the drivers were able to answer this question, most could not. In those cases, we asked the drivers how often they filled CNG gas and the quantity. Using this information and using fuel efficiency of a 3W, daily mileage of 3Ws was estimated to be 150 km.

Table 4
Fuel efficiency of vehicles based on the fuel station surveys in Delhi.

Type of vehicle	Lower range (km/L)	Sample size	Upper range (km/L)	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

3.5. Fuel efficiency

During the fuel station surveys, the drivers were asked to report their observed km per unit fuel. Most drivers reported a lower and upper bound. Some respondents mentioned that fuel efficiency depended on whether they were operating the air-conditioner (AC) or not and hence there is a lower bound and upper bound.

Among the cars, the fuel efficiency values were classified among diesel and petrol vehicles. For diesel cars, 40% have engine displacement greater than 1600 cm^3 which consisted mainly of sports utility vehicles (SUVs). Therefore, diesel cars were further segregated into two categories based on their engine displacement as ⩽1600 cm^3 and >1600 cm^3. In case of petrol cars, the proportion of cars with engine displacement greater than 1600 cm^3 is less than 0.5 percent. Table 4 shows the average values of fuel efficiency for different vehicle types with their respective lower and upper bound. When segregated by engine displacement, fuel efficiency of diesel cars with engine displacement less than 1600 cm^3 have higher efficiency than the ones with engine displacement greater than 1600 cm^3 (16.1 and 14.0 km/L, respectively). An overall average of all the diesel cars (all engine sizes) is even lesser than their petrol counterparts (10.8 and 15.3 km/L, respectively).

Central Institute of Road Transport (CIRT, 2011) publishes annual profile and performance statistics for buses operated by government-run state transport undertakings (STUs). For CNG buses operated by Delhi Transport Corporation, CIRT reports a fuel efficiency of 2.9 km/litres. Reynolds et al. (2011) estimated average fuel efficiency of a sample of in-use, 4-stroke and 2-stroke CNG-based 3Ws in Delhi as 48 km/kg and 40 km/kg, respectively.

3.6. Vehicle speeds and idling rates

The GPS data from the cars, buses, 2Ws, and 3Ws was mapped and analyzed for speed variation over time and space in Delhi. For each vehicle category, the total number of kilometers is spread across the city – over multiple road types and multiple hours. From the instantaneous speed data from the GPS logs, we separated the period of time when the vehicle speed was less than 4 km/h. We designated this speed limit as the upper limit for idling – under which is considered an average walking speed. The diurnal variation of speeds for buses and cars is presented in Fig. 5. Similar plots

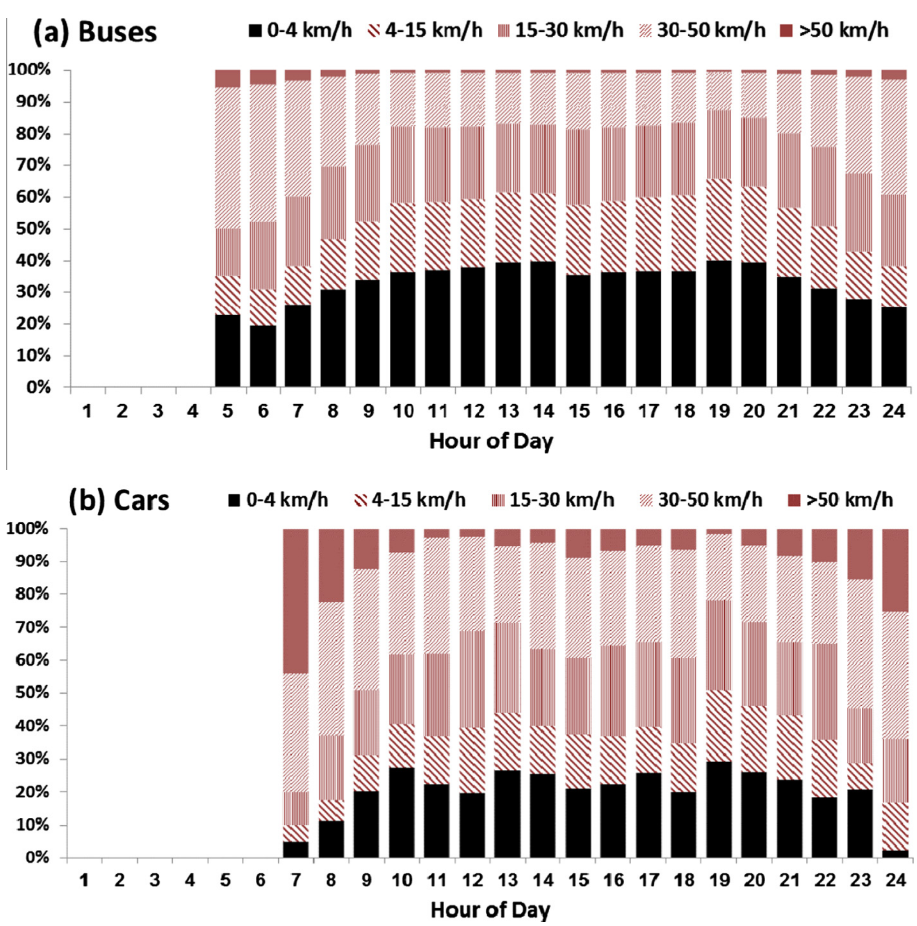

Fig. 5. Diurnal variation of vehicular speed in Delhi and its satellite cities in 2012 for (a) buses and (b) cars.

Table 5
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
Total	100	100	100	100

for 3Ws and 2Ws are not presented here since their smaller sample size in terms of number of hours of travel time within each hour of day does not allow for disaggregated representation.

The daily average speeds are summarized in Table 5 – from 8 AM to 10 PM, for buses, cars, 3Ws, and 2Ws with 15 km/h, 21 km/h, 22 km/h, and 25 km/h, respectively. The average hourly speeds were also recorded. The cars followed the hourly average trend for buses, with on an average 50% higher speed. The speeds for the 3Ws and 2Ws are better, mostly because of their nature to maneuver better through congested traffic. For the on-road conditions in Delhi, we measured 24%, 18%, 20%, and 37% of the driving time as idling for cars, 3Ws, 2Ws, and buses, respectively. In case of buses, the idling time includes the time spent at the bus stops. We find that the idling conditions are high, in spite of grade-separated junctions along most of the major arterial roads in Delhi.

In order to analyze the spatial distribution of speeds, we subdivided the area covered during the GPS mapping into 500 m × 500 m grids. For every grid, average speed value was obtained from 8 AM to 10 PM. The speed values were assigned to the grids, depending on the latitude and longitude information from the GPS units and averaged to present a spatial map for the city. For this we used speed data for buses. The average speeds of grids varied from as low as 0.31 km/h to as high as 66 km/h, with more than 50% of the grids with an average speed of 20 km/h or lower, 78% with 30 km/h or lower, and 99% with 50 km/h or lower. The spatial map as well as the distribution of the speeds over the grids is presented in Fig. 6. The distribution highlights the high variation of speed that occurs in the city. Most grids averaged within 15–20 km/h. Clearly, average speeds of buses have a strong spatial dependence due to location of the bus stops, and idling in traffic along the congested corridors.

4. Discussions

4.1. Age profile of vehicles

Age distribution of cars and 2Ws in Delhi shows that more than two-thirds of the vehicles are less than 5 years old and almost all the vehicles are within 15 years of age. This is a result of high growth rate of vehicles sold in the city. For another setting in India-Pune (2011 population-5 million), Barth et al. (2007) reported an average age of 4.6 years for passenger cars, for year 2003. The age distribution of vehicular fleet in Indian settings 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, respectively (ACEA, 2010; USDOT, 2009), which is more than four times the proportion in Delhi.

4.2. Vehicle survival functions

Using the survival function for cars and 2 Ws, we simulated the replacement of car and 2W fleet from year 2012 to 2035 (see Fig. 7). Assuming 7% year-on-year increase in the annual vehicle registration till 2020, and subsequently tapered down growth rate of 6% from 2021 through 2025, 5% from 2026 to 2030, 4% from 2031 to 2035, we estimated that 90% of the existing car fleet in

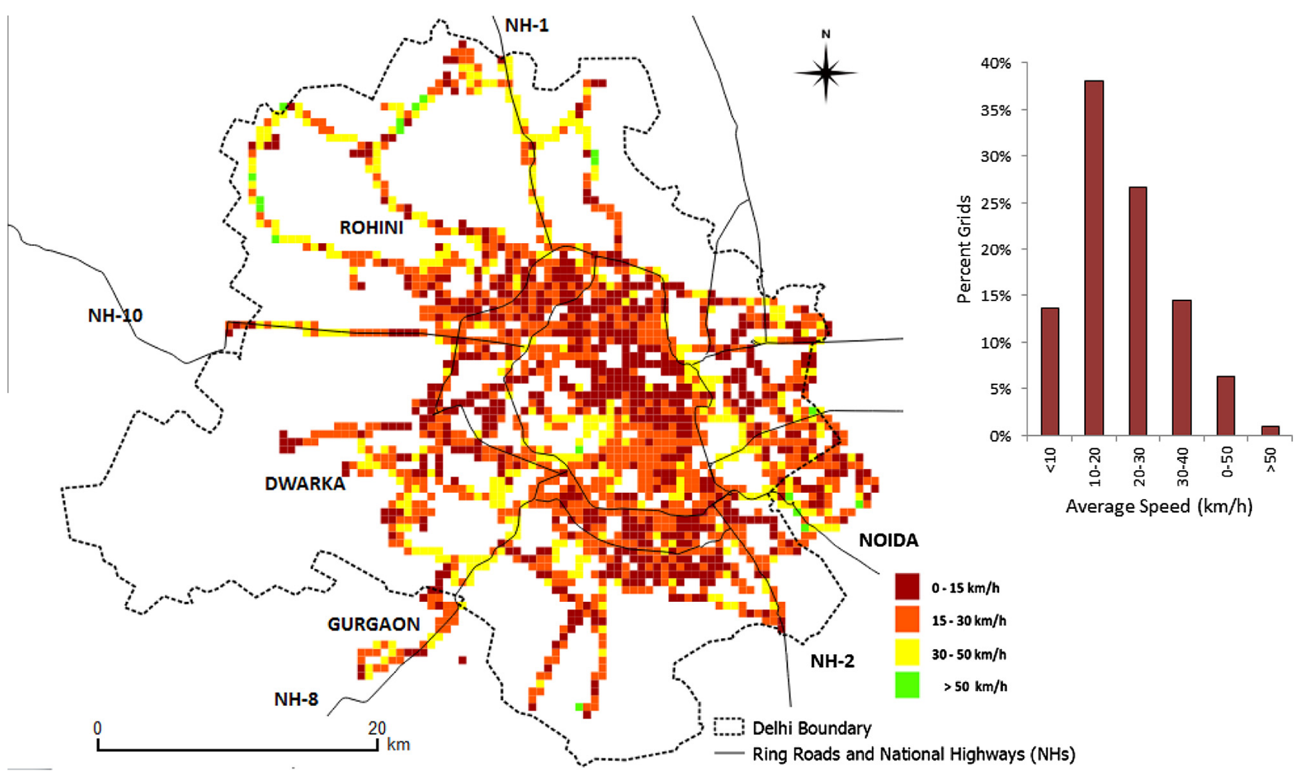

Fig. 6. Spatial variation of bus speed between 8 AM and 9 PM in Delhi in November, 2012.

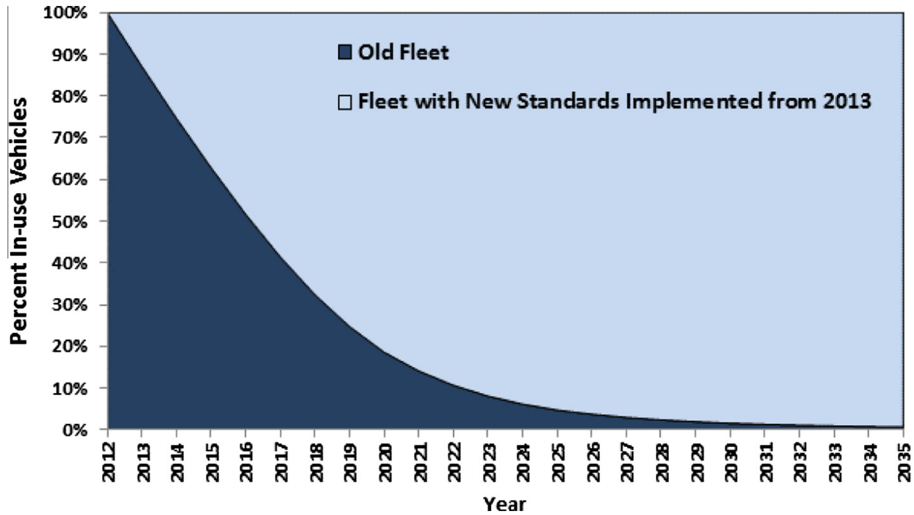

Fig. 7. Fraction of in-use cars with new standards implemented in 2013.

year 2012 will be retired by year 2023, and complete replacement will occur by year 2035. In other words, if new standards are implemented in year 2013, 90% of the fleet will follow those standards over a period of next 10 years. Therefore, early introduction of stricter standards for emissions and safety, and better infrastructure in the cities to reduce the deterioration of the engine, will have a much greater effect in a shorter time in India.

Combined with the highest per capita income (DES, 2013) and one of the highest car ownerships in the country, propensity for early replacement of vehicles is also the highest in Delhi. Hence,

Table 6
Reported annual mileage for cars, buses, and utility vehicles from various countries.

City/Country	Mileage (km/year)	Year	Notes	Source
Delhi, India	12,200	2012	All cars	This study
Great Britain	13,202	2012	All cars	DOT (2013)
France	13,250	2005	All cars	Schipper (2008)
Germany	12,550	2005	All cars	Schipper (2008)
Denmark	18,262	2005	All cars	Papagiannaki and Diakoulaki (2009)
Singapore	19,000	2010	All cars	LTA (2012)
New Zealand	12,500	2002	All cars	Gleisner and Weaver (2006)
USA	17,040	2010	All LDVs	FHWA (2010)
Chengdu, China	15,200	2009	All cars	Huo et al. (2012a)
Chongqing, China	27,000	2004	All cars	Huo et al. (2012a)
Yichang, China	25,200	2010	All cars	Huo et al. (2012a)
Beijing, China	17,500	2008	All cars	Huo et al. (2012a)
Foshan, China	22,000	2009	All cars	Huo et al. (2012a)
Tianjin, China	20,300	2006	All cars	Huo et al. (2012a)
Shanghai, China	20,000	2004	All cars	Huo et al. (2012a)
Shanghai, China	43,800–47,450	2004	Public buses	Huo et al. (2012a)
Tianjin, China	77,015	2009	Public buses	Huo et al. (2012a)
Foshan, China	107,675	2009	Public buses	Huo et al. (2012a)
Ontario, Canada	16,000	2008	LDVs	NRC (2010)
Nova Scotia, Canada	16,600	2008	LDVs	NRC (2010)
British Columbia, Canada	13,100	2008	LDVs	NRC (2010)

Table 7
Reported fuel efficiency for cars from various countries.

Country	Vehicle type	Fuel efficiency (km/L)	Year	Reference
Delhi, India	Petrol cars	15.3–16.2	2012	This study
Delhi, India	Diesel cars	14–15.3	2012	This study
China	Petrol cars	9.96	2009	Huo et al. (2012b)
China	Diesel cars	8.4	2009	Huo et al. (2012b)
Denmark	Petrol cars	12.7	2005	Papagiannaki and Diakoulaki (2009)
Denmark	Diesel cars	15.2	2005	Papagiannaki and Diakoulaki (2009)
France	All cars	13.3	2005	Schipper (2008)
Germany	All cars	12.5	2005	Schipper (2008)
Greece	Petrol cars	13.3	2005	Papagiannaki and Diakoulaki (2009)
Greece	Diesel cars	13.0	2005	Papagiannaki and Diakoulaki (2009)
Japan	All cars	9.5	2005	Schipper (2008)
Great Britain	All cars	13.0	2005	Schipper (2008)
United States	All cars	9.1	2005	Schipper (2008)

Table 8
Fuel wastage under idling conditions on the roads of Delhi.

	Cars	3Ws	Buses	2Ws
Registered fleet size	2,300,000	70,000	7000	4,600,000
Vehicles in-use per day (% total)	60	100	80	45
Average speed (km/h)	21	22	15	25
Average distance covered per day (km)	33	150	200	33
idling per day (% travel time)	24	18	37	20
Estimated time idling per day (min)	22	74	300	16
Fuel used in idling (L/day)	250,000	43,000	70,000	180,000

the observed travel and owner behavior in Delhi would therefore be different from that in smaller cities. Given that, the survival functions established in this study are applicable only for Delhi and not a representation for other Indian cities or India as a whole. Thus, there is a need for similar exercises in other cities, to ensure consistency among the distribution parameters. The methodology is being replicated in the cities of Rajkot, Vishakhapatnam, and Udaipur.

4.3. On-road vehicle mileage

The annual distances travelled by cars and 2Ws show a decreasing trend with increasing age and the rate of reduction is similar for both vehicle types. The reduction of annual distance with increasing age of vehicles was also observed in other cities and countries, for instance, in EU (Van Wee et al., 2000; Zachariadis et al., 2001), the United States (ORNL, 2011), China (Huo et al., 2012a,b), Japan (Nishimura, 2011) and New Zealand (MOT, 2011). It is observed that the rate of reduction of annual mileage with increasing age of cars varies significantly from country to country. However, Huo et al. (2012a) and Van Wee et al. (2000) both show that annual distance reduces by more than 50% after 10 years which is similar to our finding for cars. Van Wee et al. (2000) hypothesized that those with older cars, foreseeing more use of their vehicle in the near future tend to buy newer ones which are more comfortable and energy-efficient. In addition, being more fuel-efficient and less costly per kilometer driven, newer cars tend to be driven even more.

The annual mileage of cars and buses from various country and city level are presented in Table 6. Since country level estimates include cities of all dimensions, they are likely to be much lower than city level estimates in major cities. In spite of that, annual mileage estimates of Delhi from this study are the lowest compared to country level estimates of high income countries and major cities of China and Canada.

4.4. Fuel efficiency

The on-road fuel efficiency values from various countries are presented in Table 7, which shows that the fuel efficiency for Delhi fleet is among the highest. The values in the table are on-road measurements and not laboratory estimates. Earlier research have highlighted the difference between the two, with on-road values being up to 25% lower than the laboratory values, due to difference in the real world driving cycles (Schipper and Tax, 1994; Zachariadis, 2006; Huo et al., 2012a). A major factor responsible

Table 9
Fleet average emission factors for year 2012 in the greater Delhi region.

Mode	$PM_{2.5}$ (g/km)	NO_x (g/km)	CO (g/km)	VOC (g/km)	FE (km/L)
Petrol					
4W1	0.057 ± 0.215	0.243 ± 2.038	3.595 ± 20.22	0.469 ± 2.898	15.48 ± 3.449
4W2	0.120 ± 0.272	0.375 ± 0.402	8.552 ± 33.52	0.867 ± 4.171	15.11 ± 3.495
2W2S	0.125 ± 0.256	0.085 ± 0.024	2.027 ± 12.49	2.049 ± 3.739	51.45 ± 8.631
2W4S	0.025 ± 0.051	0.389 ± 0.192	2.070 ± 2.644	0.455 ± 0.789	57.69 ± 11.10
3W2S	0.107 ± 0.131	0.327 ± 0.408	2.958 ± 23.72	5.137 ± 11.93	19.26 ± 4.355
3W4S	0.024 ± 0.174	0.687 ± 0.972	2.916 ± 23.74	1.858 ± 4.329	22.15 ± 5.008
TAXI	0.118 ± 0.311	0.240 ± 0.443	8.467 ± 37.36	0.800 ± 4.642	12.48 ± 2.961
LDT	0.324 ± 0.622	1.672 ± 1.944	22.24 ± 74.72	2.456 ± 9.284	5.622 ± 1.134
Diesel					
4W1	0.194 ± 1.129	0.653 ± 1.825	2.244 ± 29.67	0.547 ± 4.610	17.80 ± 3.967
4W2	0.418 ± 1.459	1.160 ± 1.981	5.530 ± 49.44	1.026 ± 6.161	15.12 ± 2.888
3W2S	0.411 ± 0.778	1.450 ± 2.370	3.112 ± 23.53	0.954 ± 20.30	22.15 ± 5.008
3W4S	0.411 ± 0.778	1.740 ± 2.844	3.112 ± 23.53	0.952 ± 6.859	25.47 ± 5.759
TAXI	0.388 ± 1.666	1.202 ± 2.218	5.234 ± 55.00	0.981 ± 6.859	14.35 ± 3.406
BUS	2.753 ± 7.538	21.23 ± 46.65	11.92 ± 73.68	3.311 ± 17.20	3.124 ± 0.667
HDT	4.343 ± 7.538	28.34 ± 46.65	17.40 ± 73.68	4.428 ± 17.20	2.987 ± 0.667
LDT	2.435 ± 3.769	16.43 ± 29.29	10.34 ± 26.05	2.385 ± 7.594	5.622 ± 1.134
OTH	4.870 ± 7.538	31.04 ± 46.65	19.84 ± 73.68	4.928 ± 17.20	2.939 ± 0.667
CNG					
4W1	0.019 ± 0.112	0.199 ± 2.057	3.605 ± 20.22	0.472 ± 2.898	15.45 ± 3.449
4W2	0.042 ± 0.145	1.163 ± 1.981	8.582 ± 33.52	0.872 ± 4.171	15.08 ± 3.495
3W2S	0.041 ± 0.077	2.916 ± 4.741	2.966 ± 23.72	5.150 ± 11.93	19.20 ± 4.355
3W4S	0.041 ± 0.077	4.374 ± 7.112	2.924 ± 23.74	1.863 ± 4.329	22.08 ± 5.008
TAXI	0.039 ± 0.166	1.206 ± 2.218	8.499 ± 37.36	0.805 ± 4.642	12.45 ± 2.961
BUS	0.184 ± 0.502	25.58 ± 55.98	11.97 ± 73.68	3.323 ± 17.20	3.118 ± 0.667
LDT	0.244 ± 0.376	24.72 ± 43.94	10.36 ± 26.05	2.391 ± 7.594	5.616 ± 1.134
OTH	0.489 ± 0.753	46.73 ± 69.98	19.92 ± 73.68	4.944 ± 17.20	-

Note: 4W2 are the multi-utility vehicles and 4W1 are the remaining cars, jeeps, and vans; 2S is 2-stroke and 4S is 4-stroke vehicles.

for higher fuel efficiency of the car fleet is the share of small cars (IEA, 2011). For instance, in 2008, in India, 70% of cars were in the small size segment compared to ∼25% for global fleet. India also has the highest share (∼60%) of cars with engine displacement less than 1200 cm^3 and has the lowest average weight (<1000 kg). In addition to vehicle specifications (size and weight) which can be compared using vehicles sales data, the role of other factors affecting fuel economy of an urban fleet across countries such as speed distribution, congestion levels, and accessory use such as air-conditioning is largely unexplored (Schipper, 2008).

4.5. Vehicle speeds and idling rates

The average speeds observed in Delhi are also reported from other major cities in the world. Between 7 AM and 7 PM, the average speed in overall London is 29 km/h and in central London, where the congestion pricing is implemented, is 14 km/h (TFL, 2011). A large scale speed instrumentation campaign in Europe showed that overall average speed of cars is 20 km/h in the urban areas, with stopping time varying from 20% to 60% during daily congestion periods (Andre, 2000). The arterial roads in Beijing also have an average speed of 21 km/h with an idling proportion of 20% (Wang et al., 2008).

In Delhi, for more than a million cars in-use, 24% of idling can lead to a substantial amount of fuel loss, additional emissions, and additional air pollution levels on the road. The annual average mileage of 12,200 km for cars means a daily distance of 33 km. For an on-road speed of 21 km/h, this translates to 1.5 h of average daily travel time, of which 22 min are spent idling (24% of total travel time). This resulted in 250,000 L of fuel per day consumed for idling (assuming that a car can idle up to 2 h/L of petrol or diesel). For similar calculations, for 2Ws, buses, and 3Ws, idling accounts for 180,000 L, 70,000 L, and 43,000 L per day, respectively, for year 2012 (Table 8).

The Transport Department has recently included GPS logging for all 3Ws and all the vehicles are under transition to install the new equipment. In the coming years, we are hoping that similar to the buses, this data will be available for mapping and analysis.

4.6. Emission rates

After the activity data, the most important vehicle characteristic is the pollutant emission rate. Ideally, a series of emission factor tests conducted on a variety of vehicles, sampled by age and make, on a chassis dynamometer will present a database of emission factors for the on-road fleet. The Automotive Research Association of India, using the Indian driving cycle, conducted a series of these tests, as part of the multi-city particulate pollution source apportionment under the MoEF. The results were utilized for establishing total emissions analysis for Delhi, Pune, Chennai, Kanpur, Mumbai, and Bangalore (CPCB, 2010). A summary of time series of emission standards for $PM_{2.5}$, NO_x and CO is presented in Supplementary material and a summary of the derived emission factors for the in-use fleet in Delhi for 2012 and a likely fleet till 2030 is presented in Table 9. In the context of dynamic vehicle standards, age of vehicles (or model year), and survival functions are important determinants of fleet average emission factors. We did not vary the survival functions for the future years, which is also a likely scenario. With improvements in the vehicle technology and road infrastructure to reduce the wear and tear on the engines, the likeliness of vehicles surviving longer, as seen in the United States and Europe, is very high.

From the PUC data, information is also available on the emission rate for CO. However, we cannot utilize these results, as they are based on free-acceleration tests conducted for compliance and do not include a full driving cycle. We have analyzed the data from the PUC dataset to understand the trends in the emission rates and possible deterioration rates. Fig. 8 presents the percent volume of CO emissions for cars (petrol and CNG) and 2Ws. There is a significant deterioration of exhaust emissions with increasing age. The higher emission values for cars older than 2001 is due to the implementation of Bharat Stage-II emission standards which mandated reduction of CO emissions from 3% to 0.5%. In case of 2Ws, CO emission standards were reduced from 4.5% to 3.5%. For model years 2010 through 2001, in ten years, CO emissions increase up to

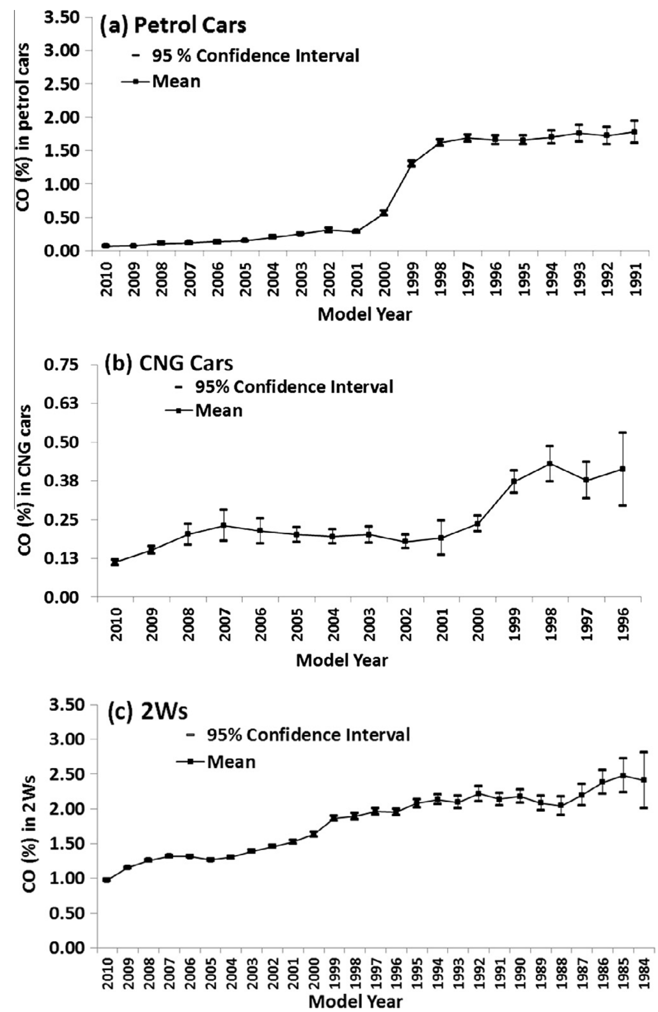

Fig. 8. Amount of CO (% volume) in the vehicle exhaust during idling from PUC database for (a) petrol cars (n = 188,304), (b) CNG cars (n = 32,857) and (c) 2Ws (n = 326,119) in Delhi.

Table 10
Data items and their correspondence with ASIF methodology.

Data	Data source	ASIF parameter
Number of In-use vehicles	PUC	A
Emission factor deterioration rates	PUC	F
Age distribution	PUC	F
Idling emission factors	PUC	F
Classification of vehicles by fuel type	PUC	S
Age distribution	Fuel station survey	F
Annual mileage	Fuel station survey	A
Fuel efficiency	Fuel station survey	I
Annual mileage	Used car sales data	A
Temporal and spatial distribution of speed	Speed survey	F

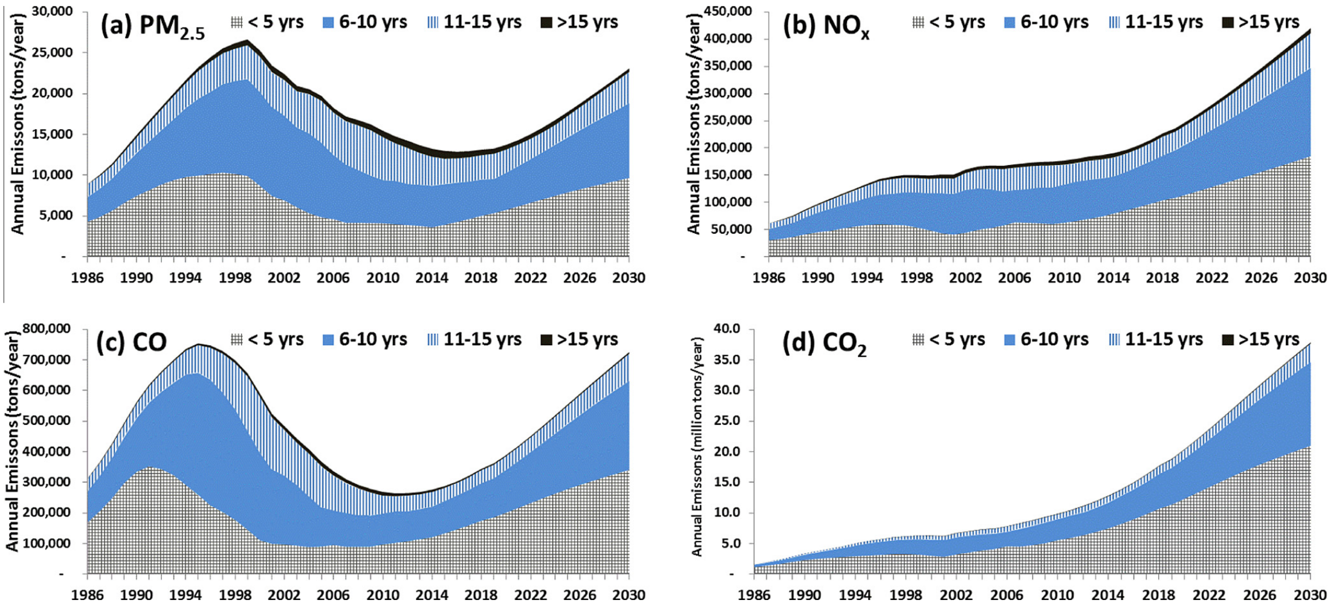

Fig. 9. Estimated annual on-road emissions in the Greater Delhi region by age group for (a) $PM_{2.5}$ (b) NO_x (c) CO and (d) CO_2.

~4 times at an average of 18% per year for petrol cars. For pre-Bharat Stage-II years, from 1998 through 1989, the rate of deterioration is 3% per year. For CNG cars, the increase is up to 1.7 times at an average rate of 7% per year. For motorcycles, from 2010 through 2001 it increases by 1.6 times with an average of 5% per year and in the subsequent years with an average of 3% per year. A similar graph for diesel cars is not possible, since their PUC test measures smoke units (Hartridge Smoke Units) and not CO emission rate.

The on-road driving speed has a significant effect on emission factors – for the moving and idling emission estimates. Many studies have shown a non-linear relationship of vehicular speed with emission factors (Krawack, 1993; Hansen et al., 1995; Jensen, 1995; Sturm et al., 1996; Ntziachristos and Samaras, 2000; Tong et al., 2000; Kean et al., 2003; Smit et al., 2008; Barth and Boriboonsomsin, 2009). Grieshop et al. (2012) looked at the variation of the emission rates with speed for the 3Ws in Delhi, and also developed a correlation for estimating possible average emission rates for 3Ws with changing driving cycle. While speed of vehicles in urban areas has temporal variations, there are also significant variations over space. For instance, sub-urban arterial roads will have much higher speed than those in commercial areas. Andre (2000) highlighted that in Europe, use of a single value of average travel speed could lead to emission estimates which differ up to 100% from the estimates obtained using a speed distribution function.

The age mix of the fleet is important for determining the fleet average emission rates for the city. Firstly, as vehicles become older, their emission behavior deteriorates (Anilovich and Hakkert, 1996; Singer and Harley, 2000; Van Wee et al., 2000; Guo et al., 2006) due to aging of catalytic converters and deterioration of emission control system of the vehicles (Zachariadis et al., 2001) in addition to other factors, such as road and driving conditions in the city. Secondly, change in technology over years makes new vehicles less polluting than their older counterparts. For instance, during last one decade, three exhaust emission standards have been introduced in India. These are – Bharat Stage II, Stage III and Stage IV (Indian counterparts of Euro II, III and IV) mandated from 2003, 2005 and 2010 onwards, respectively. This implies that vehicles bought during this decade will have varying emission factors for different years (Fig. 8).

4.7. Total emissions

The survey methods and data resources discussed in this paper help address the parameters linked to a typical emissions inventory methodology. Table 10 shows their correspondence to the parameters in ASIF methodology. Based on the parameters reported, results from an example calculation of the total emissions for $PM_{2.5}$, CO, NO_x, and CO_2, segregated by age bins, are presented in Fig. 9. The emission totals are for four age groups – vehicles <5 years, 6 to 10 years, 11 to 15 years, and >15 years. These are totals from calculations for six major categories of vehicles – all 4-wheelers, 2-wheelers, 3-wheelers, buses, heavy duty vehicles, and light-duty vehicles, for calculations performed for the period of 1990 to 2030. More details on the trends and evolution of the total emissions with technology and emission standards in Delhi are presented in Goel and Guttikunda (2014). In case of Delhi, there are stricter retirement regulations than the rest of the country, especially for the commercial sector – 3Ws, Taxis, heavy duty vehicles, and light duty vehicles. 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. There are deliberations to mandate 8 year retirement for buses, 3Ws, and Taxis; and stricter regulations for heavy duty and light duty vehicles, following pollution checks. 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%, 9%, and 10% in 1990 to 37%, 23%, 22%, and 23% in 2012, respectively. A summary of emission totals for the period of 1990 to 2012 is attached is the Supplementary material.

The study shows that car and 2W fleet in Delhi is one of the youngest, has one of the highest fuel efficiency values, and is driven for a shorter distance annually, compared to the other large cities in the world. While the lesser vehicular usage value helps in reducing energy consumption, this is less likely to have a significant impact on total emissions due to poor emission standards, higher number of vehicles, and increasing congestion on the roads. Internationally, India is lagging in settings fuel standards (Guttikunda and Mohan, 2014). Outside Asia, the European Union has adopted the ultra-low sulphur diesel (10 ppm) and the United

States has mandated sulphur content of 15 ppm. High sulphur content in the fuel leads to technology constraints for installing vehicle emission reduction technology (ICCT, 2013). Therefore, given the aforementioned vehicular usage parameters, Delhi (and India as a whole) needs to implement higher emission standards soon, in order to attain maximum emission reductions.

5. Implications

As the cities are growing every day in size and number and given how expensive it is to measure emissions for a dynamic on-road vehicle fleet (with mixed fuels, mixed engine sizes, and mixed technologies), there is no one appropriate method to estimate the emission loads on a road or for a city. The vehicle exhaust emissions are increasingly becoming the center of discussion for air pollution and climate change negotiations, which means, we need to better understand the vehicle and passenger characteristics of a city, in order to best estimate the total emission loads and how best we can address the emissions and pollution management questions.

The methods employed in benchmarking the vehicle and passenger travel characteristics in Delhi are simple and replicable. The response rates for the fuel station surveys are high, mainly because of a simple 5 point questionnaire, which the driver/owner can answer in less than 2 min, while they are filling tanks. Pollution checks are conducted in every Indian city. For replicating methods using PUC database, it is important to have a centralized and computerized database, so that the data can be used as discussed. Some cities with such online databases are Bengaluru and Mumbai. Other resources such as annual registration numbers can be obtained from the respective RTOs. We strongly feel that the exercises can be repeated and can be used to develop a dynamic passenger and vehicle characteristics map for other Indian cities and study the trends in total emissions.

In Delhi, the data collection exercises will continue to update each of the key parameters, such as on-road vehicle mix, age mix of the vehicles, annual mileage of the vehicles, on-road speeds of the vehicles, emission deterioration, and emission rates for various pollutants. In this paper, we primarily focused on the passenger vehicles and we will extend the methodology and analysis to the freight vehicles.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tbs.2014.10.001.

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