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Vehicle Stock Numbers and Survival Functions for On-road Exhaust Emissions Analysis in India: 1993-2018

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Highlights

1. Registered vehicle numbers for nine broad categories in India for 1993-2018.

2. An estimate of in-use vehicle numbers for nine broad categories in India.

3. Survival functions to estimate age-mix of the-use vehicle fleet.

4. Presentation of the fundamental equation and alternatives for vehicle exhaust emissions analysis.

Abstract: In air quality management, at urban and regional levels, road transport remains the cornerstone of residential, commercial, and industrial activities, and the vehicle exhaust emissions maintain the position of one of the key contributing sources. In Indian cities, big and small, vehicle exhaust emissions and dust from vehicle movement on the roads, contribute to as much as 50% of particulate matter pollution in a year. So, having access to a vehicle exhaust emissions inventory that is reliable and replicable is critical for air quality management and this exercise starts with access to vehicle stock numbers. These numbers are typically obtained from vehicle registration databases, traffic surveys, and other governmental records, and often require time consuming data cleaning protocols before they can used for emissions and pollution baseline analysis. This paper provides a cleaned and open-access vehicle stock database, as registered and in-use fleet, for the period covering 1993 and 2018, for all India and states, along with an estimate of age-mix of the vehicles using survival functions.

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1. Introduction

A clean air action plan for a city, a region, or a nation starts with having access to an accountable emissions inventory covering all the known sources. A typical inventory is calculated for aerosol species like particulate matter ($PM_{2.5}$, aerosols with aerodynamic size under 2.5 mm and PM_{10}, aerosols under 10 mm), black carbon (BC), and organic carbon (OC), and gaseous species like sulphur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and greenhouse gases (e.g., carbon dioxide - CO_2). The known sources of emissions range from burning of fuels, such as petrol, diesel, gas, coal, biomass and waste in the sectors such as road-rail-air-water transportation, industries, residential cooking and heating, and waste management to natural emissions in the form of sea salt, dust storms, lightning, and biogenic (Crippa *et al.*, 2023). Determining emission strengths of all these sources is a complex and challenging task (Fowler *et al.*, 2020), as it involves documenting in space and time the dynamic fuel usage patterns for anthropogenic sources and dynamic meteorology for natural sources; along with a demand for large

amounts of data from surveys and measurements (Li *et al.*, 2017; Venkataraman *et al.*, 2018b; Crippa *et al.*, 2020; McDuffie *et al.*, 2020; Crippa *et al.*, 2021; Solazzo *et al.*, 2021; Crippa *et al.*, 2023). Among all the listed sectors, road transport is likely the most complicated to establish an emissions inventory (Lekaki *et al.*, 2024). As this involves knowing not only how many vehicles are registered in the region, but also how many are on the road, how and how often are they used, how old are they, and where and when are they travelling. The last factor determines the spatial and temporal extent of the calculated total emissions.

Whether an emissions inventory is being built for a road, city, airshed, state, country, or a region, the fundamental equation follows an activity-based model using three components (a) number of vehicles (b) vehicle km travelled (c) emission factors (and fuel efficiency).

PM, BC, OC, NO_x, CO, and VOC emissions are calculated using the equation.

$$E_{v,f,g,p} = \sum [INV_{v,g} * S_f * VKT_{v,g} * EF_{v,f,g,p}]$$

And SO_2 and CO_2 emissions are calculated using the equation.

$$E_{v,f,g,p} = \sum [INV_{v,g} * S_f * VKT_{v,g} * FE_{v,f,g} * PC_{f,p}]$$

v = vehicle; f = fuel; g = age group; p = pollutant
E = the total emissions by pollutant (p), by vehicle type (v), fuel type (f), by age group (g)
INV = the total number of in-use vehicles on-road by vehicle type (v) and by age (g)
S = the share of vehicles on-road by fuel type (g) and vehicle type (v)
VKT = the annual average vehicle kilometres travelled by vehicle type (v) and by age (g)
EF = the fleet average emission factor by vehicle type (v), fuel type (f), age group (g), and by pollutant (p)
FE = the fuel economy by vehicle type (v), fuel type (f), and age group (g)
PC = the carbon and sulphur content in the fuel.

The spatial scale of the calculations from roads to cities to regions to countries, changes the complexity of the parameters in the equations. For example, for a road segment, the vehicle usage (km) is the road length, while for a city the usage depends on the commuter travel patterns and origin-destination matrix between residential, industrial, and commercial hotspots. Unfortunately, in most of the low- and middle-income countries, this information is not always readily available in a form that can be immediately used for building an operational emissions inventory. To overcome this challenge, various data resources must be evaluated and manipulated to support the analysis.

In Indian cities, road transport emissions continue to be one of the main sources of ambient $PM_{2.5}$ pollution, along with residential cooking and heating, industrial emissions including power generation and other heavy industries, open waste burning, and dust from construction and road activities. (Pant and Harrison, 2012; Guttikunda *et al.*, 2014; UEinfo, 2019; Ganguly *et al.*, 2020; Yadav *et al.*, 2022). In large cities like Bengaluru, Chennai, Delhi, Kolkata, and Mumbai, the on-road vehicle exhaust emissions, and dust resuspension on the roads due to vehicle movement, collectively contributes 30-50% of the ambient $PM_{2.5}$ pollution, on an annual basis. This fraction is higher for PM_{10} pollution, which captures most of the dust from these urban activities. For the gaseous pollutant's NO_x, CO and CO_2, transport continues to the major source of emissions (Hakkim *et al.*, 2021; Ahn *et al.*, 2023; Lekaki *et al.*, 2024). SO_2 is the only pollutant with a decline in the total emissions with periodic improvement in the sulphur content of petrol and diesel (10ppm, as of May 2024).

One of the key inputs in building vehicle exhaust emissions inventory is the vehicle stock information, segregated into vehicle types, fuel types, and age. This is necessary for understanding the overall growth in vehicle ownership, the rate of change of newer vehicles entering the fleet and establishing a fleet average emission rate. Several studies presented an estimate of air and climate pollutants for all India and for Indian cities, but none presented an open database of vehicle stock for replication and for further calculations (van Aardenne *et al.*, 1999; Reddy and Venkataraman, 2002; Gurjar *et al.*, 2004; Garg *et al.*, 2006; Singh *et al.*, 2008; Baidya and Borken-Kleefeld, 2009; Ramachandra and Shwetmala, 2009; Goel and Guttikunda, 2015a, b; Singh *et al.*, 2017; Venkataraman *et al.*, 2018a; Guttikunda *et al.*, 2019; Hakkim *et al.*, 2021; Singh *et al.*, 2022; Lekaki *et al.*, 2024). All the references

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here use the same fundamental method of multiplying three inputs – number of vehicles, vehicle usage, and an emission factor.

For the period covering 1993 and 2018, for India and its states, this paper provides a data resource of cleaned and model ready registered vehicle stock numbers, survival functions to build in-use vehicle stock numbers, a library of calculators to build first order inputs for urban vehicle exhaust emission inventories, and an overview of the use cases for further applications.

2. Methods and Inputs

2.1. Registered Vehicle Stock Numbers

The following equation refers to the calculation of the total registered number of vehicles (RNV), based on the annual sales and/or annual new registrations information.

$$RNV_v = \sum [NV_{v,g}]$$

RNV = the number of registered vehicles by vehicle type (v), as reported by MoRTH
NV = the number of new vehicles registered every year (by age (g))

RNV refers to the total number of vehicles that have been legally purchased and registered, including those in storage, inoperable, or being used infrequently. There are instances when a vehicle is re-sold and re-registered, the old registration number continues to be in the system, along with the new ownership/registration number (Mohan, 2013). In India, all the vehicles are registered for a period of 15 years. There is no prescribed retirement age for the vehicles and a provision to re-register for another 15 years can be availed, upon passing the safety and environmental checks at the regional transport office (RTO). In the National Capital Region (NCR) of Delhi, re-registration of diesel vehicles older than 10 years and petrol vehicles older than 15 years is not allowed, which are often transferred to other states for use till their end of life. Typically, when tallying the annual new registrations for RNV, summation over the past 23 years is considered, given the tendency of the vehicles to survive at various maintenance conditions (Mohan, 2013; Guttikunda and Mohan, 2014; Goel *et al.*, 2015). This should not be construed as all vehicles under 23 years of age are plying on the roads. The Ministry of Road Transport and Highways (MoRTH) annual reports publish the total number of registered vehicles in the country by state and by city for the categories listed in **Table 1** (MoRTH, 2022). For convenience, these categories are clubbed into nine broader groups – these groups are often used for emission calculations and evaluation of emission control strategies. A copy of RNV extracts from the MoRTH's annual report is included in the Supplementary Information (SI).

Table 1. Vehicle categories listed in the MoRTH annual reports and clubbed category for ease of analysis (2W, 3W, 4W = all 2-3-4 wheelers; T = taxies; LDV = light duty vehicles; HDV = heavy duty vehicles; NNRD = non-road vehicles).

	Clubbed category	MoRTH vehicle categories
1	2W	Scooters, mopeds, motorcycles
2	3W	Three wheelers with three, four, and six seaters
3	4W1	Cars
4	4W2	Jeeps and other passenger sports utility vehicles
5	4WT	Taxi motor cabs, maxi cabs, and others
6	BUS	Omni buses, stage carriages, contract carriages, private service vehicles, and others
7	LDV	Three and four-wheeler goods carriages
8	HDV	Multi-axle vehicles, trucks, and lorries
9	NNRD	Tractors, trailers, and other non-road vehicles

2.2. In-Use Vehicle Stock Numbers

The following equation refers to the calculation of converting RNV into in-use (or on-road) number of vehicles (INV) using a survival function (SF).

$$INV_{v,g} = \sum [RNV_{v,g} * SF_{v,g}]$$

SF = the survival function by vehicle (v)
g = age of the vehicle (v)

INV refers to the actual number of vehicles that are on the roads, driven and used for passenger and freight transportation, and the difference between RNV and INV is significant in India (Mohan, 2013). The MoRTH annual reports refer only to RNV, and the emission calculations must use only INV.

2.3. Survival Functions

Survival functions are used to enable the transition of RNV to INV, for the emissions and pollution models to replicate real world patterns.

$$SF_v = e^{-\left(\frac{g+\alpha_v}{T_v}\right)^{\beta_v}}$$

SF = the survival function by vehicle (v)
g = age of the vehicle
T = characteristic service life of the vehicle (v)
α, β = the shape and scale functions of the SF by vehicle (v)

Survival function model presented here is an adoption of probabilistic Weibull distribution representing the probability of a vehicle to still be in-use after a certain number of years (Zachariadis *et al.*, 1995; Baidya and Borken-Kleefeld, 2009; Goel *et al.*, 2015; Goel *et al.*, 2016). The shape and scale functions (α, β) are summarized in **Table 2** and **Figure 1** for three different scenarios – high, medium, and low survivals rates.

Table 2. Survival function parameters for nine broad categories of vehicles in India under three scenarios – high, medium, and low survival rates.

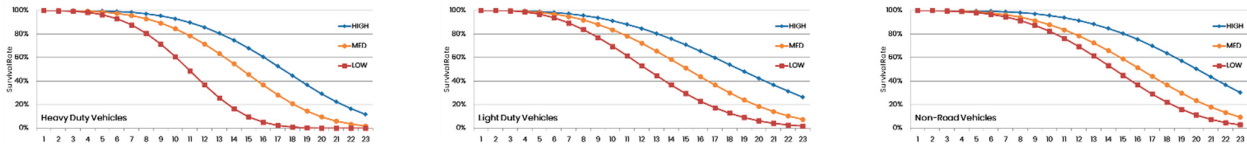|	Clubbed category	A			β			T		
		Low	Medium	High	Low	Medium	High	Low	Medium	High
1	2W	0.5	0.3	0.1	3.1	3.1	3.1	8	10	14
2	3W	-1.0	0.0	0.0	2.0	2.0	2.0	8	12	15
3	4W1	0.0	0.0	-0.5	3.0	3.0	3.0	8	12	16
4	4W2	0.5	0.5	0.0	2.5	2.5	2.5	10	12	15
5	4WT	-0.5	-0.5	-0.5	4.0	3.5	3.0	8	10	12
6	BUS	-1.0	0.0	-1.0	3.2	3.0	3.0	8	12	12
7	LDV	-1.0	0.0	0.0	2.5	3.0	3.0	12	16	20
8	HDV	1.0	1.0	0.0	3.8	3.8	3.8	12	16	18
9	NNRD	1.0	1.0	1.0	3.5	3.5	4.0	16	18	22
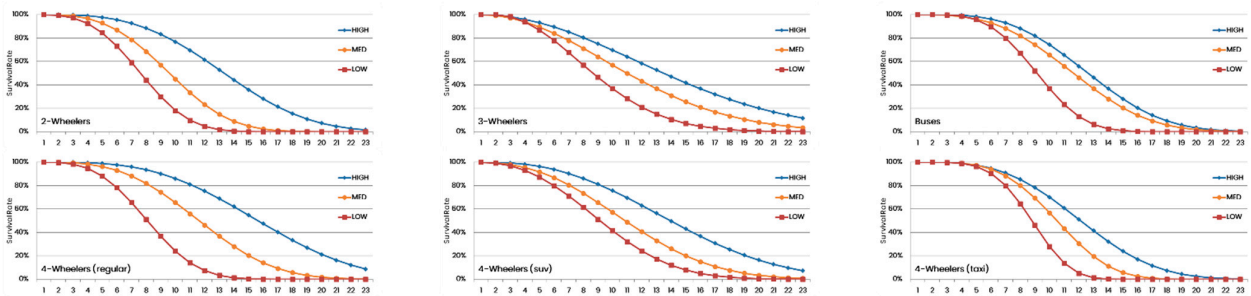
Figure 1. Illustration of survival functions for nine broad categories of vehicles in India under three scenarios – high, medium, and low survival rates.

For Tier-1 cities like Bengaluru, Chennai, Delhi, Hyderabad, Kolkata, and Mumbai, low survival functions are applicable, meaning the turnover of the vehicles, especially personal vehicles, is the highest in the cities. Similarly, for Tier-2 (medium) cities like Bhubaneswar, Coimbatore, Indore, Kanpur, Kochi, Ludhiana, Patna, Pune, and Varanasi, medium survival function is applicable. And for national level analysis, where it is assumed that a vehicle will survive in any state or till the end of its operational life, the high survival function is applicable. A copy of survival functions for the nine broad categories under the three scenarios and estimated model ready INV information by state is included in the SI. These survival functions (**Table 2**) are one operational example set based on limited number fuel station surveys conducted in Indian cities (Goel *et al.*, 2015; Goel *et al.*, 2016; BSPCB, 2019) and must be reevaluated, to represent the vehicle ownership and usage characteristics elsewhere. The characteristic service life of the vehicles (T) is based on the prevalent restrictions on the vehicle types. For examples, in the Tier-1 cities, passenger 3-wheelers and taxis, after eight years, are required to either retire them to other cities or go through stringent maintenance checks to continue to run the vehicle in the city. Most often the aged vehicles are either run unofficially in limited capacity or transferred to smaller cities. Lack of stringent inspection and maintenance programs also lead to a gradual drop in a vehicle's survival probability, after their heavy usage in the initial years. This is also reflected in the drop in the vehicle usage (km travelled per day) among the aged taxi, passenger 3-wheelers, and freight vehicles (Goel *et al.*, 2015; Malik *et al.*, 2019). For passenger vehicles, the turnover rate is higher in the big cities, which results in a sharp drop-off in the aged vehicles, irrespective of any restrictions. For example, the average turnover rate of cars is 4 to 4.5 years in Delhi (low survival) and 6 to 6.5 years in Patna (medium to high survival) (BSPCB, 2019). This also translates into a strong second-hand passenger vehicle market in India, and the assumption that at the national scale the vehicles are fully utilized in a high survival mode.

3. Open Data Resources

3.1. Vehicle Stock Numbers

Total registered number of vehicles (**Table 3**) in India touched 300 million in 2018 (as of March 31st, 2019 – end of India's financial year 2018). Of this 74.4% were 2-wheelers (2Ws), 13.4% were 4-wheelers (4Ws - including jeeps, sport utility vehicles, and taxis), 0.7% were buses (including intra- and inter-city), 8.4% were freight vehicles (including light- and heavy-vehicles), and 0.7% were non-road vehicles (MoRTH, 2022). The total registered vehicles number doubled between 2011 and 2018, increased six times between 2000 and 2018, and increased 11 times between 1993 and 2018 (**Figure 2**).

Table 3. 1993-2018 total registered vehicle fleet (in millions) in India (2W, 3W, 4W = all 2-3-4 wheelers; T = taxies; LDV = light duty vehicles; HDV = heavy duty vehicles; NRV = non-road vehicles).

	2W	3W	4W	4WT	BUS	HDV	LDV	NRV	Total
1993	18.3	0.8	3.3	0.3	0.4	2.1	1.8	0.1	27
1994	20.8	0.9	3.5	0.4	0.4	2.3	1.9	0.2	30
1995	23.3	1.0	3.8	0.4	0.4	2.2	2.5	0.2	34
1996	25.7	1.2	4.2	0.4	0.5	2.4	2.7	0.3	37
1997	28.4	1.3	4.6	0.4	0.5	3.4	2.3	0.3	41
1998	31.3	1.5	5.0	0.5	0.5	2.6	3.2	0.3	45
1999	34.1	1.6	5.5	0.6	0.6	2.7	3.5	0.3	49

Year									
2000	38.6	2.0	6.4	0.7	0.6	2.9	3.9	0.4	56
2001	41.8	2.0	7.0	0.7	0.6	2.9	4.1	0.4	59
2002	46.8	2.2	7.7	0.8	0.8	3.2	4.5	0.4	66
2003	51.9	2.3	8.5	0.9	0.8	3.3	4.7	0.4	73
2004	58.8	2.5	9.4	0.9	0.9	3.8	5.1	0.5	82
2005	64.7	2.6	10.5	1.0	1.0	4.1	5.5	0.5	90
2006	69.1	2.8	11.6	1.1	1.4	4.3	6.2	0.6	97
2007	75.4	3.1	12.8	1.3	1.4	4.6	6.7	0.6	106
2008	82.4	3.4	14.0	1.4	1.5	4.9	7.3	0.7	115
2009	91.6	3.6	15.5	1.6	1.5	5.1	7.9	0.7	128
2010	101.9	4.0	17.5	1.8	1.6	5.5	8.6	0.8	142
2011	115.5	4.4	19.6	2.0	1.7	6.0	9.4	0.9	159
2012	133.2	4.9	22.9	2.2	1.8	6.2	10.7	1.1	183
2013	141.5	4.8	24.3	2.1	1.8	6.5	11.3	1.2	194
2014	156.7	5.2	26.9	2.3	1.8	6.9	12.3	1.3	214
2015	171.7	5.5	29.7	2.4	1.7	7.7	13.2	1.3	233
2016	187.2	5.7	32.5	2.7	1.9	7.7	14.4	1.6	254
2017	204.4	6.3	35.4	2.9	1.9	9.3	14.3	1.9	276
2018	223.0	6.9	37.3	3.1	2.1	10.0	15.3	2.2	300
2018%	74.4%	2.3%	12.4%	1.0%	0.7%	3.3%	5.1%	0.7%	

Most of the increment comes from the 2W and 4W sectors, mostly due to lack of similar rate of interest in meeting the travel demand via mass-transit facilities in the big and medium size cities. The total bus number barely doubled since 2005, while the over demand for public transport increased at least 10 times in the same period. For example, a white paper in 1997 for Delhi's air pollution estimated that the city needs at least 15,000 public transport buses to meet the estimated travel demand in 2000 and the same assessment was made in the clean air action plan proposed as part of the India's national clean air programme in 2019-21, while the city continues to operate less than 4000 buses to meet the demand. The city operated 2000 buses in 1997 (CPCB, 1997; Guttikunda *et al.*, 2023b). The public transportation demand management scenario is similar in other cities. A gradual increase in the demand for total freight vehicles is an indicator of growing economy, demand for raw and finished products, urbanization with demand more commercial amenities, and overall gross domestic product of the country (Guttikunda and Ka, 2022).
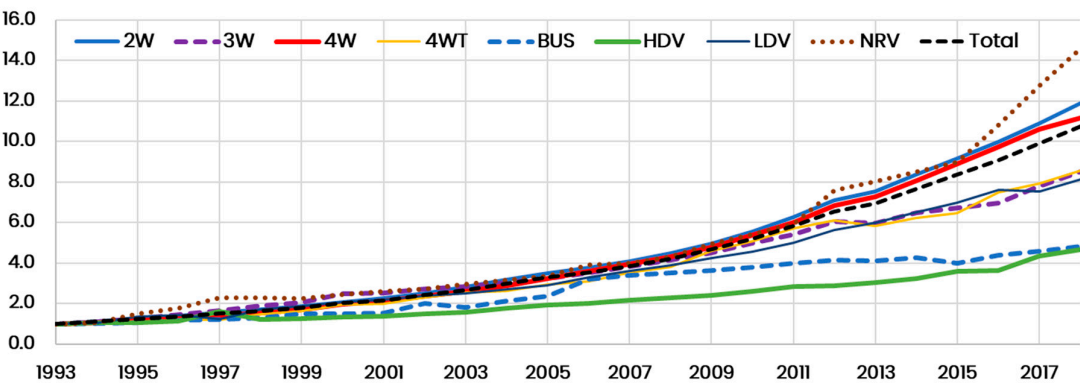

Figure 2. Registered vehicle number growth presented as a ratio of numbers in 1993 (2W, 3W, 4W = all 2-3-4 wheelers; T = taxies; LDV = light duty vehicles; HDV = heavy duty vehicles; NRV = non-road vehicles).

Total registered vehicle estimates by state for select years between 1993 and 2018 is presented in **Table 4**. This table includes 29 states and 7 union territories (including Delhi). As of 2024, there are

28 states and 8 union territories, with the state Jammu & Kashmir broken into 2 union territories with Ladakh added to the list and Dadar and Nagar Haveli and Diu and Daman combined into one union territory. In 2000, 3 new states were constituted - Chhattisgarh was cut from Madhya Pradesh, Jharkhand from Bihar, and Uttarakhand from Uttar Pradesh. In 2014, then 29th state Telangana was cut from Andhra Pradesh. The vehicle registration numbers for these new states started a year after the state's formation. Till then, their vehicle registration tally is included in the old states. States with the largest population also host the largest fleets. As of March 31st, 2019, the Gujarat, Karnataka, Maharashtra, Madhya Pradesh, Rajasthan, Tamil Nadu, and Uttar Pradesh have more than 15 million RNVs. Delhi with less than 20 million population (1.5% of the total) has approximately 12 million registered vehicles (4% of the total). The least vehicle density per capita is in the Northeastern states of Assam, Arunachal Pradesh, Manipur, Meghalaya, Nagaland, Sikkim, and Tripura.

Table 4. 1993-2018 (for select years) total registered vehicle fleet (in millions) by state.

	1993	1995	2000	2005	2010	2015	2018
Andaman & Nicobar Islands	0.01	0.01	0.03	0.03	0.07	0.11	0.14
Andhra Pradesh	1.61	2.58	4.05	7.22	10.19	8.53	11.67
Arunachal Pradesh	0.01	0.02	0.02	0.02	0.14	0.26	0.23
Assam	0.35	0.36	0.55	0.91	1.58	2.85	3.97
Bihar	1.22	1.33	0.97	1.45	2.67	5.48	8.55
Chhattisgarh			0.86	1.54	2.77	4.81	6.38
Chandigarh	0.31	0.37	0.39	0.65	1.02	0.84	1.02
Diu and Daman	0.01	0.02	0.04	0.06	0.08	0.11	0.12
Delhi	2.28	2.68	3.55	4.50	7.24	9.94	11.40
Dadar Nagar Haveli	0.01	0.01	0.01	0.05	0.08	0.11	0.00
Goa	0.18	0.21	0.34	0.53	0.77	1.13	1.40
Gujarat	2.73	3.38	5.60	8.62	12.99	20.36	25.20
Himachal Pradesh	0.09	0.12	0.22	0.33	0.62	1.18	1.63
Haryana	0.84	1.07	1.99	3.09	5.41	8.68	11.43
Jharkhand			0.91	1.51	3.11	3.35	4.30
Jammu Kashmir	0.16	0.20	0.33	0.52	0.93	1.37	1.82
Karnataka	1.81	2.25	3.56	6.22	9.82	16.15	20.90
Kerala	0.89	1.17	2.15	3.76	5.98	10.09	13.25
Lakshadweep	0.00	0.00	0.00	0.01	0.01	0.02	0.02
Maharashtra	3.27	4.03	6.88	11.02	17.50	27.87	35.39
Meghalaya	0.04	0.04	0.06	0.10	0.18	0.29	0.37
Manipur	0.05	0.06	0.08	0.12	0.21	0.31	0.36
Madhya Pradesh	1.89	2.31	3.10	4.61	7.36	11.98	15.30
Mizoram	0.02	0.02	0.03	0.05	0.09	0.17	0.26
Nagaland	0.08	0.10	0.17	0.20	0.29	0.38	0.49
Odisha	0.54	0.66	1.11	1.94	3.34	5.83	8.28
Punjab	1.64	1.92	2.92	4.04	5.27	9.60	10.61
Puducherry	0.11	0.13	0.25	0.38	0.67	0.86	1.06
Rajasthan	1.44	1.77	2.96	4.75	7.99	13.64	17.72
Sikkim	0.01	0.01	0.01	0.02	0.04	0.05	0.07
Tamil Nadu	2.15	2.77	5.17	10.05	15.64	24.20	30.18
Tripura	0.03	0.03	0.05	0.11	0.19	0.33	0.50
Telangana						8.82	12.50
Uttarakhand			0.37	0.64	1.00	1.89	2.75
Uttar Pradesh	2.48	2.99	4.91	7.99	13.29	23.94	32.71
West Bengal	1.01	1.24	1.89	2.87	3.26	7.61	7.80

An estimated national average age-mix of the in-use fleet using the high survival rates is presented in **Figure 3**. Overall, up to 70% of the fleet tend to be under 10 years age. The past emission inventory studies indicated that ~20% of the fleet older than 10 years age hosts most of the super-emitters (aka vehicles with the highest emission rates) and account for the largest chunk of the total emissions of $PM_{2.5}$, NO_2, CO and VOC's (Baidya and Borken-Kleefeld, 2009; Guttikunda and Mohan, 2014; Sadavarte and Venkataraman, 2014; Hakkim *et al.*, 2021; Debbarma *et al.*, 2024). This is often a symptom of poor maintenance of the older vehicles.
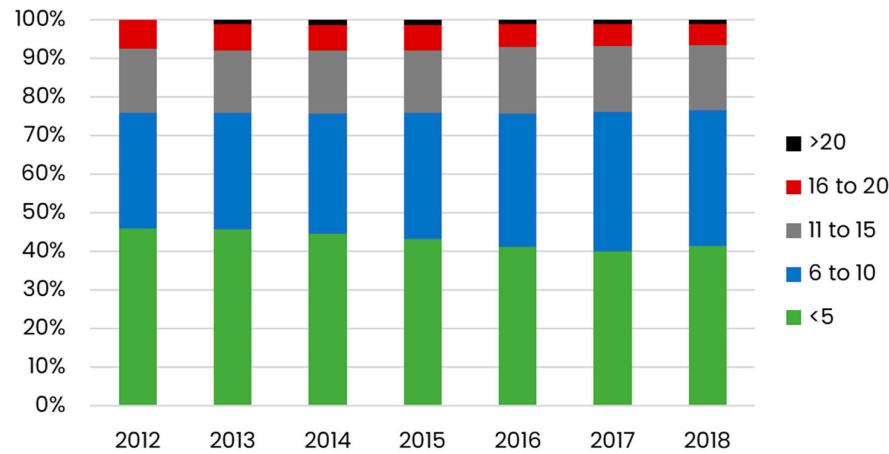
Figure 3. An estimated age-mix of India's in-use vehicle fleet using the high survival rates.

The evolution of vehicle standards in India is presented in **Figure 4**. From no norms in late 1990s to introducing Bharat Standard (BS) 6 in 2020, all the new vehicle and fuel standards were introduced in Delhi first, then the metropolitan cities, and after 2-5 years nationwide. The bifurcated standards had limited effect on reducing the overall emissions, except for in the cities with the new standards, where the passenger vehicles travelling within the city limits benefitted by emitting lesser emissions (Guttikunda and Mohan, 2014). In 2020, BS6 was introduced nationwide under "one nation – one fuel" motto. The overall fleet will take at least 5-8 years, depending on state and city, to host a fleet fraction dominant of the BS6 vehicles.
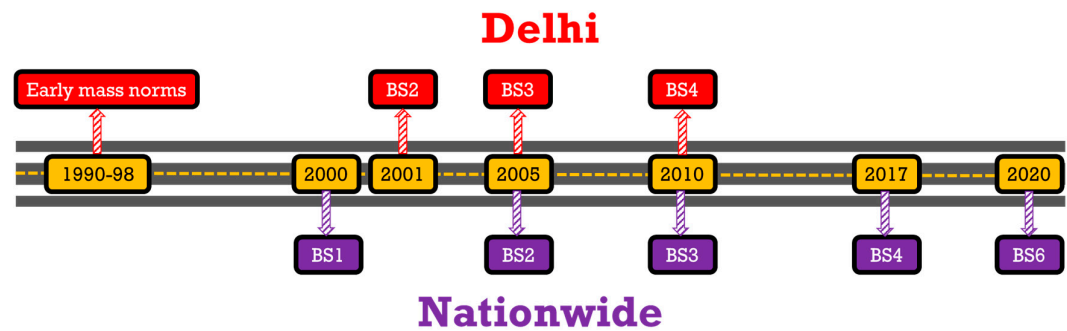

Figure 4. Timeline of introduction of various vehicle and fuel standards in Delhi and India (source: https://dieselnet.com).

A copy of estimated in-use vehicle fleet, including age-mix using the high survival rates is included in the SI. Other sources of RNV include a new resource VAHAN, which presents analytics by state and RTO (https://analytics.parivahan.gov.in). The online database includes RNV and NV by vehicle model and fuel type. Only the data posted on the portal is public and there are no clear guidelines to access the full database at the RTO level. Annual sales information by vehicle model

and fuel type can be purchased from the institutions like Society of Indian Automobile Manufacturers (SIAM).

3.2. Vehicle Exhaust Emissions Analysis Tools

The fundamental equation for building vehicle exhaust emissions is multiplying three parameters – number of vehicles, vehicle km travelled (usage) and an emission factor. When the data is scarce, this equation has versions that can be used to deduce similar emission estimates, with some accountable uncertainty (1) a method using information on total fuel consumed, share of fuel consumed in various modes, fuel efficiency of the modes, and an emission factor (b) a method using information on total passenger trips, share of trips in various modes, average trip length of various modes, and an emission factor. An example calculator of these methods is available @ https://urbanemissions.info/tools, along with resources to establish representable inputs for use in emissions analysis. These include:

- A method to convert fleet average speeds and fleet average travel time per day into vehicle km travelled per day.
- A method to calculate how many additional buses are required to support odd-even or an equivalent scheme (with and without fuel mix exemptions).
- A method to calculate total fuel wasted from idling in the city and to calculate savings from traffic management.
- A method to calculate fuel and emission benefits of shifting a share of 2-wheeler and 4-wheeler trips to buses and non-motorized transport.
- A method to estimate vehicle exhaust emission factors using emission standards and deterioration rates.
- An example set of survival rates based on vehicle age for nine broad vehicle categories in **Table 2** (to convert yearly RNV into INV).
- A method to spatially disaggregate (grid) the total vehicle exhaust emissions using multiple grid-level proxies as weights such as density (km per grid) of various road types, population density, landuse-landcover, and information on commercial and industrial activities.
- A library of emission factors for aerosols and gaseous species.

The lack of a single emission factor database in India, makes it difficult to accurately estimate, validate, and evaluate the total emissions and the effectiveness of existing emission control policies. A representative sample of emission factor databases available for open use are (a) the GAINS (Greenhouse gas and Air pollution Interactions and Synergies) modelling system, which provides a repository of regional level average factors (GAINS, 2022) (b) Central Pollution Control Board (CPCB), New Delhi, India, which provides a repository of emission factors based on a limited series of tests on various vehicle types and age mixes (CPCB, 2011) (c) (Goel and Guttikunda, 2015a) which provides a database of emission factors applicable for large cities, derived from a combination of vehicle age-appropriate emission standards and deterioration rates (d) (Jaiprakash and Habib, 2018) which provides a database for emission factors for 4-wheelers based on tests using on-board testing equipment.

4. Discussion

The vehicle stock database presented here is in operational use for an all-India air quality forecasting system, along with emissions and pollution analysis for 60 cities under the Air Pollution knowledge Assessments (APnA) program for Indian cities (https://urbanemissions.info). The APnA city program is also supporting India's National Clean Air Program (NCAP) to establish layers of information necessary for building an emissions and pollution analysis framework for 131 cities designated as non-attainment areas (CPCB, 2019; Ganguly *et al.*, 2020; CREA, 2023; Guttikunda *et al.*, 2023a). A localized emission inventory is necessary for establishing the emission baselines for these cities. Especially for a sector like road transport, which is linked to all the other sectors delivering raw material, finished products, and people, reliability and replicability of an inventory is important to build confidence in the overall modelling exercise. Availability of long-term open vehicle stock information is the first step in this process. Future applications of this database include (a) a long-term emissions inventory for air quality and climate management (b) evaluation of the emission

mitigation strategies at urban and regional scale and (c) support to urban and national clean air action plans.

Additional databases relevant for road transport emissions analysis are available for the designated NCAP urban airsheds (with a spatial resolution of 0.01º, approximately 1km). These include: (a) gridded and geospatial shape files of road density of primary, secondary, tertiary, and other road types (b) landuse-landcover shares at the grid level covering urban, barren, agricultural, other vegetation, and water types (c) gridded urban-rural classification using built-up area extracts from satellite retrievals (d) gridded multi-year population density and (e) gridded commercial activity density as number of establishments of hotels, hospitals, industries, markets, cinema halls, malls, apartment complexes, and other buildings. These geospatial layers of information can be strategically used for spatial allocation of the total vehicle exhaust emissions calculated using the vehicle stock numbers and as inputs to land use regression models for spatial allocation of information from monitoring networks and surveys.

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