Gaseous and Particulate Matter Emissions from Road Transport: The Case of Kolkata, India

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Abstract – Indian cities are highly dependent on road transport for freight and passenger traffic movements. The estimated road transport led yearly emission inventory of pollutants for 25 million-plus population cities of India indicates vehicle stock as the critical contributor to air pollution in cities. During 2025 the city of Kolkata will be responsible for the emission of 21 668.24 Gg of CO₂ followed by 272.81 Gg of CO, 98.21 Gg of NO_x, 16.9 Gg of CH₄, 93.39 Gg of SO₂, 8.6 Gg of PM, and 38.55 Gg of HC due to its 2.79 million vehicles. The total vehicle stock of 25 leading Indian cities increased by 19 % during 2015–2017, and during the same period, Rajkot and Vadodara had the highest rise of 97 % and 94 % respectively. Out of 25 cities total CO₂ (220 560 Gg) and CO (3185 Gg) vehicular emissions during 2017, Delhi was the highest contributor with 22 % and 20 % respectively followed by Bengaluru (12 %, 12 %), and Chennai (9 %, 8 %). The GHG emission per unit area of Kolkata during 2017, due to on-road vehicular emission, was the highest amongst the 25 cities of India. For Kolkata, cars were responsible for 35 % for CO₂, 55 % of CO, 75 % of CH₄, 27 % of PM, omnibuses for 41 % for NO_x emission, taxis for 83 % of SO₂, and two-wheelers for 36 % of HC emissions.

Keywords – Air pollution; emission inventory; GHG emission per unit area; Indian cities; motor vehicle emission

1. INTRODUCTION

Kolkata city, the erstwhile capital of the British Indian Empire, is a fast-growing metropolis now where along with the growth of population and economic activities, the level of air pollution is also increasing significantly [1]. Recent research, covering 109 Indian cities, has put Kolkata under the severely vulnerable tag due to the higher status of ambient particulate matter of diameter less than or equal to 2.5 micrometres (PM_{2.5}) and thereby indicating the urgency on prioritizing a clean-air action plan for the city at the earliest [2]. The World Health Organisation (WHO) report covering 4000 cities of 100 countries for the year 2016, released during June 2018, revealed that Kolkata was only second after Delhi in terms of highly polluted cities of India. The air quality of Kolkata worsened more rapidly than that of Delhi [3]. The Central Pollution Control Board (CPCB) of India also expressed concern about the faster deterioration of air quality of Kolkata which is the most important city of eastern India in terms of economic reasons [4].

Indian cities, in general, are characterized by the high motor vehicle population as they are excessively dependent on their road network for freight and passenger traffic movements. The World Bank [5] estimated that about 60 % of freight and 85 % of passenger traffic movements usually depend on on-road transportation only in India. Accordingly, cities are

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overly reliant on on-road transportation, and the majority of motor vehicles are running with diesel and petrol as clean fuel like compressed natural gas (CNG) is yet to be available in most of the cities [6]. Indian cities are now accommodating 35 % of India's massive population and at the same time, contributing to about 69 % of its gross domestic product [7], [8]. The motor vehicle stock in Indian cities has grown steadily in the past. It is expected to continue with the momentum in the future due to the increase in population, migration, and economic growth [9], [10]. The researchers indicated that transport sectors played a significant role in polluting the environment in Indian cities [11]–[13]. The road transport was found alone responsible for 94.5 % and 53.3 % of carbon dioxide (CO₂) and carbon monoxide (CO) emission, respectively, in India [14]. The transport sector contributed most of the oxides of nitrogen (NO_x), CO, and non-methane volatile organic compound (NMVOC) emissions in the capital city of Delhi [15]. The vehicular emission concentrations in Indian cities are significant and require policymakers' attention [16]. The vehicular emissions are not only pronounced in big cities, but smaller cities are also equally affected [17]. Although the respective local government has been trying to phase out old automobiles, still the cities are housing an abundance of poorly maintained old motor vehicles.

At the city level, there exists a mismatch between the official and actual size of the vehicle stock, which influences vehicular emission estimations [18], [19]. The two-wheelers and diesel automobiles are increasing in cities and are the major contributors to air pollution [20], [21]. The intra-city buses for travel across cities are significantly contributing to pollutants during peak periods [22]. The various control measures enacted by the regulatory authorities of Delhi failed to curb the NO_x emissions from automobiles [23]. The cities required controlling the ever-increasing population of two-stroke two-wheelers for reducing the emission of hydrocarbon compounds (HC), carbon dioxide (CO₂), and CO in India [24]. Researchers advocated phasing out of old automobiles, rigorous periodic pollution tests, and better technology in terms of fuel combustion as the solutions for vehicular emission problems in India [25]–[27]. Stricter policy-led norms and fast adaptation of CNG as fuel by the public transport automobiles are the need of the hour [28].

Indian environment watchdog, National Green Tribunal (NGT) has recently reprimanded CPCB for the rapidly deteriorating ambient air quality of Indian cities [29]. A city like Kolkata has reached threatening dimensions in terms of air pollution in Kolkata because of the ever-increasing two-wheelers population, the predominance of older vehicles, high vehicle density, bad road conditions, and the absence of a mass traffic system [30]. A comparatively recent study highlighted extremely high PM concentrations (PM₁₀ = 445 µg m⁻³ and PM_{2.5} = 313 µg m⁻³) during the winter months in Greater Kolkata [31].

Against this background, this study has built up greenhouse gas (GHG) inventory for the city of Kolkata due to its road transport sector following a bottom-up approach. The total emissions have been worked out by summing every vehicle's emission and compared the same with other leading cities of the country. In the Indian city context, the bottom-up approach has been used to develop emission inventories for the road transport sector for different states as well as for a specific city like Delhi [14], [20], [32]. The present study differs from them in the following ways. First, it estimated the road transport led emission load of Kolkata up to 2025 based on the projected automobile population of the city. Second, it estimates city-wise road transport led inventory of GHG emissions across 25 leading million plus populated cities for the years 2015–2017, including Kolkata. Third, it computed and compared GHG emissions per unit area of the 25 cities for the years 2015–2017 to understand the variations of emissions across leading cities of the country from the road

transport sector. Finally, emissions due to different types of road transport vehicles have been compared across five Indian metropolitan cities, including Kolkata for the year 2017.

2. LOCATION OF STUDY

Kolkata city is the capital of the state of West Bengal (Fig. 1). As per the 2011 population census, Kolkata ranked third amongst the cities of India in terms of population and has a high population density (persons per sq. km) of 24 306. The city is on the eastern bank of the river Ganges and the Bay of Bengal is about 120 km away from the city. Kolkata has a tropical wet and dry climate with an annual mean temperature of 26.8 °C. The city experiences three seasons, summer, monsoon, and a short winter of about two months with temperature 9–23 °C range [33]. Summer is a long season with daily temperatures ranging from 27–38 °C. Rainy weather starts from mid of June when the south-west monsoon rich with moisture gathered from the Bay of Bengal flows over the city and continues till the end of September. The minimal geographic expansion, high population density, traffic congestion, poverty, and increasing vehicle stock make Kolkata an ideal city for a case study of air pollution caused by its road transport sector [31]. The 2011 census of India indicated 53 urban agglomerations in the country with a human population of 1 million or more. Out of them, 25 leading million-plus Indian cities have been considered in this study (Fig. 1) for road transport led annual emission inventory estimation which includes top-five metropolitan cities of the county like Mumbai, Delhi, Kolkata, Chennai, and Bengaluru [34].

Fig. 1. Kolkata and 24 other million-plus Indian cities.

3. METHODOLOGY

In general pollutants and gases like particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), nitrous oxide (N₂O), sulphur dioxide (SO₂), methane (CH₄), non-methane volatile organic compounds (NMVOC), and hydrocarbon (HC) are

associated with the vehicular exhaust. Depending upon the type of engine, fuel used, vehicle age, and condition of using the emissions from vehicles vary. Road transport is a critical contributor to air pollution in the Indian city context because of excess use of diesel as fuel and non-availability of environment-friendly fuel like CNG gas in many Indian cities including Kolkata.

3.1. Assessment of Motor Vehicle Population and Projection

The category-wise motor vehicle population data of Kolkata, for twelve years (2006–2017) were collected from the Indiatat [35] and Open Government Data (OGD) platform of the Government of India [36]. The category-wise motor vehicle population data of 24 other million-plus cities, for three years (2015–2017), also collected from the same sources. The online sources reported data in two broad categories, i.e., transport and non-transport. The transport category includes multi-axle/articulated, vehicles like trucks & lorries (TL), light motor vehicles (goods) or LMVG, buses, taxis, light motor vehicles, (passenger) or LMVP. The non-transport category includes two-wheelers (TW), cars, jeeps, omnibuses, tractors, trailers, and other miscellaneous vehicles. The two-wheelers were then subdivided into TW motorcycles (4-Stroke TW or 4S-2W) and TW scooters (2-Stroke TW or 2S-2W). Indiatat and OGD data of TW do not provide the population of 4S-2W and 2S-2W separately. The proportion of 4S-2W and 2S-2W out of the total of TW was taken as 72:28 based on MoRTH report [37]. We used future growth forecasting techniques like the compound annual growth rate (CAGR) of respective category vehicles for the period 2006–2016 of Kolkata in projecting the total motor vehicle population of the city up to the year 2025.

3.2. Calculation of Emission Load

In order to calculate the emission load due to road transport for the period 2015–2025, this study has used the following IPCC equation, Eq. 1 [38].

$$E_i = \sum (Veh_j \cdot D_j) \cdot EF_{i,j,km}, \quad (1)$$

where

E_i Total emissions load (i);

Veh_j Number of different types of city vehicles (j);

D_j Kilometer traveled/vehicles/year (j) km;

$EF_{i,j,km}$ Emission of pollutants (i) from vehicle type (j) per travelled kilometre.

We used the motor vehicle utilization rate (average kilometre travelled per year) in India from the CPCB study [39]. The CPCB study found out the vehicle utilization rate based on a primary survey of six Indian cities. This study used the average utilization rates of different types of automobiles to reflect pan India status. Annual average kilometre travelled for TW(4S-2W), TW(2S-2W), car, car CNG, jeep petrol, omnibus, truck lorries, bus (diesel) and CNG taxi were 15 756, 13 444, 62 963, 62 963, 62 963, 41 914, 24 333, 41 914, and 62 963 kilometres, respectively. Similarly, for LMVP, tractor, trailer, and LMVG were 29 333, 21 000, 63 000 kilometres per year, respectively [40].

3.3. Quantification of Emission Factors

The Automotive Research Association of India, ARAI [41] undertook a pioneering attempt during 2007 to develop the emission factors for automobiles plying on the Indian road. This project aimed at the development of typical values of pollutants emitted by different types of automobiles to the atmosphere. The automobiles of five different generations (viz, 1991–96,

1996–2000, post-2000, and post 2005) were considered for understanding the relationship between technology and emission factors and after that use of the relationships to indicate the emission factors for automobiles plying on Indian roads. Different researchers in the field, as well as agencies from time to time, contributed to further update the emission factors as applicable in India. Emission factors, usually expressed in gram per kilometre (gm per km), depends on various factors like actual driving condition, road unevenness, the laden weight of the automobile, acceleration or de-acceleration, vehicle age, fuel condition, ambient temperature, and vehicle maintenance. It is not possible to have a pan world standardized emission inventory as the ground conditions are different. Different pieces of the literature on the even subject also used these emission factors for different types of automobiles plying in the country. It is challenging to have the exact break up of different types of two-wheelers plying on the road, so in the case of two-wheelers, the average of emission factors (4S-2W and 2S-2W) have been considered for generalization. The emission factors of different types of vehicles in India considered for this study can be seen in Table 1.

TABLE 1. EMISSION FACTORS OF DIFFERENT TYPES OF AUTOMOBILES IN INDIA IN GM KM⁻¹

Vehicle type	CO ₂	CO	NO _x	CH ₄	SO ₂	PM	HC
Truck, Lorries	515.2	3.6	6.3	0.09	1.42	0.28	0.87
LMVG & LMVP	60.3	5.1	1.28	0.18	0.029	0.2	0.14
Buses	515.2	3.6	12	0.09	1.42	0.56	0.87
Taxis	208.3	0.9	0.5	0.01	10.3	0.07	0.13
2S-2W	26.58	1.37	0.2	0.18	0.023	0.045	2.53
4S-2W	26.95	4.47	0.61	0.18	0.023	0.011	1.57
Car	223.6	1.98	0.2	0.17	0.053	0.03	0.25
Jeep	223.6	1.98	0.2	0.17	0.053	0.03	0.25
Omnibuses	515.2	3.6	12	0.09	1.42	0.56	0.87
Tractor	515.2	5.1	1.28	0.09	1.42	0.2	0.14
Trailer	515.2	5.1	1.28	0.09	1.42	0.2	0.14
Others	343.87	3.86	3.89	0.11	1.94	0.24	0.54

Note: The emission factors have been taken from [14], [42]–[48].

3.4. Calculation of Road Transport Emission of Cities

Measurement and quantifications of city-level road transport emission, both city-wise total emission and per unit area wise emissions, is essential in order to understand the pollution contribution and effect changes in technologies in emission parameters [14]. Emissions of primary pollutants (PM, CO, CO₂, NO_x, SO₂, CH₄, and HC) by road transport during 2017–2025 for Kolkata and during 2015–2017 for other 24 Indian cities were calculated out using the IPCC equation for different category of vehicles following their respective India specific mass emission factors [38]. The GHG gas emissions per unit of the geographical area-wise, expressed in gigagrams (Gg) or megagrams (Mg), for all the 25 cities for the period 2015–2017 was then calculated to assess emission intensity per unit city area by using Eq. (2):

$$\text{Emission per unit area of city} = \frac{\sum (Emission_{ij})}{Area_i} \quad (\text{in Gg or Mg km}^{-2}), \quad (2)$$

where $Area_i$ = geographical area of municipal administration of the i^{th} city (km^2) and j^{th} type of vehicle. The geographical area of the cities was collected from respective city municipality websites.

Vehicle type-wise emission analyses were also carried out for five major Indian metropolitan cities using the IPCC equation for the year 2017, including Kolkata, to understand the contribution of dominant sources of emission in the total emissions of the cities in comparative terms.

4. RESULTS AND DISCUSSION

4.1. Vehicle Population for Kolkata

Fig. 2 and depict the status of registered vehicles in the city of Kolkata both for the period 2006–2017 (actual) and 2018–2025 (projected). The registered automobiles increased from a mere 0.9 million to 1.71 million during 2006–2017 in Kolkata, with a steady rate of increase of 84 %. During this period, excepting for the tractor, trailer, and jeep category of automobiles, all other categories registered a definite increase. The projected vehicle stock, category wise, between 2018 and 2025 indicates that Kolkata will be the abode of about 2.79 million vehicles by 2025. During 2016–2017, LMVG registered highest rise in number (240 % followed by LMVP (132 %), taxi (129 %), omnibus (114 %), car (107 %), 4S-2W (79 %) and 2S-2W (79 %). A personalized vehicle like cars accounted for more than 39 % (0.67 million out of 1.71 million) of the total vehicle population of the city during 2017. If other personalized vehicles like TW (4S-2W and 2S-2W) are considered, then car and TW accounted for the major share, i.e., about 83 % of the total vehicle population of Kolkata during the year 2017. There will be mammoth 1.15 million personalized cars plying on the roads of the city which would account for about 41 % of the total during 2025. Another major contributor (40 %) of total vehicles on the road by 2025 would be two-wheelers. Therefore, personalized cars and two-wheelers together would account for the bulk of the vehicle population (81 %) of the city during 2025.

Fig. 2. Vehicle population in Kolkata (2006–2025).

4.2. Vehicular Emission in Kolkata

The emissions of PM, CO, CO₂, NO_x, SO₂, CH₄, and HC during 2015–2025, for different vehicle categories in respect of Kolkata city, have been calculated out using IPCC, 2006 equation. The rising trend of annual emission of CO₂ in Kolkata from 2015–2025 can be seen in Fig. 3A. The emission of CO₂ will be 21 668.24 Gg during 2025 in India, which is about 104 % more than the 2015 value of 10 603.14 Gg. The increase in CO₂ can be attributed mainly to a 107 % increase in the total number of cars during the period 2015–2025. Cars alone will be responsible for about 75 of the total CO₂ emission during 2025, followed by other types of automobiles like omnibuses (8 %), taxi (7.6 %), and LMVG (3 %).

CO₂ emission, Kolkata (2015–2025), Gg

(a)

CO emission, Kolkata (2015–2025), Gg (b)

NO_x emission, Kolkata (2015–2025), Gg (c)

Fig. 3. Annual emission of Kolkata (2015–2025): A) CO₂; B) CO; (C) NO_x; (D) CH₄; (E) SO₂; (F) PM; (G) HC.

The CO emission inventory of 126.15 Gg during 2015 will be increased to 272.81 Gg during 2025 by registering a rise of about 116 %, as can be seen in Fig. 3B. The cars will be the main contributor with 53 % of the total emission of CO emission during 2025 followed by LMVG (25 %) and 4S-2W (8 %). The projected increase of two-wheelers by 163 % during 2015–2025 will surely be a contributor to CO presence in the atmosphere as evident from the fact that they will be contributing to about 9 % of the total CO emission of 272.81 Gg during 2025.

The 52.66 Gg of NO_x emission during 2015 will be increased to 98.21 Gg by 2025 due to vehicular road traffic as can be seen in Fig. 3C. The highest contribution of 42 % of total NO_x emission during 2025 will come from omnibuses, followed by 17 % from LMVG, 15 % from cars, and about 11 % from the buses.

During 2015 the CH₄ emission from road vehicles was 7.85 Gg which will shoot up 16.9 Gg during 2025 in Kolkata, the increase being 115 %. Four types of automobiles like 4S-2W (5 %), 2S-2W (2 %), Cars (73 %), and LMVG (14 %) will be responsible for about 94 % of

CH₄ emission during 2025 as can be seen in Fig. 3D. As it is evident from Fig. 3E, there will be 93.39 Gg SO₂ emissions in Kolkata due to the vehicle population by 2025, which is about 102 % more than that of 2015 emissions. The major contributors to the pool of SO₂ will be three types of vehicles like taxis, cars, and omnibuses, and out of these three, taxis alone responsible for 86 % of the total SO₂ emission inventory of the city by 2015.

During 2025 there will be 8.60 Gg of PM pollution in the city due to vehicle population, as shown in Fig. 3F, which will be about 110 % higher than that of 2015 emissions. The main contributor to PM pollution in Kolkata during 2025 will be four types of automobiles viz. LMVG (31 %), Car (25 %), Omnibuses (23 %), and Taxis (6.4 %) constituting about 84.5 % of the total during 2025. HC emission also includes other volatile organic compounds (VOCs) which may not be directly harmful to health at the concentration found in the ambient air. However, they support the formation of hazardous NO₂ and O₃ in the atmosphere. During 2015 the road vehicles contributed to about 19.6 Gg of HC formation which is expected to increase to 38.55 Gg during 2025 indicating a considerable sharp rise of about 97 % as can be seen in Fig 3(G). The major contributor of HC will include emissions from 4S-2W (20 %), 2S-2W (13 %), cars (47 %) during 2025. Interestingly, two-wheelers (both 4S-2W and 2S-2W) together will be responsible for 33 % of the total HC pollution coming out from the road vehicular transport sector in the city.

4.3. GHG Emissions of Kolkata and 24 Other Indian Cities

The IPCC, 2006 equation and category wise break up of total vehicles in the cities were used to calculate GHG emission for 25 leading million-plus Indian cities, including Kolkata. GHG emissions for 25 leading million-plus Indian cities for the year 2017 and category-wise vehicles of the cities responsible for the emissions can be seen in Table 2. Table 2 indicates that the total vehicle stock of 25 cities increased by 11 % during 2015–2016, 7 % during 2016–2017, and 19 % during 2015–2017. Table 2 also reveals that Delhi topped the list with mammoth 10.26 million vehicle stock during 2017, followed by cities like Bengaluru (6.83 million), Chennai (5.30 million), Ahmedabad (3.90 million), Mumbai (3.05 million), and Surat (2.89 million). It is interesting to note that the city of Kolkata is in 14th place out of 25 cities figured in Table 2.

In case of increase in vehicle stock of the cities, the highest rise during 2015–2017 took place for Rajkot and Vadodara with a remarkable 97 % and 94 % respectively. The vehicle stock for Bengaluru also grew by 24 % during 2015–2017 followed by Kolkata (22 %), Aurangabad (21 %), Nagpur (20 %), Mumbai (19 %), and Meerut (18.62 %). Interesting to note that the vehicle population increased in Rajkot (84 %) and Vadodara (82 %) mostly during 2015–2016.

As the economy progressed, the population of the cities also increased which led pro-rata increase in total passenger travel demand with time. Accordingly, the transport emission load of Indian cities also increased with time. During 2017, all the 25 leading Indian cities emitted 220 560 Gg of CO₂ (Table 2). Also, during 2017, across all the 25 cities, the leading CO₂ emitting city was Delhi with 22 % of total emission (48317 Gg.), followed by Bengaluru (26 285 Gg, 12 %), Chennai (19 418 Gg, 9 %), Mumbai (15 989 Gg, 6 %), Ahmedabad (13 104 Gg, 6 %) and Kolkata (12 757Gg, 6 %). In terms of CO emission, Delhi also remained on the top during 2017 with 20 % of the total emission (630 Gg) followed by cities like Bengaluru (369 Gg, 12 %), Chennai (270 Gg, 8 %), Ahmedabad (214 Gg, 7 %), Mumbai (188 Gg, 7 %), and Kolkata (151 Gg, 5 %). During 2017, Bengaluru had the highest NO_x emission (121 Gg, 14 %.) followed by Delhi (110 Gg, 12 %), Chennai (89 Gg, 10 %), Kolkata (59 Gg, 7 %), and Ahmedabad (57 Gg, 6 %). In terms of CH₄ emissions, the top five cities were Delhi (65 Gg, 19 %), Bengaluru (45 Gg, 13 %), Chennai (38 Gg, 11 %), Ahmedabad (27 Gg, 8 %),

both Mumbai and Jaipur jointly stood seventh (20 Gg, 6 %) while Kolkata (10 Gg, 2.9 %) ranked 8th only. For SO₂ emission, again Bengaluru topped the list with 108 Gg (16 %) followed by Delhi (102 Gg, 15 %) Chennai (97 Gg, 14 %), Mumbai (82 Gg, 12 %), and Kolkata in the 5th position with 8 % (52 Gg) of the total emission. It can also be seen from Table 2 that Kolkata was in the 5th rank, shared jointly with Mumbai, for PM (5 Gg, 6 %) emission while for HC emission, Kolkata ranked 8th with 24 Gg (4 %) emission amongst the 25 cities.

TABLE 2. TOTAL GHG EMISSION IN 25 CITIES, 2017

Metro Cities	Total no of vehicles, Mln			Total Emission in 25 cities, 2017, Gg						
	2015	2016	2017	CO ₂	CO	NO _x	CH ₄	SO	PM	HC
Ahmedabad	3.42	3.66	3.90	13 104	214	57	27	25	6	51
Rajkot	0.98	1.81	1.93	4932	89	23	8	10	2	25
Vadodara	1.04	1.90	2.02	5756	99	25	8	14	3	26
Surat	2.46	2.67	2.89	7400	135	29	10	7	3	37
Allahabad	0.90	1.06	1.02	1330	35	10	3	4	1	13
Kanpur	1.46	1.54	1.63	4585	65	18	5	4	1	22
Meerut	0.53	0.57	0.62	1581	26	6	3	3	1	8
Varanasi	0.77	0.78	0.91	2023	39	12	5	7	1	12
Lucknow	1.71	1.82	1.98	5445	81	15	7	10	2	26
Bengaluru	5.52	6.07	6.83	26 285	369	121	45	109	10	92
Chennai.	4.93	4.94	5.30	19 418	270	89	38	97	7	71
Madurai	0.95	0.96	1.04	2175	39	13	6	15	1	14
Delhi	8.74	9.70	10.26	48 317	630	110	65	103	13	139
Bhopal	1.08	1.06	1.26	3743	56	22	6	12	2	17
Indore	1.71	1.81	1.93	6353	93	46	10	13	3	27
Hyderabad	2.37	2.37	2.71	8882	140	45	13	29	4	36
Jaipur	2.25	2.43	2.58	9339	121	42	20	32	3	35
Jodhpur	0.92	0.98	1.05	3663	50	21	7	13	2	14
Kota	0.65	0.72	0.76	2074	31	10	4	5	1	10
Nagpur	1.28	1.48	1.53	3411	62	16	7	6	1	20
Nashik	0.62	0.68	0.71	2121	35	8	3	5	1	9
Aurangabad	0.43	0.75	0.52	1158	25	8	4	2	1	7
Mumbai	2.57	2.82	3.05	15 989	196	39	20	82	4	41
Pune	2.34	2.52	2.72	8720	133	33	16	17	3	36
Kolkata	1.40	1.61	1.71	12 757	151	59	10	52	5	24
Total	51.03	56.71	60.86	220 560	3185	879	351	676	81	810

4.4. GHG Emissions Per Unit Area of 25 Cities

The city-wise emission per unit area for 25 cities for the year 2017 in respect of PM, CO, CO₂, NO_x, SO₂, CH₄, and HC due to on-road vehicle stock is summarized in Table 3. It can be seen from Table 3 that though many cities outnumbered Kolkata in terms of their vehicle stock, regarding GHG gas emissions per unit city area, it remained in the top position. The CO₂ emission contribution per unit area was highest in Kolkata with 62.23 Gg km⁻² during

2017, which was much higher than the 25-city average of 24.52 Gg km⁻². Other significant cities in terms of higher CO₂ emission contribution per unit area were Delhi (61.94 Gg km⁻²), Jodhpur (46.61 Gg km⁻²), Chennai (45.58 Gg km⁻²), Bengaluru (37.07 Gg km⁻²), Mumbai (36.53 Gg km⁻²), Rajkot (29.01 Gg km⁻²), and Ahmedabad (28.24 Gg km⁻²) as can be seen from Table 3.

Kolkata was in the 2nd position in terms of CO (737 Mg km⁻²) emission per unit area while the leading position was with Delhi (808 Mg km⁻²). Cities like Jodhpur (634 Mg km⁻²), Chennai (633 Mg km⁻²), Rajkot (523 Mg km⁻²), and Bengaluru (521 Mg km⁻²) had much higher CO emission per unit area than the 25-city average of 372 Mg km⁻². Kolkata topped the list of NO_x emissions per unit area with 290 Mg km⁻² during 2017. Cities like Jodhpur (266 Mg km⁻²), Chennai (210 Mg km⁻²), and Bengaluru (170 Mg km⁻²) were also found to be well ahead of the 25-city per unit area average of NO_x emission (110 Mg km⁻²). Kolkata held the 7th position, amongst the 25 cities for CH₄ emission per unit area (51 Mg km⁻²) after cities like Chennai (89 Mg km⁻²), Jodhpur (86 Mg km⁻²), Delhi (84 Mg km⁻²), Varanasi (65 Mg km⁻²), Bengaluru (63 Mg km⁻²), and Ahmedabad (51 Mg km⁻²). However, with 254 Mg km⁻² of SO₂ emission and 23 Mg km⁻² of PM emission per unit area, Kolkata outpaced the other cities by a significant margin. In terms of HC emission, Kolkata ranked 8th with 106 Mg km⁻² where the leading cities were Delhi (178 Mg km⁻²), Jodhpur (173 Mg km⁻²), Chennai (168 Mg km⁻²), Allahabad (158 Mg km⁻²), Rajkot (145 Mg km⁻²), and Bengaluru (129 Mg km⁻²).

All the 25 major million-plus cities are very important from the viewpoint of the Indian economy as they are the centre of many commercial and industrial establishment and providing livelihood and to a large chunk of the Indian population since the independence of the country. A recent report, Global Metro Monitor [8] indicates that higher CO₂ emitting cities are also in the list of top ten wealthiest cities of India in terms of their Gross Domestic Product (GDP) contribution towards the national economy. The economic progress has also contributed towards total passenger travel demand and hence surge in the vehicle population. Fig. 4(A)–(C), drawn with the inputs from Table 3 present the increasing nature of emissions per unit area for the 25 cities during 2015–2017. The highest increase was recorded for Rajkot and Vadodara with 116 % and 104 % respectively during 2015–2017. Allahabad was the only city where CO₂ emission per unit area gone down by 35 % during 2015–2017. Interestingly, the CO₂ emission per unit area for Delhi, with the largest vehicle stock, marginally increased by 15 % (from 54 Gg km⁻² to 62 Gg km⁻²) during 2015–2017. The other cities with a comparative higher increase of CO₂ emission were Bhopal (26 %), Meerut (23 %), Nagpur (23 %), Bengaluru (22 %), Indore (22 %), Aurangabad (21 %), and Kolkata (21 %) during 2015–17. The average increase of CO emission per unit area across the 25 cities during 2015–2017 was 19 %. However, massive CO emission increased in Vadodara (111 %, 146 to 308 Mg km⁻²) and Rajkot (106 %, 235 to 483 Mg km⁻²) during 2015–2017. CO emissions per unit area also grew in Nagpur (27 %) followed by Delhi (24 %), Bangalore (24 %), Bhopal (23 %), Indore (20 %), Jaipur (19 %), and Kolkata (19 %) during 2015–2016. The average increase in NO_x emission per unit area across the 25 cities during 2015–2017 was 21 %. However, NO_x emission significantly increased in cities like Bhopal (108 %), Vadodara (99 %), Rajkot (93 %), Indore (92 %), Delhi (50 %), Nagpur (29 %), Pune (28 %), Bengaluru (17 %) and Kolkata (15 %) during 2015–2016. The average increase in CH₄ emission per unit area across the 25 cities during 2015–2016 was 24 %. Again, Vadodara and Rajkot led the cities in terms of increase of CH₄ emission with 74 % and 72 % respectively during 2015–2016 followed by Delhi (36 %), Pune (31 %), Nagpur (25 %), Varanasi (20 %), Bhopal (19 %), Bengaluru (18 %), and Kolkata (15 %). The average SO₂ emission per unit area across the 25 cities during 2015–2017 was 16 %. The city of Pune had the highest increase in

SO₂ emission per unit area during 2015–2016 with 137 % followed by Rajkot (112 %), Delhi (99 %), Vadodara (94 %), Mumbai (77 %), Bengaluru (62 %), and Nagpur (60 %). Kolkata had a modest increase in SO₂ emission of 8 % per unit area during 2015–2017.

TABLE 3. GHG EMISSION FOR 25 INDIAN CITIES PER UNIT AREA DURING 2017

Metro Cities	Nr. of road vehicles	% of total	Area*, km ²	CO ₂	CO	NO _x	CH ₄	SO ₂	PM	HC
				Gg km ⁻²	Mg km ⁻²					
Ahmedabad	3 904 952	6.44	464	28.24	462	122	59	53	12	109
Rajkot	1 926 305	3.18	170	29.01	523	137	45	60	14	145
Vadodara	2 021 688	3.33	300	19.19	331	84	28	47	8	86
Surat	2 886 950	4.76	326.5	22.66	415	88	32	23	9	114
Allahabad	1 022 995	1.69	82	16.22	421	124	37	52	11	158
Kanpur	1 632 682	2.69	403.7	11.36	162	45	12	10	3	55
Meerut	623 559	1.03	141.9	11.14	181	41	20	19	4	57
Varanasi	906 833	1.50	82.1	24.64	471	145	65	87	13	142
Lucknow	1 978 345	3.26	349	15.60	233	44	21	27	4	75
Bengaluru	6 833 080	11.27	709	37.07	521	170	63	153	15	129
Chennai	5 298 883	8.74	426	45.58	633	210	89	228	17	168
Madhurai	1 037 239	1.71	148	14.69	265	91	39	98	7	92
Delhi	10 260 052	16.92	780	61.94	808	141	84	133	17	178
Bhopal	1 255 784	2.07	285.9	13.09	197	78	22	41	6	59
Indore	1 934 588	3.19	530	11.99	176	87	19	24	6	50
Hyderabad	2 714 510	4.48	367	24.20	381	124	35	79	11	99
Jaipur	2 583 107	4.26	484.6	19.27	250	87	42	66	7	72
Jodhpur	1 051 813	1.73	78.6	46.61	634	266	86	166	20	173
Kota	763 690	1.26	527	3.94	59	18	7	10	1	19
Nagpur	1 526 777	2.52	227.4	15.00	274	72	32	28	6	89
Nashik	707 918	1.17	264.2	8.03	133	32	11	17	3	33
Aurangabad	515 481	0.85	139	8.33	183	58	26	15	6	47
Mumbai	3 052 901	5.03	437.71	36.53	447	89	46	187	10	93
Pune	2 717 322	4.48	331.3	26.32	400	99	47	52	9	109
Kolkata	1 709 192	2.82	205	62.23	737	290	51	254	23	119
Total	60 866 646	100	330*	24.52*	372*	110*	41*	77*	10*	99*

Source: Author's calculations using [38] equation. * 25 city average

** City geographical area

Though the average PM emission per unit area across the 25 cities during 2015–2017 was 21 %, two cities like Vadodara and Rajkot registered a much higher rise of 112 % and 103 % respectively during the same period. Bhopal (48 %), Indore (45 %), Delhi (42 %), Nagpur (30 %), and Bengaluru (23 %) were the other cities with a reckonable rise in PM emission during 2015–2017 as can be seen from the Fig. 4(A)–(C) and also Table 3. In comparison, Kolkata had a modest rise of PM (15 %) during the same period.

Fig. 4. GHG emission per unit area across 25 cities: A) 2015; B) 2016; C) 2017.

The HC emission per unit area across the 25 cities during 2015–2017 was 20 %. Again, the two cities of Rajkot and Vadodara topped the list of increase in HC emission level during 2015–2017 with 94 % and 92 % respectively. Three cities like Bengaluru, Bhopal, and Kolkata came next with a 22 % rise of HC in each of the cities during 2015–2017.

4.5. Emission from Different Vehicle Types of Metropolitan Cities

Emission contributions from different types of vehicles during 2017 for the top five metropolitan cities, i.e., Bangalore, Mumbai, Delhi, Chennai, and Kolkata were calculated using the IPCC equation and summarized in Table 4. It can be observed that in Bangalore, out of 26 143 Gg of CO₂ emissions during 2017, the highest emission came from cars (71.18 %, 18 609 Gg), followed by taxis (7.06 %, 1845 Gg), truck and lorries (5.06 %, 1323 Gg) and buses plus omnibuses combination (7.61 %, 1991 Gg). Similarly, the highest contributor of CO in Bangalore was cars (47.4 %, 164.8 Gg) followed by two-wheelers (18.86 %, 65.6 Gg), LMVG (11.39 %, 39.6 Gg), and LMVP (10.99 %, 38.2 Gg). The highest contributor for NO_x were buses plus omnibuses combination (40.58 %, 46.4 Gg) followed by trucks and lorries (14.16 %, 16.2 Gg). For CH₄, the highest contributor was cars (61.01 %, 14.2 Gg) while for SO₂, PM and HC, the highest contributors were taxis (83.91 %, 91 Gg), cars (22.8 %, 2.5 Gg), two-wheelers (58.09 %, 42.3 Gg) respectively. Emission analysis of Mumbai, based on the vehicle types, reveals that cars and taxis (car: 80 %, taxis 10 %) together contributed to about 90 % of CO₂ emission of 15956 Gg while cars and two-wheelers (car: 61 %, two-wheelers 13 %) together contributed about 74 % of CO emission of 187.8 Gg during 2017. Similarly, two-wheelers were the primary source of HC emission (16 Gg; 48 %), CH₄ (2.0 Gg; 15 %), and PM (0.6 Gg; 12 %) in Mumbai. Cars were a major source for CH₄ (9.8 Gg, 72 %), HC (14.4 Gg, 43 %), PM (1.7 Gg, 36 %), and NO_x (11.5 Gg, 32 %) emission while taxis accounted for very high SO₂ (76.9 Gg, 94 %) emission in the city of Mumbai. In Kolkata, cars (9451 Gg, 74 %) and omnibuses (1041 Gg, 8 %) contributed the majority (82 %) of total CO₂ emissions (12757 Gg) while Car (83.7 Gg, 58 %) and LMVG (27.4 Gg, 19 %) contributed for 77 % of total CO emission in the city during 2017. Taxis and cars were a major source of SO₂ emission (43.5 Gg, 83 %) and CH₄ emission (7.2 Gg, 75 %). Cars (1.3 Gg, 26 %), Omnibuses (1.1 Gg, 23 %), and LMVG (1.1 Gg, 22 %), together contributed about 71 % of total PM in the city air. Cars (10.6 Gg, 48 %) and two-wheelers (6.7 Gg, 31 %) jointly contributed to about 79 % of total HC in the city. In the case of Delhi, a city with a large vehicle stock, 90 % of total CO₂ (43106 Gg) was emitted by its cars while car (381.7 Gg, 64 %) and LMVG (93.1 Gg, 16 %) together contributed 80 % of total CO emission during 2017. Cars (38.6, 38 %) and LMVG (23.4 Gg, 23 %) jointly contributed to 61 % of total NO_x emitted in the city. The single most significant SO₂ contributor was the taxies (89.4 Gg, 86 %) plying in Delhi city while cars (5.8 Gg, 42 %) and LMVG (3.7 Gg, 26 %) were the leading contributors of total PM. Cars (48.2 Gg, 43 %) and two-wheelers combination (59.0 Gg, 52 %) was responsible for 95 % of HC emission of Delhi. For Chennai city, cars were the leading contributor (12 959 Gg, 67 %) for total CO₂ emission (19266 Gg) during 2017 while cars (114.8 Gg, 45 %) and two-wheelers (52.5 Gg, 21 %) combination was responsible for 66 % of CO emission in the city. Buses (21.3 Gg, 25 %), Truck and lorries (16.5, 20 %), and cars (11.6 Gg, 14 %) together emitted the bulk (59 %) of total NO_x in the city. Cars (9.9 Gg, 59 %) and two-wheelers (4.3 Gg, 26 %) jointly emitted 85 % of total CH₄ while taxis of Chennai solely contributed 84 % (81.5 Gg) of SO₂ emission.

Comparison across five cities reveals that cars were responsible for 49 % of CO₂ emission for Chennai followed by 40 % for Bengaluru, 35 % for Kolkata, 24 % for Mumbai, and only 12 % for Delhi during 2017. Also, cars were responsible for 64 % of the total CO of Delhi, followed by 61 % for Mumbai, and 55 % for Kolkata. NO_x emissions of Kolkata (41 %) and

Bengaluru (21 %) were due to omnibuses while for Delhi (38 %) and Mumbai (32 %) it was cars. SO₂ emission was hugely dependent on taxis as revealed from Table 4 that they were contributing 94 % of the total for Mumbai followed by Delhi (86 %), Chennai (84 %), Bengaluru (84 %), and Kolkata (83 %). Cars were responsible for CH₄ and PM emission for Bengaluru (CH₄, 61 %; PM, 23 %), Mumbai (CH₄, 72 %; PM, 36 %), Kolkata (CH₄, 75 %; PM, 27 %), Delhi (CH₄, 74 %; PM, 42 %) and Chennai (CH₄, 59 %; PM, 22 %). Two-wheelers contributed 60 % of total HC for Chennai, 58 % for Bengaluru, 52 % for Delhi, 48 % for Mumbai, and 36 % for Kolkata.

TABLE 4. EMISSION FROM DIFFERENT VEHICLE TYPES IN FIVE METROPOLITAN CITIES OF INDIA (GG), 2017

BL	TL	LG	BU	TA	LP	TW	CA	JP	OB	TT	TL	OT	Total
CO ₂	1323	468	930	1845	314	793	18 609	108	1061	158	121	412	26 143
CO	9.3	39.6	6.5	8.0	38.2	65.6	164.8	1.0	7.4	1.6	1.2	4.6	347.6
NO _x	16.2	9.9	21.7	4.4	9.6	5.7	16.7	0.1	24.7	0.4	0.3	4.7	114.3
CH ₄	0.2	1.4	0.2	0.1	1.4	5.4	14.2	0.1	0.2	0.03	0.0	0.1	23.2
SO ₂	3.7	0.2	2.6	91.2	0.2	0.4	4.4	0.0	3.0	0.4	0.3	2.3	108.7
PM	0.7	1.6	1.0	0.6	1.5	1.5	2.5	0.0	1.2	0.06	0.1	0.3	11.0
HC	2.2	1.1	1.6	1.2	1.1	42.3	20.8	0.1	1.8	0.04	0.0	0.7	72.9
MU													
CO ₂	54.3	177.9	295.3	1555	212	299.1	12 838	415.5	80.2	2.07	1.1	25.32	15 956
CO	0.4	15.1	2.1	6.7	20.6	24.7	113.7	3.7	0.6	0.0	0.0	0.3	187.8
NO _x	0.7	3.8	6.9	3.7	5.2	2.1	11.5	0.4	1.9	0.0	0.0	0.3	36.4
CH ₄	0.0	0.5	0.1	0.1	0.7	2.0	9.8	0.3	0.0	0.0	0.0	0.0	13.5
SO ₂	0.2	0.1	0.8	76.9	0.1	0.2	3.0	0.1	0.2	0.0	0.0	0.1	81.7
PM	0.0	0.6	0.3	0.5	0.8	0.6	1.7	0.1	0.1	0.0	0.0	0.0	4.7
HC	0.1	0.4	0.5	1.0	0.6	16.0	14.4	0.5	0.1	0.0	0.0	0.0	33.5
KL													
CO ₂	185.9	323.5	337.3	879.6	54.8	126.7	9451	0.0	1041	55.4	2.42	299.7	12 757
CO	1.3	27.4	2.4	3.8	4.6	17.0	83.7	0.0	7.3	0.6	0.0	3.4	151.4
NO _x	2.3	6.9	7.9	2.1	1.2	2.3	8.5	0.0	24.2	0.1	0.0	3.4	58.8
CH ₄	0.0	1.0	0.1	0.0	0.2	0.9	7.2	0.0	0.18	0.0	0.0	0.1	9.6
SO ₂	0.5	0.2	1.0	43.5	0.0	0.1	2.2	0.0	2.9	0.2	0.0	1.7	52.1
PM	0.1	1.1	0.4	0.3	0.2	0.1	1.3	0.0	1.1	0.0	0.0	0.2	4.8
HC	0.3	0.8	0.6	0.6	0.1	8.7	10.6	0.0	1.8	0.0	0.0	0.5	3.80
DL													
CO ₂	39.6	1101	900.1	1807	0.0	1105	43 106	0.0	0.1	2.3	0.0	22.6	48 083
CO	0.3	93.1	6.3	7.8	19.2	91.4	381.7	0.0	0.0	0.0	0.0	0.3	600.0
NO _x	0.5	23.4	21	4.3	4.8	7.9	38.6	0.0	0.0	0.01	0.0	0.3	100.7
CH ₄	0.0	3.4	0.2	0.1	0.7	7.5	32.8	0.0	0.0	0.0	0.0	0.0	44.5

SO₂	0.1	0.5	2.5	89.4	0.1	0.5	10.2	0.0	0.0	0.0	0.0	0.1	103.5
PM	0.0	3.7	1.0	0.6	0.8	2.1	5.8	0.0	0.0	0.0	0.0	0.0	13.9
HC	0.1	2.6	1.5	1.1	0.5	59.0	48.2	0.0	0.0	0.0	0.0	0.0	113.0
CN													
CO₂	1346	349.3	913	1649	76.3	635.1	12 959	179	190.5	29.8	127	813	19 266
CO	9.4	29.5	6.4	7.1	19	52.5	114.8	1.6	1.3	0.3	1.3	9.1	252.3
NO_x	16.5	7.4	21.3	4.0	4.8	4.5	11.6	0.2	4.4	0.1	0.3	9.2	84.2
CH₄	0.2	1.0	0.2	0.1	0.7	4.3	9.9	0.1	0.0	0.0	0.0	0.3	16.8
SO₂	3.7	0.2	2.5	81.5	0.1	0.3	3.1	0.0	0.5	0.1	0.4	4.6	97.0
PM	0.7	1.2	1.0	0.6	0.8	1.2	1.7	0.0	0.2	0.0	0.1	0.6	8.0
HC	2.3	0.8	1.5	1.0	0.5	34	14.5	0.2	0.3	0.0	0.0	1.3	56.4

Abbreviations: TL: Truck, Lorries; LG: LMVG; BU: Buses; TA: Taxis; LP: LMVP; TW: Two-wheelers; CA: Car; JP: Jeep; OB: Omnibuses; TT: Tractor TL: Trailer; OT: Others; BL: Bangalore; MU: Mumbai; KL: Kolkata; DL: Delhi; CN: Chennai.

5. CONCLUSION

City-wise emission inventory, exclusively for the road transport sector, is of utmost importance for India as the country depends heavily on the road network for freight and passenger traffic movements. Benefits from city-wise emission inventory would be in terms of timely policy prescription mitigation of vehicular emission and reduction of GHG emissions. The road transport led emission inventory for a representative Indian city, i.e., Kolkata for the period 2015–2025 has been assessed. The road transport led emission inventory for 25 million-plus population Indian cities including Kolkata for the year 2015–2017 has been assessed and their GHG emissions per unit area have been compared. It is estimated that there would be about 2.79 million vehicle stock in the city of Kolkata during 2025 resulting in increased emission of pollutants in the city by 2025. By 2025 the vehicular emission of Kolkata will reach to massive 21 668.24 Gg of CO₂, 272.81 Gg of CO, 98.21 Gg of NO_x, 16.9 Gg of CH₄, 93.39 Gg of SO₂, 8.6 Gg of PM, and 38.55 Gg of HC.

The rapid urbanization of the cities led to an increase in total passenger travel demand with time. Accordingly, the vehicle stock of the 25 million-plus leading cities increased by 19 % during 2015–2017. In terms of vehicle stock, Delhi topped the list with mammoth 10.26 million vehicles during 2017, followed by cities like Bengaluru (6.83 million), Chennai (5.30 million). Ahmedabad (3.90 million), Mumbai (3.05 million), and Surat (2.89 million). The city Rajkot and Vadodara had the highest rise of vehicle stock with 97 % and 94 % respectively followed by the south Indian city Bengaluru (24 %), Kolkata (22 %), Aurangabad (21 %), Nagpur (20 %), Mumbai (19 %) and Meerut (18.62 %). With the increase in vehicle stock, the transport emission load on the Indian cities also increased [49]. During 2017, all the 25 leading Indian cities together emitted 220560 Gg of CO₂. Delhi had the highest vehicular emission contribution during 2017 with 22 % of the total CO₂ emission followed by cities like Bengaluru (26 285 Gg, 12 %), Chennai (19 418 Gg, 9 %), Mumbai (15 989 Gg, 7 %), Ahmedabad (13 104 Gg, 6 %) and Kolkata (12 757 Gg, 6 %). In terms of CO, NO_x, CH₄, SO₂, PM, and HC emission Kolkata ranked sixth (151 Gg, 5 %), fourth (59 Gg, 7 %), eighth (10 Gg, 2.9 %), fifth (52 Gg, 8 %), fifth (5 Gg, 6 %) and eighth (24 Gg, 4 %) respectively out of the 25 cities total emission (3185 Gg).

In terms of GHG emissions per square kilometre of the city area, Kolkata topped the list amongst 25 million-plus cities. The CO₂ emission contribution per unit area was highest in Kolkata with 62 Gg km⁻² during 2017, which was significantly higher than the 25-city average of 24 Gg km⁻². The city also outpaced the other 24 cities by a significant margin with 254 Mg km⁻² SO₂ emission, 23 Mg km⁻² PM emission, and 290 Mg km⁻² for NO_x during 2017. Kolkata occupied the second position in terms of CO emission per unit area (737 Mg km⁻²), the seventh position for CH₄ emission (51 Mg km⁻²), and the eighth position for HC emission per unit area (106 Mg km⁻²) amongst the 25 cities considered in this study.

Emission analysis based on pollution contribution of different types of road transport vehicles for five metropolitan cities, i.e., Bangalore, Mumbai, Delhi, Chennai, and Kolkata reveal that cars were primarily responsible for CO₂, CO, NO_x, CH₄, and PM emission in these five cities during 2017. At the same time, taxis were responsible for SO₂ emission and two-wheelers for HC emission. For Kolkata, cars were responsible for 35 % for CO₂, 55 % of CO, 75 % of CH₄, 27 % of PM, omnibuses for 41 % for NO_x emission, taxis for 83 % of SO₂, and two-wheelers 36 % for HC emissions during 2017. The identification of vehicle categories responsible for major emissions in cities will be handy for the city policymakers to come up with appropriate policy options to curb emissions from the road transport sector.

Alarmed by the huge vehicular pollution in cities, the central government has taken several initiatives like increasing the CNG network to cover more cities, expansion of metro rail networks, and introducing electric vehicles in the cities. However, most remarkable was the recent decision to leapfrog from BS-IV fuel to BS-VI fuel without shifting to BS-V fuel (Indian equivalent to Euro-IV to Euro-VI) and hence directed only BS-VI compliant vehicles should be sold in the country from April 1st, 2020. No doubt, this drastic step was the need of the hour for Indian cities, and it is likely to improve the city air quality. However, the existing BS-IV compliant vehicles have been allowed to remain operational for their entire duration of registration. Both BS-VI fuel and BS-VI compliant vehicles will surely bring down vehicular emission resulting in better air quality in cities. This study, therefore, is very timely and vital from the point of view that it would provide a benchmark to the policymakers and researchers for comparing the emission improvement in the 25 representative cities of India resulting from new initiatives to clean city air in the years to come. Our study has a few limitations as well. The non-availability of updated (type-wise) vehicle utilization rates and emission factors for diesel and gasoline vehicles separately under different engine standards like BS-I to BS-V impaired the total emission estimation. Further, the non-availability of data regarding the numbers of the new vehicles added up in the city stock with technologies per year and year-wise phasing out of vehicles with old technologies made it difficult to bring out the benefits of technological improvements in emission reduction at different point of time.

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REFERENCES

- [1] Khare A. Planet earth and automobiles, with special reference to the Indian Vehicle Industry. *Technovation* 1998;18(5):353–359. [https://doi.org/10.1016/S0166-4972\(98\)00017-0](https://doi.org/10.1016/S0166-4972(98)00017-0)
- [2] Pal R., et al. 18-Year Ambient PM_{2.5} Exposure and Night Light Trends in Indian Cities: Vulnerability Assessment. *Aerosol and Air Quality Research* 2018;18:2332–2342. <https://doi.org/10.4209/aaqr.2017.10.0425>

- [3] WHO. Global Urban Ambient Air Pollution Database (update 2016) [Online]. [Accessed 02.06 2020]. Available: <https://www.who.int/airpollution/data/cities-2016/en/>
- [4] Central Pollution Control Board. National Ambient Air Quality Status 2009. Delhi: Ministry of Environment & Forests, 2009.
- [5] World Bank. India transportation, 2011 [Online]. [Accessed 12.05.2020]. Available: <https://www.worldbank.org/en/news/feature/2011/09/23/india-transportation>
- [6] Mondal R., et al. Ground level concentration of nitrogen oxides (NO_x) at some traffic intersection points in Calcutta. *Atmospheric Environment* 2000;34(4):629–633. [https://doi.org/10.1016/S1352-2310\(99\)00216-2](https://doi.org/10.1016/S1352-2310(99)00216-2)
- [7] Gurjar B. R., Nagpure A. S. Indian megacities as localities of environmental vulnerability from air quality perspective. *Journal of Smart Cities* 2015;1(1):15–30. <https://doi.org/10.18063/JSC.2015.01.003>
- [8] Bouchet M., et al. Global Metro Monitor Brookings 2018. Washington: MPP, 2018.
- [9] Ramanathan R. Link between population and number of vehicles. Evidence from Indian cities. *Cities* 2000;17(4):263–269. [https://doi.org/10.1016/S0264-2751\(00\)00022-6](https://doi.org/10.1016/S0264-2751(00)00022-6)
- [10] Das A., Parikh J. Transport scenarios in two metropolitan cities in India: Delhi and Mumbai. *Energy Conversion and Management* 2004;45(15–16):2603–2625. <https://doi.org/10.1016/j.enconman.2003.08.019>
- [11] Badami M. G. Transport and urban air pollution in India. *Environmental Management* 2005;36(2):195–204. <https://doi.org/10.1007/s00267-004-0106-x>
- [12] Mukherjee A., Mukherjee G. Occupational exposure of the traffic personnel of Calcutta to lead and carbon monoxide. *Pollution and Research* 1998;17(4):359–362.
- [13] Kazimuddin A., Banerjee L. Fighting for Air. Down to Earth. 2000.
- [14] Ramachandra T. V., Shwetmala. Emissions from India's transport sector: State wise synthesis. *Atmospheric Environment* 2009;43(34):5510–5517. <https://doi.org/10.1016/j.atmosenv.2009.07.015>
- [15] Gurjar B. R., et al. Emission estimates and trends (1990–2000) for mega-city Delhi and implications. *Atmospheric Environment* 2004;38(33):5663–5681. <https://doi.org/10.1016/j.atmosenv.2004.05.057>
- [16] Nagpure A. S., Gurjar B. R. Development and evaluation of vehicular air pollution inventory model. *Atmospheric Environment* 2012;59:160–169. <https://doi.org/10.1016/j.atmosenv.2012.04.044>
- [17] Rajasekhar R. V. J., et al. A study on automobile emission patterns in Madurai city. *Pollution Research* 2005;24(4):767–768.
- [18] Goyal P., Mishra D., Kumar A. Vehicular emission inventory of criteria pollutants in Delhi. *Springer Plus* 2014;2:216. <https://doi.org/10.1186/2193-1801-2-216>
- [19] Goel R., et al. Assessment of motor vehicle use characteristics in three Indian cities. *Transport Research Part D: Transport and Environment* 2015;44:254–265. <https://doi.org/10.1016/j.trd.2015.05.006>
- [20] Sindhwani R., Goyal P. Assessment of traffic-generated gaseous and particulate matter emissions and trends over Delhi (2000–2010). *Atmospheric Pollution Research* 2014;5(3):438–446. <https://doi.org/10.5094/APR.2014.051>
- [21] Venkatasamy S., Vijay Bhaskar B. Emission Inventory-A preliminary approach to primary pollutants. *Current Science Association* 2016;111(11):1831–1835. <https://doi.org/10.18520/cs/v111/i11/1831-1835>
- [22] Mahesh S., Ramadurai G. Analysis of driving characteristics and estimation of pollutant emissions from intra-city buses. *Transportation Research Procedia* 2017;27:1211–1218. <https://doi.org/10.1016/j.trpro.2017.12.071>
- [23] Mohan M., Dagar L., Gurjar B. R. Preparation and validation of gridded emission inventory of criteria air pollutants and identification of emission hotspots for megacity Delhi. *Environmental Monitoring and Assessment* 2007;130:323–339. <https://doi.org/10.1007/s10661-006-9400-9>
- [24] Baidya S., Borken-Kleefeld J. Atmospheric emissions from road transportation in India. *Energy Policy* 2009;37(10):3812–3822. <https://doi.org/10.1016/j.enpol.2009.07.010>
- [25] Gurjar B.R., et al. Human health risks in megacities due to air pollution. *Atmospheric Environment* 2010;44(36):4606–4613. <https://doi.org/10.1016/j.atmosenv.2010.08.011>
- [26] Mahadevappa H. A study on air pollution by automobiles in Bangalore city. *Management Research and Practice (MRP)* 2012;4(3):25–36.
- [27] Singh R., Sharma C. Assessment of emissions from transport sector in Delhi. *Journal of Scientific and Industrial Research* 2012;71(2):155–160.
- [28] Nagpure A. S., Sharma K., Gurjar B.R. Traffic induced emission estimates and trends (2000–2005) in megacity Delhi. *Urban Climate* 2013;4:61–73. <https://doi.org/10.1016/j.uclim.2013.04.005>
- [29] National Green Tribunal. Compliance report before the national green tribunal principal bench, O.A. No 681 of 2018 New Delhi. New Delhi: NGT, 2018.
- [30] Ghose M. K., Paul R., Banerjee S. K. Assessment of the impacts of vehicular emissions on urban air quality and its management in the Indian context: the case of Kolkata (Calcutta). *Environmental Science and Policy* 2004;7(4):345–351. <https://doi.org/10.1016/j.envsci.2004.05.004>
- [31] Das R., et al. Trace Element Composition of PM_{2.5} and PM₁₀ from Kolkata - A Heavily Polluted Indian Metropolis. *Atmospheric Pollution Research* 2015;6(5):742–750. <https://doi.org/10.5094/APR.2015.083>
- [32] Singh R., and Sharma, C., Agrawal, M. Emission inventory of trace gases from road transport in India. *Transportation Research Part D: Transport and Environment* 2017;52:64–72. <https://doi.org/10.1016/j.trd.2017.02.011>

- [33] Spiroska J., Rahman M. A., Pal S. Air pollution in Kolkata: An analysis of current status and interrelation between different factors. *SEEU Review* 2011:8(1):182–214. <https://doi.org/10.2478/v10306-012-0012-7>
- [34] Census. Urban Agglomerations Census 2011. India. [Online]. [Accessed on 12.05.2020]. Available: <https://www.census2011.co.in/urbanagglomeration.php>
- [35] Indiatat. Socio-economic statistical information about India, 2018. [Accessed 12.06.2020]. Available: <http://www.indiatat.com/transport/30/vehicles/289/stats.aspx>
- [36] OGD. Open Government Data Platform. Government of India, 2018. [Accessed 02.08.2020]. Available: https://data.gov.in/search/site?query=transport&filter%5Bfield_group_name%3Aname%5D=Road+Transport
- [37] Ministry of Road Transport & Highways. Road Transport Year Book (2011–12). New Dehli: MoRTH, 2012.
- [38] IPCC. 2006 Guidelines for National Greenhouse Gas Inventories [Online]. [Accessed 16.02.2020] Available: <https://www.ipcc-nggip.iges.or.jp/public/2006gl/>
- [39] Central Pollution Control Board. Status of pollution generated from road transport in six megacities ministry of environment, forest and climate change. New Delhi: CPCB, 2015.
- [40] Ministry of Road Transport & Highways. The Working Group Report on Road Transport for the Eleventh Five Year Plan, Planning Commission. New Dehli: MoRTH, 2007.
- [41] ARAI Revision. The Automotive Research Association of India. Emission Factor Development for India Vehicles, Air Quality Monitoring Project-Indian Clean Air Programme, 2008. [Online]. [Accessed 28.10.2020]. Available: http://www.cpcb.nic.in/Emission_Factors_Vehicles.pdf
- [42] Central Pollution Control Board. Transport fuel quality for the year 2005. New Dehli: CPCB, 2005.
- [43] Mittal M. L., Sharma C. Anthropogenic emissions from energy activities in India: generation and source characterization. (Part II): emissions from Vehicular Transport in India. 2003.
- [44] European Environment Agency. EMEP/CORINAIR Atmospheric Emission Inventory Guidebook. Copenhagen: EEA, 2001.
- [45] Reynolds C. C. O., Grieshop A. P., Kandlikar M. Climate and health relevant emissions from in-use Indian three-wheelers fuelled by natural gas and gasoline. *Environmental Science and Technology* 2011:45(6):2406–2412. <https://doi.org/10.1021/es102430p>
- [46] Mashelkar R. A., et al. Report of the expert Committee on auto fuel policy. New Dehli: Ministry of Petroleum and Natural Gas, 2002.
- [47] UNEP. Global environment outlook. London: Earthscan, 1999.
- [48] Kandlikar M., Ramachandran G. The causes and consequences of particulate air pollution in urban India: a synthesis of the science. *Annual Review of Energy and the Environment* 2000:25(1):629–684. <https://doi.org/10.1146/annurev.energy.25.1.629>
- [49] Dutta G., Dutta A. Indian growth story of automobile sector and atmospheric emission projection. *Pollution Research* 2018:37(1):131–143.