Emissions inventory for road transport in India in 2020: Framework and post facto policy impact assessment

Namita Singh (namita.msu@gmail.com)
Indian Institute of Technology Bombay
Trupti Mishra
Indian Institute of Technology Bombay
Rangan Banerjee
Indian Institute of Technology Bombay

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Abstract

India's growing population and economic development lead to an increase in transport emissions. Quantification of emissions at frequent intervals is required to assess the emission levels and impact of control policies implemented. Implemented policies affect the fleet configuration over time. Therefore, in the present paper, an age-wise emission analysis framework was developed for the road transport sector with updated fleet characteristics corresponding to the vehicles' age. The results show that fuel consumption is estimated to be 92 (87–95) Mt, and total CO_2, CO, PM, and NOx vehicle emissions are estimated to be 274 (265–292) Tg, 4463 (3253–6676) Gg, 164 (119–250) Gg, and 2378 (2191–3045) Gg, respectively for the reference year 2020. The study contributes by developing an inventory for the fleet of 2020 used as a benchmark to compare past emissions inventories, evaluate control policies, estimate state-wise vehicle emissions inventories, and identify significant emitters in the fleet. Sensitivity analysis indicates the considerable variation in total emissions resulting from different age-mix of vehicles. Among the investigated policies, advancement in emission norms followed by fuel efficiency improvement in vehicles led to a substantial reduction in gaseous pollutants. Based on the inventory results, suitable policies are suggested for India's future fleet, and the need for country-level fleet characteristics data is recommended.

1 Introduction

Globally the transport sector is responsible for 25% of total carbon dioxide (CO_2) emissions from fuel combustion in 2018 (IEA, 2020). It is the fastest growing sector and is a major contributor of global greenhouse gas emissions (Hasan et al. 2019). In India, it is the third most CO_2 emitting sector, and within the transport sector, road transport contributed more than 90% of total CO_2 emissions (IEA, 2020; Ministry of Environment Forest and Climate Change, 2018). The greenhouse gas (GHG) emissions in India consisted of 70% CO_2 and 30% non-CO_2 (methane, nitrous oxide, F-gas) emissions (Olivier and Peters 2020). With economic development in India, the vehicle ownership level has increased with a growth rate of 10.4% for two-wheelers and 11% for cars from 2001 to 2015 (Singh et al. 2020), leading to an increase in emission levels on the road. An increase in vehicle population also contributed significantly to India's air pollution (Guttikunda & Kopakka, 2014). Serious health issues are observed due to high exposure to air pollution (PM and NOx) in India (Guttikunda et al. 2015). Hence, various transport policies were introduced in the past, which impacted the vehicle exhaust emission and influenced the characteristics of the vehicles present in the fleet and their activity levels. Vehicle population with fleet configuration and their activity profile have been significantly affected by the transport policies (Nesamani 2010; Zhang et al. 2014). Therefore, the present paper's objectives are (1) to develop a road transport inventory for the fleet of 2020, (2) conduct multi-year inventories to compare results with past inventories, (3) analyse state-wise emissions and spatial distribution of vehicle emissions per unit area of the states, (4) estimate sensitivity analysis, and (5) examine the impact of different transport control policies implemented in India between 2000 to 2020.

The reforms introduced before the year 2000 were catalytic converters and lead-free petrol in vehicles in 1994-95. The diesel quality improved by introducing 0.5% sulfur diesel in 1996 and 0.25% Sulphur diesel in 1999 (reducing the concentration of SO_2 emitted from the vehicles) (Aggarwal & Jain, 2014). Most of the transport policies were first introduced in metropolitan cities and later in other parts of India. The auto-fuel norms were introduced before 2000 (in 1999), giving a clear-cut road map for passenger vehicle technology changes and corresponding fuel quality for the country (GoI, 2014). Under this policy, vehicles follow the strict emission standard norms introduced as Bharat Stage (BS) norms, equivalent to the Euro norms implemented in Europe. According to the timeline, the BS-IV was implemented entirely in India by 2017. The Ministry of Road Transport & Highways issued a draft notification for the BS-VI emission standards, which would apply to the vehicles manufactured in the year 2020. This initiative would leapfrog from BS-IV to BS-VI emission norms in India by skipping the BS-V emission standard (ICCT, 2016).

Significant policy initiatives were introduced in India to control vehicular emissions, such as a shift in technology, a shift to alternate fuel, and advancement in emission norms from 2000 to 2020. These policies enacted as 1) conversion of two-stroke (2s) engine to four-stroke (4s) engine in two-wheelers and three-wheelers (i.e., shifting to less polluting and more fuel-efficient technology). 2) removal of older heavy diesel vehicles (15 years older) from the fleet in a megacity like Delhi, 3) the introduction of compressed natural gas fuel (CNG) (started in Delhi and later implemented in other cities of India) and biofuel in vehicles (blended with gasoline and diesel) as alternate fuels, 5) diffusion of electric and hybrid cars in the domestic market under the programs National Electric Mobility Mission Plan (Government of India, 2014b) and Faster Adoption and Manufacturing of Electric vehicles (FAME) programs in India. The share of electric vehicles increased from 0.04% in 2011 to 0.8% in 2020 in India. Simultaneously, other alternate fuels such as biofuels, liquified natural gas, and hybrid vehicles grew their share to 1.2% in 2020 in India. CNG is the third most significant road transport fuel in India after gasoline and diesel. However, their share in vehicles remained the same in India's total mix from 2011 to 2020 (CMIE,2020). In the present analysis, gasoline, diesel, and CNG fuels were analyzed in the vehicle mix.

To analyse the impact of vehicle control policies on total road transport emissions, a vehicle emission inventory was developed for 2020. We reviewed past literature on vehicle emissions analysis and found studies following IPCC suggested approaches that estimated emissions using Tier I, Tier II, and Tier III models (IPCC, 1998) (Penman, Gytarsky, Hiraishi, Irving, & Krug, 2006). The choice of method depends on the data availability and objective of the study. Tier I and tier II approach estimate total vehicle emissions by using fuel combustion data from the road transport sector, whereas the Tier III approach involves the vehicles' activity data to analyze total emissions. Tier III approach is an advanced level of analysis and required comprehensive data on vehicle categories and sub-categories. For developing countries like India, national-level emission analysis is complicated due to the unavailability of vehicle characteristics data. Past studies on the Indian road transport sector which have used Tier I and II approaches were Ramanathan and Parikh (1999), Fulton and Eads (2004), Singh et al. (2008), Schipper, Fabian, and Leather (2009), and Ramachandra and Shwetmala (2009). Only a few studies have examined the Tier III

approach to estimate vehicle emissions for India, such as Baidya and Borken-Kleefeld (2009), Pandey and Venkataraman (2014), and Prakash and Habib (2018a). The emission analysis improved with each study, including age-wise segregation of vehicles on the road and reducing uncertainty in total road transport emissions. However, these studies did not highlight the changes over time in the fleet characteristics such as fuel efficiency, the annual average distance traveled, fuel and technology share, and emission norms. Therefore, the present study exhibited a change in fleet characteristics over time with different policies implemented and examined the impact on vehicle emissions (CO_2, CO, PM, and NOx) from the road transport sector at the national and state-level for India in the reference year (2020).

2 Methodology And Data Assumption

The road transport emission inventory for the reference year was determined using the Tier III activity approach model, a bottom-up model. The comprehensive model was built using various fleet configuration assumptions under different transport policies from 2000 to 2020. The assumptions for the model will be explained in detail in this section.

Figure 1 illustrated the study's framework with input parameters involved, analysis required and expected output. The input parameters consisted of vehicle categories and sub-categories, vehicle population based on their survival fractions on the road, fuel efficiency of vehicles, the annual average distance traveled, fuel share, and emission factors. Each input parameter and its assumptions are discussed in detail in the data assumption section of methodology. The method applied was the IPCC bottom-up approach (Tier III) model and uncertainty analysis (sensitivity analysis). The expected outcomes showed reference year (2020) fuel consumption and vehicle emissions (CO_2, CO, PM, and NOx) and the impact of different policies implemented in India from 2000 to 2020 on total vehicle emissions.

2.1 Vehicle Population

Vehicle population is an essential input parameter in the model. The registered vehicle population for India from 1991 to 2020 was used in the model. The vehicles were recorded as two-wheelers (2W), four-wheelers (4W), Bus, Goods vehicles, and Others. These categories were further divided into sub-categories based on the technology and fuel type in them. Figure 2 shows the trend in registered vehicles from 1991 to 2020.

The compound annual growth rates (CAGR) in registered vehicles are 5% for Heavy Diesel Vehicles (HDV), 10% for Light Diesel goods vehicles (LDV), 4% for Buses, 8% for taxis, 8% for passenger three-wheelers (3W) autorickshaws, 9% for motorized two-wheelers (2W), and 6% for four-wheelers (4W) such as cars and jeeps in India from 1991 to 2020 (MoSPI, 2018; CMIE, 2020). Vehicle population on the road is affected by their sales and survival fraction concerning their age (Yan et al., 2014). The survival fraction of vehicles determines their age in the fleet, which affects their emission levels. Emission norms before the year 2000 were not actively implemented in India; however, in 2000, Bharat stage norms became active, and a complete road map of their implementation till 2020 was designed to control vehicle

emissions. In 2017, BS-IV standards were expected to be implemented nationwide in India. For the reference year emission analysis, vehicles' age-wise segregation is required to estimate the emission levels from vehicles running on different BS norms, fuel type, and kilometers traveled. Therefore, we used the model given by Pandey & Venkataraman (2014) to examine the survival fraction of vehicles for the national fleet of 2020. The analysis by Goel & Guttikunda (2015) and Malik & Tiwari (2017) have also determined the survival fraction of vehicles. However, in the Goel and Guttikunda study, the survival fraction of vehicles was determined for Delhi based on a policy to scrap ten years of diesel vehicles and 15 years old gasoline vehicles, which did not apply to the other states of India. And in Malik & Tiwari's (2017) study, the survival fraction was estimated for the freight vehicles along India's major highways. Therefore, the reported survival fraction values by Pandey & Venkataraman (2014) were considered suitable for the present analysis. Eq. (1) was used to estimate the survival fraction of vehicles where α and L_{50} values for 2w and 3w were – 2.9 and 10.1; for 4ws, the values were – 5.2 and 19.8; for buses and goods vehicles, α and L_{50} were – 4.5 and 13 respectively (Pandey & Venkataraman, 2014).

$$Su(i,a) = \frac{1}{1+e^{\left[\alpha\left(1-\frac{a}{L_{50}}\right)\right]}} \tag{1}$$

In the equation, Su(i, a) is the survival fraction of vehicle type 'i' (two-wheeler, three-wheeler, four-wheelers, bus, light diesel vehicles, heavy diesel vehicles) of age 'a'. The estimated Su(i, a) is multiplied with the vehicle population of a particular category (type) in a given year 'a' to obtain the new vehicle population on-road for the given reference year. Using this function, we divided vehicles (from 1991 to 2020) into five different age-groups such as till-2000, post-2000, post-2005, post-2010, and post-2015. The age-group till-2000 included all the vehicles registered before 2000, post-2000 included vehicles registered from 2001 to 2005, post-2005 included vehicles registered from 2006-10, post-2010 included vehicles registered from 2011–2015, and post-2015 included vehicles registered from 2016–2020 in India. The vehicle categories and sub-categories with fuel and technology types considered in the study are shown in Table 1.

Table 1
Vehicle categories analyzed in the study.

Category	Sub-category	Fuel type
Motorized Two-Wheeler (2W)	Two-stroke (2s) (2W 2s)	Gasoline (G)
	Four-stroke (4s) (2W 4s)	
Four-wheelers (4W) (personal)	Car	Gasoline (G)/ Diesel (D)
	Jeep	
Four-wheelers (4W) (inter-para transit)	Taxi	Gasoline (G) /Diesel (D) /CNG (C)
Motorized Three-Wheeler (3W)	Two-stroke (2s) (3W 2s)	Gasoline (G) / Diesel (D) /CNG (C)
	Four-stroke (4s) (3W 4s)	
Public transport	Bus	Diesel (D) / CNG (C)
Light commercial vehicle (LDV)	Three-wheeler	Diesel (D)
Heavy Diesel vehicle (HDV)	Trucks	Diesel (D)

The state-wise road transport emission analysis was conducted using the vehicle population data reported by the Vahan portal of the Centre for Monitoring Indian Economy (CMIE, 2020). Registered vehicle data is available for all the states and union territories except Andhra Pradesh, Ladakh, Madhya Pradesh, Telangana, Jammu and Kashmir, Andaman & Nicobar Islands, and Lakshadweep in the absence of digitized RTO (Regional Transportation Office)). In the study, out of 12 vehicle categories, only eight are used for the analysis. These vehicle categories are further segregated based on age, technology, and fuel, as shown in Table 1.

2.2 Fuel Efficiency of vehicles

Fuel efficiency measures the distance traveled per volume of fuel consumed by the vehicle on the road. Its unit is kilometers per liter (km/L). Fuel efficiency also regulates greenhouse gas emissions (such as CO_2) from the vehicle exhaust. There is a lack of age-wise data of fuel efficiency (corresponding to the age of the fleet vehicles) for different vehicle categories running on diesel, gasoline, and CNG at a national level. We assumed fuel efficiency data from Goel & Guttikunda (2015) to analyze the change in fleet configuration over time. Delhi was the study region in Goel & Guttikunda's (2015) study, but further analysis of different regions (cities) made the authors generalize the values for national-level analysis (Goel et al., 2016). Therefore, we assumed fuel efficiency to be constant across the different states for emission analysis. Figure 3 gives the fuel efficiency adopted for vehicles in five different age-groups

fueled by gasoline (G), diesel (D), and CNG (C). The plot shows the mean value of fuel efficiency in different vehicle categories with error bands.

Vehicles present in post-2015 have higher fuel efficiency than automobiles in previous age-groups, indicating improved fuel efficiency with time. The Coefficient of variation (CV) value is less than one showing low variance in the range (mean, minimum, and maximum) of data for each vehicle category (values below 30% for all the age-groups and vehicle categories).

2.3 Annual Average Distance Traveled of vehicles

Annual average distance traveled (ADT) is the kilometers traveled by a vehicle annually. It is also addressed as vehicle kilometers traveled. Change in ADT depends on the urban infrastructure and urban density of the region. Such data are missing at a national level, hence for the present analysis, it is assumed from Goel & Guttikunda (2015) study. The authors extended their analysis for other states of India and generalized the ADT values for national-level analysis (Goel et al., 2016). For the present investigation, the data were categorized into five age-groups for eight vehicle categories considered in the fleet of 2020. Statistical analysis is performed on the data such as mean, standard deviation, and Coefficient of variation (CV) for the age-wise analysis. The Coefficient of variation value for ADT is below one, and more specifically, less than 30% indicating low variance in the data. Figure 4 shows the annual average distance plot for on-road vehicle categories with error bands (standard deviation of the mean value).

2.4 Fuel share in vehicles

Fuel share is the fuel mix on the road for different vehicle categories present in the fleet of 2020. Automobile fuels such as gasoline and diesel are the dominant transportation fuels in India. The alternate fuel CNG was introduced in early 2000 in buses, taxis, and passenger auto-rickshaws (three-wheeler). However, fuel share data at the national level for different vehicle categories are not available. Therefore, for the present study, it was assumed from various secondary sources such as Aggarwal and Jain (2014), Prakash and Habib (2018), Iyer (2012), MOPNG (2011), MOPNG (2013), MOPNG (2015), and CMIE (2020) Vahan portal for state-wise fuel share among the registered vehicles. The Coefficient of variation value was less than 1 for fuel share. The fuel share values assumed for the fleet of 2020 are shown in Fig. 5.

Heavy diesel vehicles (HDV) such as trucks and light diesel vehicles (LDV) such as three-wheeler goods have diesel fuel in them. Buses have diesel and CNG fuel, but share varies in each age-groups. Taxis and three-wheeler passengers (3W) are gasoline, diesel and CNG fueled. Their percentage varied in each age-groups with CNG share comparatively higher in recent years compared to previous years such as in pre-2000, post-2000, and post-2005. Private vehicles such as two-wheelers (2W), two-strokes, and four-strokes have gasoline as the dominant fuel, and four-wheelers such as cars and jeep have a higher share of vehicles running on gasoline than on diesel. Car owners covering long distances prefer diesel cars and are heavy in size, whereas those covering shorter distances and smaller sizes prefer gasoline cars (Gilmore & Patwardhan, 2016). In India, gasoline cars' sales are higher than diesel cars (Prakash & Habib,

2018). Over the years, gasoline, diesel, and CNG shares vary depending on the technology improvement, improvement in fuel efficiency, and policy norms introduced by the government. Alternate fuel vehicles such as battery-charged electric vehicles, hybrid vehicles, and liquified petroleum gas (LPG) vehicles have a meager share on the road (CMIE, Vahan portal). Hence, these fuels were not included in the calculation of the reference year emission analysis.

2.5 Emission Factors

Emission factors are the emission norms or emission standards implemented to control vehicle exhaust emissions. It depends on various factors such as the vehicle's age, usage, maintenance of the vehicle, speed, road type, vehicle category, fuel type, and fuel quality are just a few to mention. In India, actual on-road emission factors of pollutants based on vehicle testing programs are not available nationally. However, the secondary data available was given by the Automotive Research Association of India (ARAI) (ARAI, 2007) obtained during the certification of new vehicles (Suman Baidya, 2008). In the recent study by Jaiprakash and Habib (2018), emission factors of gaseous pollutants (CO, CO_2, and NOx) were measured for light-duty vehicles such as two-wheelers, cars, and three-wheelers in Delhi and further used to investigate emission inventory at a national level for the reference year 2013. Therefore, emission factors for CO, PM, and NOx in the present analysis are assumed from regulatory agency, literature, and secondary data sources in India such as ARAI (2007), Baidya and Borken-Kleefeld (2009), Jaiprakash et al. (2017), and transport policy.net (https://www.transportpolicy.net/topic/emissions-standards/). The Coefficient of variation analysis for most of the emission factors is more than 30% ($CV \geq 1$). The emission factor for CO_2 emission was assumed from the fuel emission factor divided by the fuel efficiency of the vehicles running on respective fuels (WRI, 2015). We did not use CO_2 emission factors in the literature as values increase with the successive shift in vehicle emission standards from BS-II to BS-III (Aggarwal & Jain, 2014).

Emission factors of gaseous pollutants are controlled by India's emission norms known as Bharat Stage (BS) norms. These norms were introduced in 2000 in megacities of India as BS I and later in the rest of India. BS-IV was expected to be implemented nationwide in 2017. For the analysis, the vehicle age-groups till-2000, post-2000, post-2005, post-2010, and post-2015 are assumed to be running no-BS norms, BS-I, BS-II, BS-III, and BS-IV standards, respectively. Figure 6 (a), (b), (c), and (d) give emission factors of CO_2, CO, PM, and NOx for the vehicles in the fleet of 2020. The plot shows the mean value of the emission factor with error bands.

2.6 State-wise vehicle data assumptions

Vehicle emission analysis from different states and union territories of India was carried out using the registered vehicle population available from 2011 to 2020 from the Centre for Monitoring Indian Economic (CMIE) Vahan portal. Analysis of all the states and union territories except Andhra Pradesh, Ladakh, Madhya Pradesh, Telangana, Jammu and Kashmir, Andaman & Nicobar Islands Lakshadweep in the absence of digitized RTO. Registered vehicles were subjected to survival fraction to segregate the vehicles according to the age-groups post-2010 (2011–2015) and post-2015 (2016–2020). Other fleet characteristics such as fuel efficiency, the annual average distance traveled, and emission factors were

assumed similar to national level input data for the post-2010 and post-2015 vehicles. Unlike developed countries, in India, travel characteristics data at national and state-levels are not available on a regular interval except through a few occasional travel surveys conducted as a part of independent studies. Fuel share data vary for different states in the quantification and is assumed from CMIE. These states are Assam (AS), Bihar (BR), Chhattisgarh (CG), Gujarat (GJ), Haryana (HR), Himachal Pradesh (HP), Jharkhand (JH), Karnataka (KA), Kerala (KL), Maharashtra (MH), Odisha (OR), Punjab (PB), Rajasthan (RJ), Tamil Nadu (TN), Uttar Pradesh (UP), Uttarakhand (UK), West Bengal (WB), Arunachal Pradesh (AP), Chandigarh (CH), NCT of Delhi (DL), Goa (GA), Manipur (MN), Meghalaya (ML), Mizoram (MZ), Nagaland (NL), Puducherry (PY), Sikkim (SK) and Tripura (TR). State-wise vehicle stock data is shown in Fig. 7, and Fuel share in these states is shown in Fig. 8.

According to Fig. 7, HDV stock is largest in Maharashtra, followed by UP, Odisha, and Karnataka, and the LDV share is highest in Bihar, followed by Maharashtra, UP, and Rajasthan. For private vehicles, the 2W population is highest in UP, followed by Maharashtra and Tamil Nadu. Whereas, 4W population is highest in Maharashtra, followed by UP, Gujarat, and Karnataka. For Inter-para transit (IPT) vehicles (3W and taxi), 3W (passenger) population is high in Maharashtra, followed by UP, Gujarat, and Karnataka. The taxi population is highest in Maharashtra and Karnataka, whereas public transport (bus) stock is highest in UP, followed by Tamil Nadu, Maharashtra, and Karnataka. The North-Eastern states have a lower vehicle population in India. In Fig. 8, the fuel share plot shows gasoline and diesel as the dominant fuels, followed by CNG fuel in different states of India. The share of electric vehicles has also increased in Indian states and union territories in the past five years. However, for state-wise vehicle emission estimation, gasoline, diesel, and CNG fuels were considered in the study. Vehicle emissions (CO_2, CO, PM, and NOx) per unit area (Mg/sq.km) of the given states are also estimated to analyse the total strength of emissions in a particular area of the state.

2.7 Fuel consumption and emission analysis model

In the present paper, road transport emission inventory for the fleet of 2020 is analyzed using Tier III bottom-up model. The above input parameters such as vehicle population, fuel efficiency, the annual average distance traveled, fuel share, and emission factors of gaseous pollutants are incorporated in the model shown in Eq. (2).

$$FC_{total} = \sum_i \sum_g \sum_k \left(VP_{i,g,k} \times ADT_{i,g,k} \times FS_{i,g,k} \times FE_{i,g,k}^{-1} \times FD_i\right) \quad (2)$$

In the equation, FC_{total} is the total fuel consumption for the reference year (2020). The parameter 'i' is the vehicle type (two-wheeler, four-wheeler, taxi, three-wheeler, bus, HDV, and LDV); 'g' is the age group of vehicles on-road (till 2000, post-2000, post-2005, post-2010, and post 2015); 'k' is the fuel type (gasoline, diesel, and CNG); VP is the vehicle population of in-use vehicles (based on survival fraction), ADT is the annual average distance traveled, FS is the fuel share for each vehicle category in different age-groups, FE is the fuel efficiency of a vehicle, and FD is the fuel density. Fuel density (kg/L) for gasoline, diesel and CNG is 0.74 kg/L, 0.88 kg/L and 1 kg/L respectively (Aggarwal & Jain, 2014).

Similarly, the quantification of vehicle emissions for the reference year is evaluated by using equations (3) and (4) for CO_2 emission and Eq. (5) for air pollution (CO, PM, and NOx) estimation.

$$ECO_2 = \sum_i \sum_g \sum_k \left(VP_{i,g,k} \times ADT_{i,g,k} \times FS_{i,g,k} \times EF_{CO2\,i,g,k}\right) \quad (3)$$

$$EF_{CO2,\,i,g,k} = \frac{EF_k}{FE_{i,g,k}} \quad (4)$$

In Eq. (3), ECO_2 is the total CO_2 emission from the reference year, and $EF_{CO2i,g,k}$ is the emission factor of vehicles depending on the vehicle type (i), age (g), and fuel type (k). Here, $EF_{CO2i,g,k}$ is determined using Eq. (4), where emission factor of fuel 'EF_k' (gasoline = 2.27 kg CO_2/L; diesel = 2.64 kg CO_2/L; CNG = 2.69 kg CO_2/L) (WRI, 2015) is divided by the fuel efficiency '$FE_{i,g,k}$' depending on the vehicle type (i), age group (g) and fuel type (k).

$$EAP = \sum_i \sum_g \sum_k \left(VP_{i,g,k} \times ADT_{i,g,k} \times FS_{i,g,k} \times EF_{i,g,k}\right) \quad (5)$$

In Eq. (5), EAP is the total emission of air pollutants (CO, PM, and NOx), and $EF_{i,g,k}$ is the emission factor of air pollutants (CO, PM, and NOx) depending on the vehicle type (i), age group (g) and fuel type (k). The model was used for multi-year vehicle emission analysis at a national scale for India and for its different states.

2.8 Policy Analysis

Significant policies to control vehicle emissions were implemented in India since 2000. These policies influence the fleet characteristics and configuration, which overall impact the vehicular emissions. Therefore, in the present study, the impact of India's transport policies from 2000 to 2020 is analyzed. Here, vehicle emissions in different scenarios are estimated and compared with the 'no policy' scenario. The No-policy scenario is the no-improvement and zero policy implementation scenario. The different scenarios considered for policy analysis are shown in Table 2. We estimated vehicle emissions (CO_2, CO, PM, and NOx) from each scenario and compared them with the 'no policy scenario' to analyze the percentage change in total emissions from the policies implemented in India till 2020.

Table 2
Policy scenarios for India

	Scenarios for the fleet of 2020	Description of the scenario
1	No-policy scenario	Assuming the absence of all the significant policies such as introduction and shift to CNG fuels, Shift to 4-stroke technology in two-wheelers and three-wheelers on the road, improvement in fuel efficiency of vehicles, and introduction of emission norms
2	Shift to CNG scenario	Analyzing the impact of CNG introduction in buses (from 0 % to 10 %), taxis (from 0 % to 20%) and three-wheelers (from 0 % to 20 %) for the fleet of 2020
3	Shift to 4-stroke technology scenario	Analyzing the impact of the shift in technology from two-stroke (2s) vehicles to four-strokes (4s) vehicles. We assumed shift in 2s:4s from 30:70 in 2000 to 4:96 in 2020 for two-wheelers and for three-wheelers we assumed increase in 4s vehicles from 0–25% from 2000 to 2020
4	Improvement in Fuel Efficiency scenario	Fuel efficiency of vehicles have improved for vehicles as follows- by 28% for HDV and Buses, 10% for LDV, 38% for Taxis, 80% for 3W, and 32% for Private vehicles such as 2W and cars from 2000 to 2020
5	Shift in Emission norms (BS norms) scenario	Emission norms such as Bharat Stage have reduced vehicular emissions. We have analyzed no BS norms to BS-IV norms for the fleet of 2020. BS-IV norms have significantly reduced emission factors of gaseous pollutants. In 2017, BS-IV was expected to be implemented nationwide in India

3 Result And Discussion

The road transport emission inventory is developed in the study with the models and refined assumptions for the input parameters (fleet characteristics) discussed in the methodology and data assumption section. Using the same model, we also analyzed the impact of different policies implemented from 2000 to 2020 on India's total vehicle emissions.

3.1 Fuel consumption

Fuel consumption was analyzed for the fleet of 2020 using Eq. (2) in the methodology section. The estimated fuel consumption in 2020 was 92 (87–95) Mt, where 61% (55.67 Mt) comes from diesel, 36% (32.87 Mt) from gasoline, and 4% (3.23 Mt) from CNG (mean value of result plotted with standard deviation) shown in Fig. 9. The estimated values are compared with PPAC (Petroleum Planning and Analysis Cell) (MOPNG, 2013a) fuel consumption values for the year 2009-10. The analysis showed a 9% increase (from 51 Mt to 56 Mt) in diesel consumption, and a two-times increase in gasoline consumption (from 15.7 Mt to 32.87 Mt) in a decade (2010 to 2020) from the road transport sector. An increase in private transport (two-wheelers and gasoline-fueled cars) increased gasoline consumption. The increase in diesel consumption was mainly due to an increase in the freight transport sector from 2010 to 2020. CNG was introduced after 2000, but its diffusion in the fleet is shallow, which caused only a 4% share in

total fuel consumption. We also compared Prakash and Habib (2018) study's values, where they presented the results for the reference year 2013 and indicated consumption of diesel increased by 7% (from 52 to 56 Mt), gasoline increased by 37% (from 24 to 33 Mt), and CNG share almost doubled (from 1.6 to 3.2 Mt).

3.2 Vehicle Emissions

estimated vehicle emissions for the reference year 2020 for India and its states by incorporating the values of the input parameters in the equations (3), (4), and (5) in the methodology section. Vehicle CO_2 emission was analysed using Eqs. (3) and (4). The result of the analysis is shown in Fig. 10, where vehicles of different age-groups, categories, and fuel types contributed to the total vehicle emission from the fleet of 2020.

Figure 10 (a) showed CO_2 emission from the on-road vehicles in the reference year 2020. According to the analysis, the total CO_2 emission was estimated to be 274 (265–292) Tg (Tera-gram). Freight vehicles (HDV and LDV) fuelled by diesel have the highest contribution with 38% (104 Tg), followed by private transport vehicles (2W and cars) with 36% (97.5 Tg), public transport with 15% (41.3 Tg), and IPT (inter-para transit vehicles) such as three-wheelers passenger and taxis with 11% (31.2 Tg). Diesel fuelled vehicles made a significant contribution with 61%, followed by gasoline vehicles (37%) and CNG vehicles (2%) in the total CO_2 emissions. Age-wise emission analysis indicated significant emissions from post-2015 vehicles (0 to 5 years of age in the fleet of 2020) with 47% of total CO_2 emission. The shares of till-2000, post-2000, post-2005, and post-2010 age-group vehicles in the fleet of 2020 were 1%, 4%, 16%, and 32% respectively. Emission control policies for the road transport sector are designed specifically to regulate air pollution. Their impact on GHG, such as CO_2, act as the co-benefit effect of the implemented policies.

Figure 10 (b) showed CO emission from the on-road vehicles in the reference year 2020. CO is the primary pollutant emitted from the transport sector, contributing a significant share (90%) of the total emission (Lathia & Dadhaniya, 2019). CO emission was controlled significantly after the introduction of emission norms in India in early 2000. The total CO emission for the fleet of 2020 was estimated to be 4463 (3253–6676) Gg (Giga-gram), where gasoline fuelled vehicles made a significant contribution with 76% of the total CO emissions, followed by diesel (23%) and CNG vehicles (1%). Gasoline vehicles such as private two-wheelers and cars emitted 71% of the total CO emission (3159 Gg). Age-wise CO emission analysis indicated significant contribution from post-2015 vehicles about 40% (1789.11 Gg), followed by post-2010 vehicles (31%), post-2005 vehicles (13%), post-200 vehicles (7%), and till-2000 registered vehicles (9%).

Figure 10 (c) showed PM emission from the on-road vehicles in the reference year 2020. Like CO emissions, PM emission was also regulated with the introduction of emission norms in India from 2000 to 2020. We assumed nationwide implementation of BS-IV standards in post-2015 vehicles. Total PM emission for the fleet of 2020 was estimated as 164 (119–250) Gg, where gasoline vehicles contributed the highest (103 Gg), followed by diesel and CNG vehicles. Although diesel vehicles have high PM

emission factors, gasoline-fuelled two-wheelers' share is higher in the fleet, leading to significant gasoline vehicles' contribution. Age-wise emission analysis indicated that post-2015 vehicles contributed 36% of the total PM emission, followed by post-2010 vehicles (28%), post-2005 vehicles (21%), post-2000 (12%), and till-200 registered vehicles (4%) in the fleet of 2020.

Figure 10 (d) showed NOx emission from the fleet of 2020 with a total estimated value of 2378 (2191–3045) Gg from the on-road vehicles. Like CO and PM, NOx emission was also controlled from 2000 to 2020 by emission (BS) norms in India. As a result, the fleet of 2020 emitted 57% NOx from gasoline-fuelled vehicles, 42% from diesel-fuelled vehicles, and 1% from CNG-fuelled vehicles. Similar to PM, the emission factor of NOx was higher in diesel-fuelled vehicles; however, their share in the fleet was presided by gasoline-fuelled vehicles. Age-wise emission analysis, indicated the share of post-2015, post-2010, post-2005, post-2000, and till-2000 registered vehicles as 31%, 38%, 21%, 8%, and 3% in the fleet of 2020.

Tail-pipe emissions are governed by the quality of the automotive fuels and are determined by vehicle type and technology, fuel type, age of the vehicles, vehicle maintenance, and driving pattern, to list a few (GoI, 2014). Emission control policies such as auto fuel norms BS-I, BS-II, BS-III, and BS-IV were gradually made stringent, and fuel quality was improved with the BS norms. However, emission levels have still increased. The estimated results showed that the post-2015 registered vehicles are the significant emitters in the fleet of 2020. Private transport two-wheelers and freight vehicles are also detected as the significant emitters in the fleet of 2020. The main reasons are the unconstraint growth in vehicle population, especially two-wheelers, which dominated the fleet with over 70% of its share. And higher emission rates of freight vehicles in the fleet. An increase in transport demand and mobility increased transport emissions, congestions, oil demand, and pollution-related health effects (Guttikunda et al., 2015). Therefore, policies that target the heavy emitters and constraint the increasing vehicle population (and vehicle mobility) should be proposed for India.

3.3 State-wise vehicle emission analysis

State-wise vehicle emissions were estimated using the same methodology and assumptions as of the national level inventory for the fleet of 2020. In the present study, 30 states and union territories are analysed and denoted with their respective short forms in the emission plots. These states are Assam (AS), Bihar (BR), Chhattisgarh (CG), Gujarat (GJ), Haryana (HR), Himachal Pradesh (HP), Jharkhand (JH), Karnataka (KA), Kerala (KL), Maharashtra (MH), Odisha (OR), Punjab (PB), Rajasthan (RJ), Tamil Nadu (TN), Uttar Pradesh (UP), Uttarakhand (UK), West Bengal (WB), Arunachal Pradesh (AP), Chandigarh (CH), NCT of Delhi (DL), Goa (GA), Manipur (MN), Meghalaya (ML), Mizoram (MZ), Nagaland (NL), Puducherry (PY), Sikkim (SK) and Tripura (TR). The fleet of 10 years (2011–2020) was examined to evaluate total vehicle emissions from each state.

We also estimated vehicle emissions (CO_2, CO, PM, and NOx) per unit area (square kilometer) for the given states and union territories in India which are shown in Fig. 12 (a) for CO_2 Mg/ km^2, 12 (b) for CO Mg/ km^2, 12 (c) for PM Mg/ km^2, and 12 (d) for NOx Mg/ km^2. Spatial allocation of the vehicle emissions to a geographic area gives the intensity of the emission per unit area and can be useful in suggesting

mitigation strategies that can be assigned to the particular state. According to our analysis, Delhi and Chandigarh have the highest emissions per unit area for all the pollutants (For Delhi, CO_2 = 4698 Mg/ km^2, CO = 41 Mg/ km^2, PM = 0.9 Mg/ km^2, NOx = 17 Mg/ km^2; for Chandigarh, CO_2 = 4650, CO = 42 Mg/ km^2, PM = 1.1 Mg/ km^2, NOx = 18).

In Delhi over the year, various measures have been adopted to control vehicle emissions such as odd-even rule for a private vehicle, scrappage of 10- and 15-years old diesel and gasoline vehicles, pollution under control (PUC) test for automobiles, a comparatively higher share of CNG (9.6%), and Electric and other alternate vehicles (5.9%) compared to other states of India (CMIE, 2020). However, vehicle emissions are still increasing due to massive population influx (migration), demographic marginalization, and urban sprawl (Aggarwal & Jain, 2014). Whereas Chandigarh has a 1% share of CNG vehicles and a 3% share of electric and other alternate fueled vehicles (CMIE, 2020). It has three major national highway connectivity due to adjoining cities increasing the number of commuting vehicles (Bhargava et al. 2018). Both these states have high population density (Delhi = 11,320 and Chandigarh = 9258 people per square kilometers). Hence high vehicle population, which results in high emission per unit area. The spatial distribution of emissions shows heterogeneity in state-wise emissions and the need for region-specific policy formulation along with national policies.

3.4 Comparison with the past studies

Multi-year road transport inventories were estimated to compare the present analysis with India's past studies for different reference years. We also validated the model and the assumptions for the fleet characteristics for the age-wise vehicle emission analysis. We compared the present results with Tier I, Tier II, and Tier III estimated analysis and plotted them together in Fig. 13 (a) for CO_2, Fig. 13(b) for CO, Fig. 13 (c) for PM, and Fig. 13 (d) for NOx emission.

The Tier I studies included in the comparison are Ohara et al. (2007), Van Aardenne et al. (2005), IIASA (2008), and Garg et al. (2006). The Tier II studies included are Fulton and Eads (2004), Borken et al. (2007), Singh et al. (2008), Ramachandra and Shwetmala (2009), and Singh et al. (2017). The Tier III studies included were ADB (2006), Baidya and Borken-Kleefeld (2009), Sadavarte and Venkataraman (2015), and Prakash and Habib (2018). The results of the multi-year vehicle emissions analysis for 2000, 2005, 2010, 2013, and 2015 are within the range of past estimated emissions of CO_2, CO, PM and NOx from the road transport sector of India. The comparison also validates the inventory model and data assumptions for the fleet characteristics of the vehicles.

3.5 Sensitivity analysis

The input parameters such as vehicle population, fuel efficiency, the annual average distance traveled, fuel share, and emission factors of CO_2 and gaseous pollutants are used in the model to estimate on-road emissions. Therefore, the influence of the range of values of these parameters on total vehicle emissions was examined using sensitivity analysis. Mean values of input parameters are used to estimate emissions for the reference year. The influence of minimum and maximum fuel efficiency values, the annual average distance traveled, fuel share, and emission factors of vehicular pollutants are

applied for sensitivity analysis. The influence of survival fraction values estimated from a primary survey for Delhi vehicles and National highways freight vehicles are also compared with the present study analysis (Pandey and Venkataraman, 2014).

The results of the sensitivity analysis indicated uncertainty in the CO_2 emission from the mean value as -3% and + 10%, for CO emission it is -27% and 50%, for PM emission it is -27% and 53%, and NOx emission it is -8% and 28% for the fleet of 2020. Survival fraction is an essential input variable and affects the age-mix of vehicles in the fleet, hence influencing vehicles' overall emission levels. We compared the change in emissions using different survival fractions available in the literature for the Indian fleet. Estimating emissions using survival fraction data from the Delhi fleet (Goel, Guttikunda, Mohan, & Tiwari, 2015) reported a reduction in CO_2, CO, PM, and NOx emissions by 11%, 34%, 40%, and 23%, respectively. The decline in emission is mainly due to the scrappage policy in Delhi of removing ten years old diesel and 15 years old vehicles gasoline vehicles from the fleet. Delhi follows a strict emission control policy compared to other states and cities of India. Estimating emissions using survival fractions of surveyed freight vehicles in India (Malik & Tiwari, 2017) on major national highways (NH-8, NH-3, NH-6, and NH-2) reported a reduction in CO_2, CO, PM, and NOx emission by 70%, 53%, 102%, and 81% respectively. Significant emission reduction is observed using survival fractions from Malik and Tiwari (2017) as more than 90% of the HDVs and LDVs are ≤ 8 years of age on these major highways of India.

3.6 Policy Analysis

Quantification of vehicle emissions for different years is required to assess the impact of implemented policies and suggest suitable mitigation strategies for future years. An inventory developed for a reference year act as a benchmark for comparison with previous and future emission inventories compiled for different years and policy scenarios.

Policies affect the fleet configuration by influencing their characteristics, such as survival fraction of vehicles depending on their age in the fleet, fuel efficiency, the annual average distance traveled, fuel and technology share, and emission factors of vehicles. The policies considered for the investigation are discussed in Table 2. The resultant percentage change in vehicle emission in different scenarios compared to the ‘No-policy’ scenario gave results that are reported in Table 3. Shift to CNG fuel in India from 2000 to 2020 resulted in 1%, 4%, 4%, and 3% decrease in CO_2, CO, PM, and NOx emissions. A CNG vehicle has a lower emission factor for gaseous pollutants (CO, PM, and NOx), and is an alternate fuel to diesel and gasoline in India. However, their share in the fleet is far less than diesel and gasoline-fueled vehicles, leading to a negligible decrease in these gases.

Technology shift in the fleet from two-strokes to four-strokes in motorized two-wheelers and three-wheelers passengers led to a 0.1% increase in CO_2 emission and 11%, 15%, and 1% decrease in air pollutants CO, PM, and NOx respectively. Two-wheelers sales and registration dominated the fleet with over 70% registered vehicles in the fleet, whereas three-wheelers are the feeder systems which provide point-to-point service on-road in all the urban and semi-urban area (Iyer, 2012). Therefore, Motorized 2W and 3W are critical in improving India's transportation and must be paid attention to reduce vehicle

emissions. Four-stroke engines meet the emission standard targets and are more fuel-efficient than two-stroke engines. However, an increase in 2W and 3W registration (sales and usage) on-road hampered the gain achieved by technology improvement.

Fuel efficiency (FE) improvement regulates the CO_2 emission levels and influences air pollutant emissions. An estimated ≥ 30% FE improvement in all road transportation modes led to a decrease in CO2, CO, PM, and NOx emissions by 44%, 62%, 42%, and 28%, respectively. Freight vehicles such as trucks and buses have high NOx emission factors followed by private vehicles; therefore, significant fuel efficiency standards are required for India's freight vehicles to regulate the NOx emission levels.

Auto fuel norms are introduced in India to control vehicle emissions and decrease the harmful effect on human health with air pollution exposure. Auto fuel norms such as BS norms have significantly reduced emissions from 2000 to 2020 in India with their timely implementation in passenger vehicles. Implementation of BS norms (BS-IV till 2020) led to a 43% decrease in CO_2 emission, 90% decrease in CO emission, 90% decrease in PM emission, and 63% decrease in NOx emission.

Table 3
Influence of different policies on total vehicle emissions for the fleet of 2020

	Percentage decrease in vehicle emissions	**CO_2**	**CO**	**PM**	**NOx**
1)	Shift to CNG	-1%	-4%	-4%	-3%
2)	Shift from two-strokes to four strokes	0.1%	-11%	-15%	-1%
3)	Improvement in Fuel efficiency	-44%	-62%	-42%	-28%
4)	Shift from no BS to BS-IV	-43%	-90%	-90%	-63%

4 Conclusion And Policy Recommendations

In the present analysis, we estimated road transport inventory for India and its states using secondary data. For the fleet of 2020, total CO_2, CO, PM, and NOx vehicle emissions are estimated to be 274 (265–292) Tg, 4463 (3253–6676) Gg, 164 (119–250) Gg, and 2378 (2191–3045) Gg, respectively. Freight (HDV) and private (2W) vehicles are the significant emitters. HDVs have high emission factors, and 2Ws constitute more than 70% of the fleet population. India's growing population and the economy will increase passenger and goods mobility, which would increase transport emissions, oil demand, and pollution-related health effects. Therefore, suitable mode-specific strategies are recommended to control emissions in the future, such as fuel efficiency programs for freight vehicles, alternate fuel CNG and electric vehicle ownership for passenger mobility, shift to BS-VI norms and scrappage of heavy emitters from the fleet.

Maharashtra, Tamil Nadu, Gujarat, UP, Rajasthan, and Karnataka together contribute 57% of CO_2, 60% of CO, 59% of PM, and 58% of NOx emissions to the total state-wise emissions in 2020 compared to the rest of the states of India. Spatial allocation of vehicle emissions to the states' geographical area indicates that Delhi and Chandigarh have high emissions per unit area. Therefore, state-wise comprehensive mitigation programs are recommended to control vehicle emissions, such as increasing electric and other alternative fuel vehicles and shifting to the less polluting mode of transport.

The present study's objectives are achieved by developing a road transport inventory for the reference year using different secondary data assumptions and validating the estimated values with past studies on India. We also estimated sensitivity analysis to examine the influence of a diverse range of fleet characteristics on total vehicle emissions. Age of vehicles (survival fraction) is an essential parameter in the age-wise vehicle emission analysis as it results in maximum variability in total emission. And the values of other input parameters such as fuel efficiency, vehicle distance traveled, fuel share, and emission factors correspond to the age of a vehicle in the fleet and policies implemented at that time. Sensitivity analysis indicates the survival fraction of vehicles as the significant fleet characteristics as it affects the age-mix of vehicles in the fleet and hence influences the overall emissions. Therefore, the study recommends timely country-level and state-level fleet characteristics data for India.

An inventory developed for a reference year act as a benchmark for comparison with previous and future emission inventories compiled for different years and policy scenarios. In the current analysis, previous emission inventories and policies implemented are compared to the fleet of 2020. Advancement in emission norms (BS norms) led to a significant reduction in gaseous pollutants, followed by fuel efficiency improvement in vehicles. With the introduction of the BS-VI norm and Fuel efficiency program for passenger cars in 2021, a considerable reduction in vehicle emissions is expected. Therefore, we have summarized India’s effort to reduce vehicle GHG and air pollution emissions from the road transport sector.

The scope of the study is limited to the tail-pipe emissions of GHG such as CO_2 and air pollutants such as CO, PM, and NOx. The analysis can be extended to other pollutants and future road transport emission inventory for India. The current inventory can be used to analyse the impact of different mitigation measures on India's future fleet. These measures include policies that are either government-regulated or have incentives attached to them. In 2020, the government ordered leapfrog from BS-IV to BS-VI emission norm in private vehicles. This initiative would reduce NOx and PM emissions considerably compared to BS-IV vehicles. In February 2021, the government announced an incentive-based vehicle scrappage program to be implemented in India soon. Implementation of this policy is expected to reduce the age of vehicles in the fleet and, therefore, reduce emissions. An increasing share of alternate fuels such as CNG, biofuel, and electric vehicles in the future will mitigate on-road emissions. Various subsidies and infrastructure investments are made in India to increase electric vehicles' share in the fleet. Therefore, the present fleet can be the benchmark for future emission and policy analysis for the Indian road transport sector.

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

All data generated or analysed during this study are included in the article as figures and tables. The supplementary information files are available from the corresponding author on request.

Competing interest

The authors declare that they have no competing interests

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Author contribution statement

NS: Writing- original draft, Investigation, Conceptualization, Methodology, Validation, Software, Formal analysis, Writing- review & editing. TM: Writing- review & editing, Supervision. RB: Writing- review & editing, Supervision.

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Figures

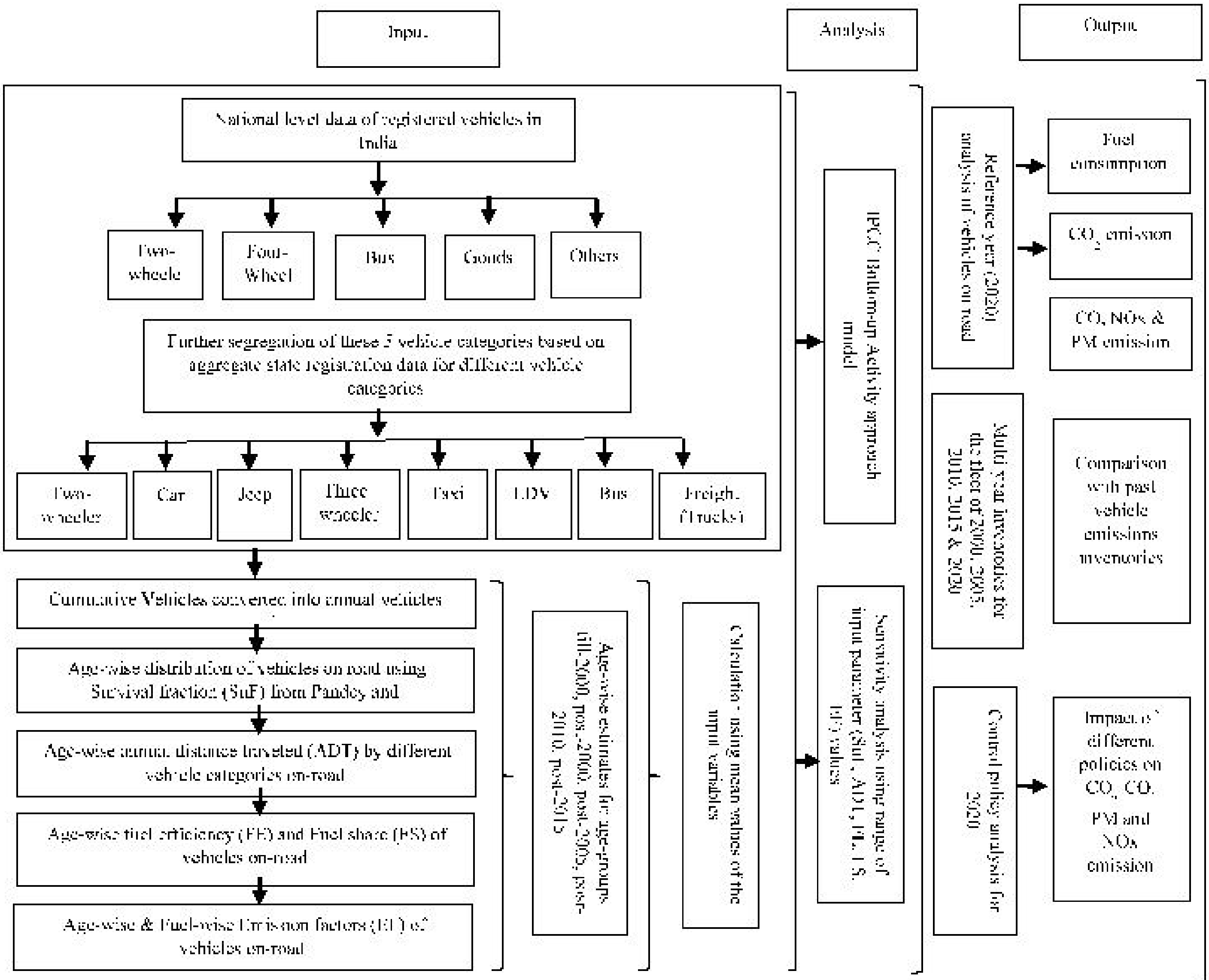


Figure 1

Framework of the study

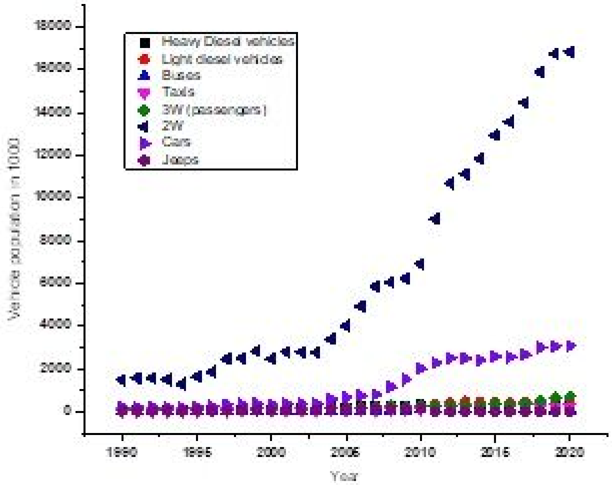


Figure 2

Trend in registered vehicle population in India from 1991 to 2020

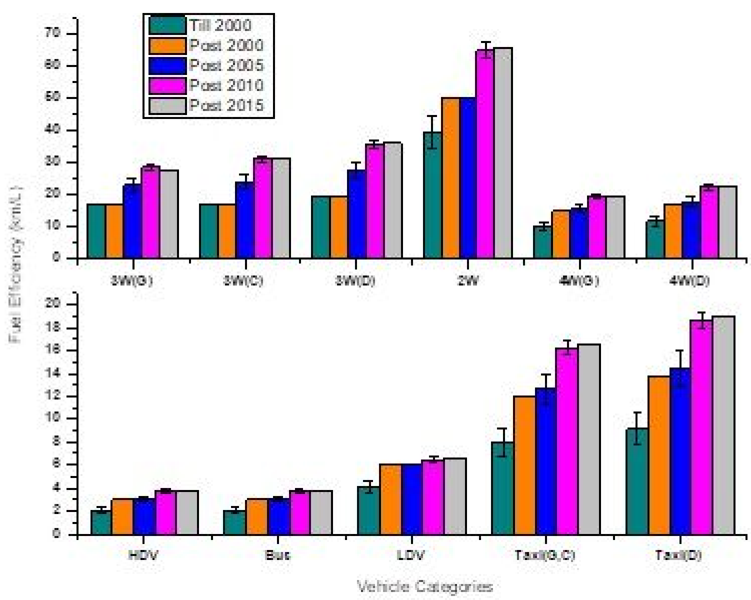


Figure 3

Fuel efficiency of vehicle categories in different age groups on the road

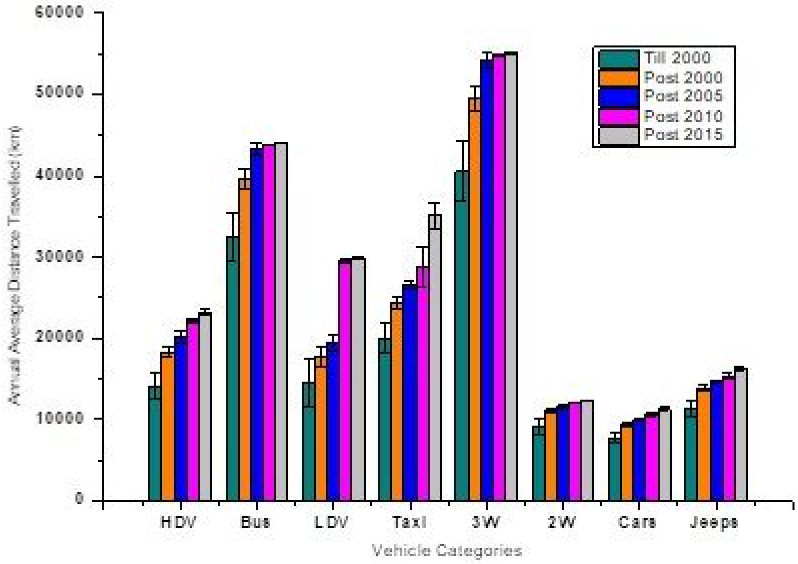


Figure 4

Annual average distance traveled of vehicle categories in different age-groups on-road

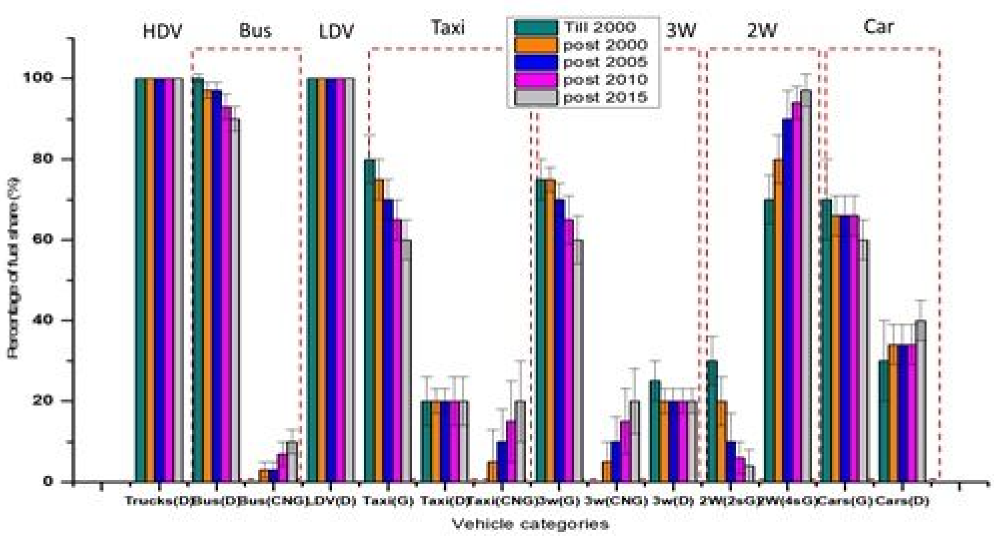
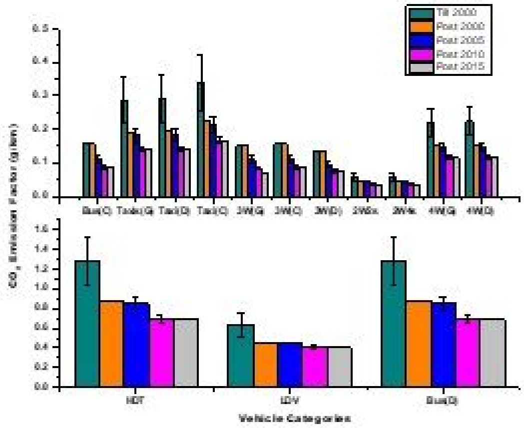
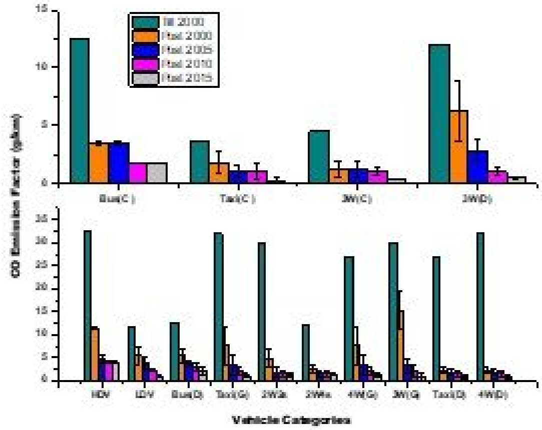


Figure 5

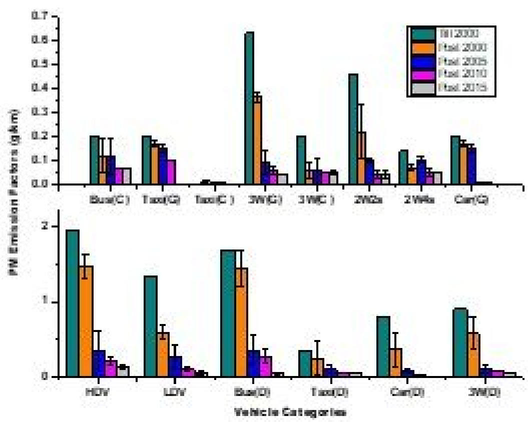
Fuel share of vehicle categories on-road in India in different age-groups



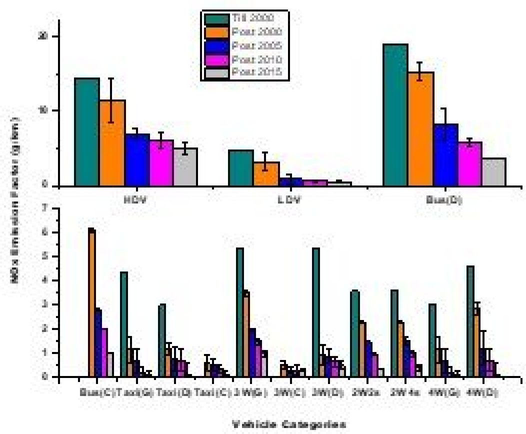
(a) CO_2 emission factors



(b) CO emission factor



(c) PM emission factors



(d) NOx emission factors

Figure 6

Emission factors used in the study (a) CO2, (b) CO, (c) PM, and (d) NOx

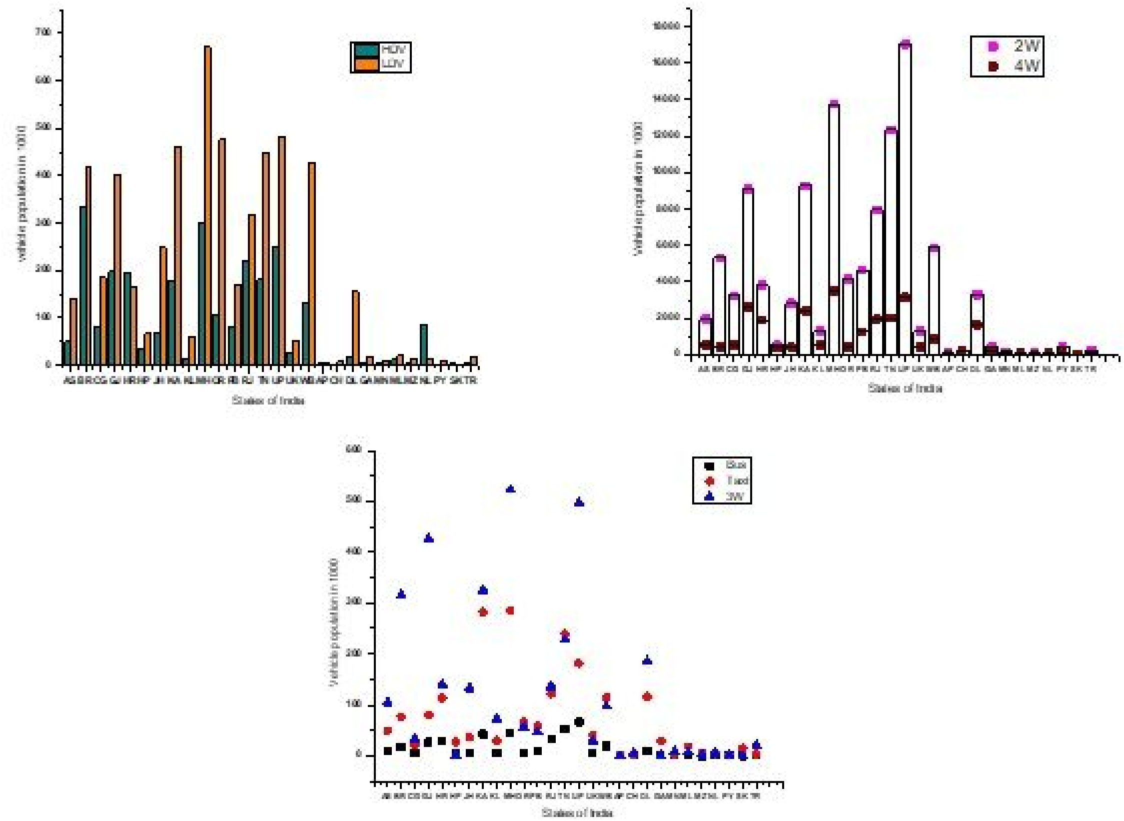


Figure 7

State-wise vehicle stock for the reference year 2020

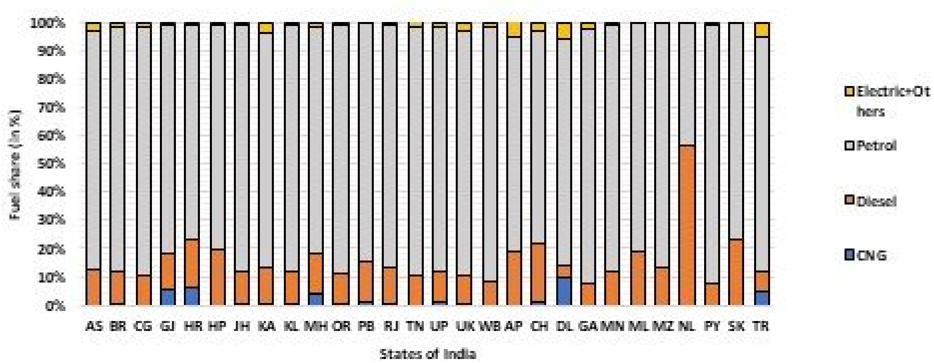


Figure 8

State-wise fuel share in the reference year 2020

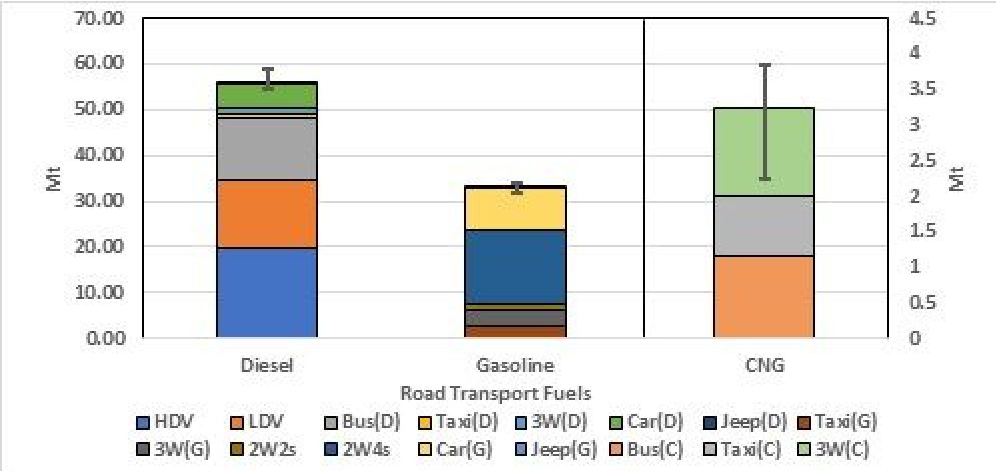
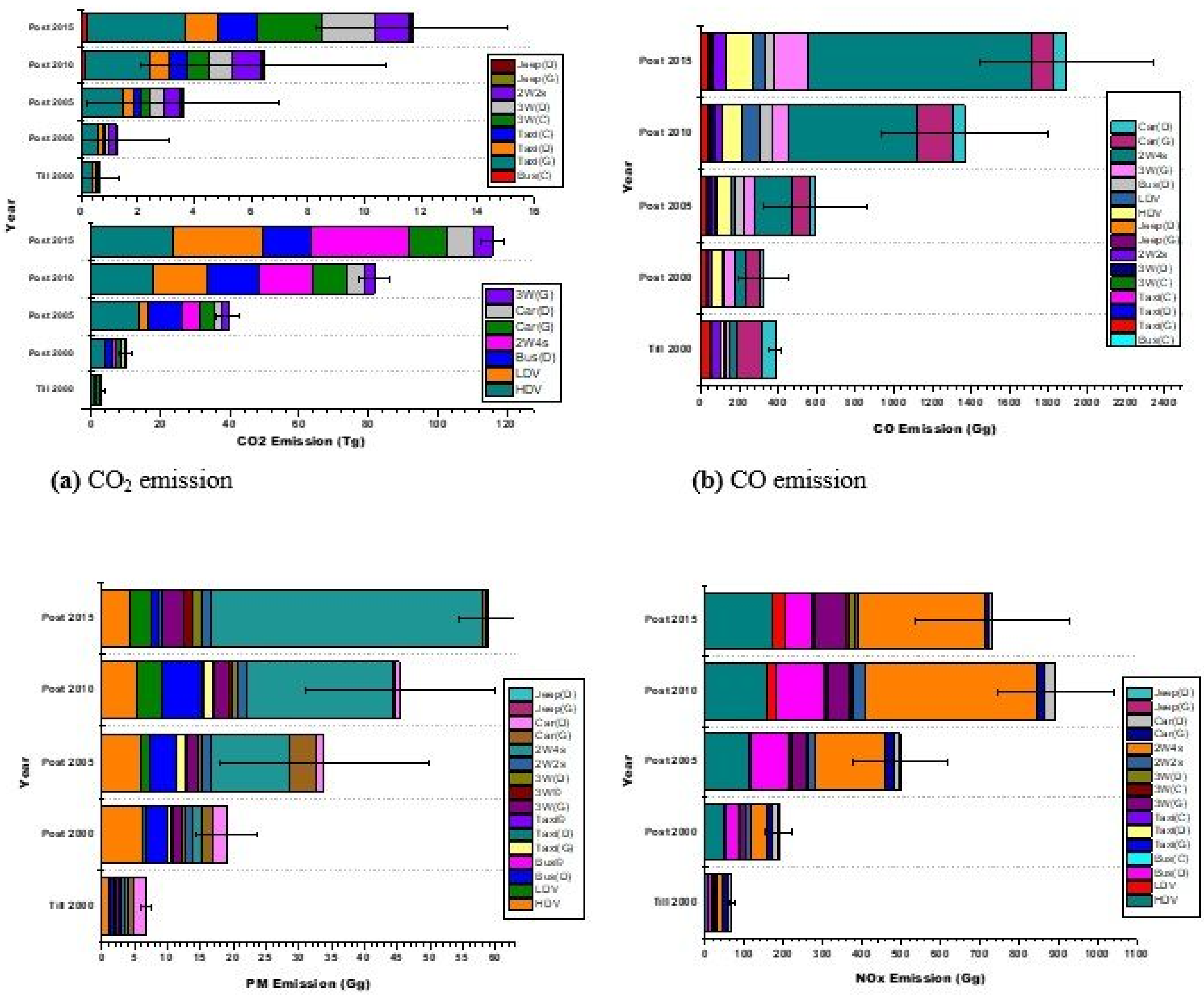


Figure 9

Fuel consumption from the reference year 2020



(a) CO_2 emission

(b) CO emission

(c) PM emission

(d) NOx emission

Figure 10

Emissions from the road transport sector of India (2020)- (a) CO2, (b) CO, (c) PM, (d) NOx

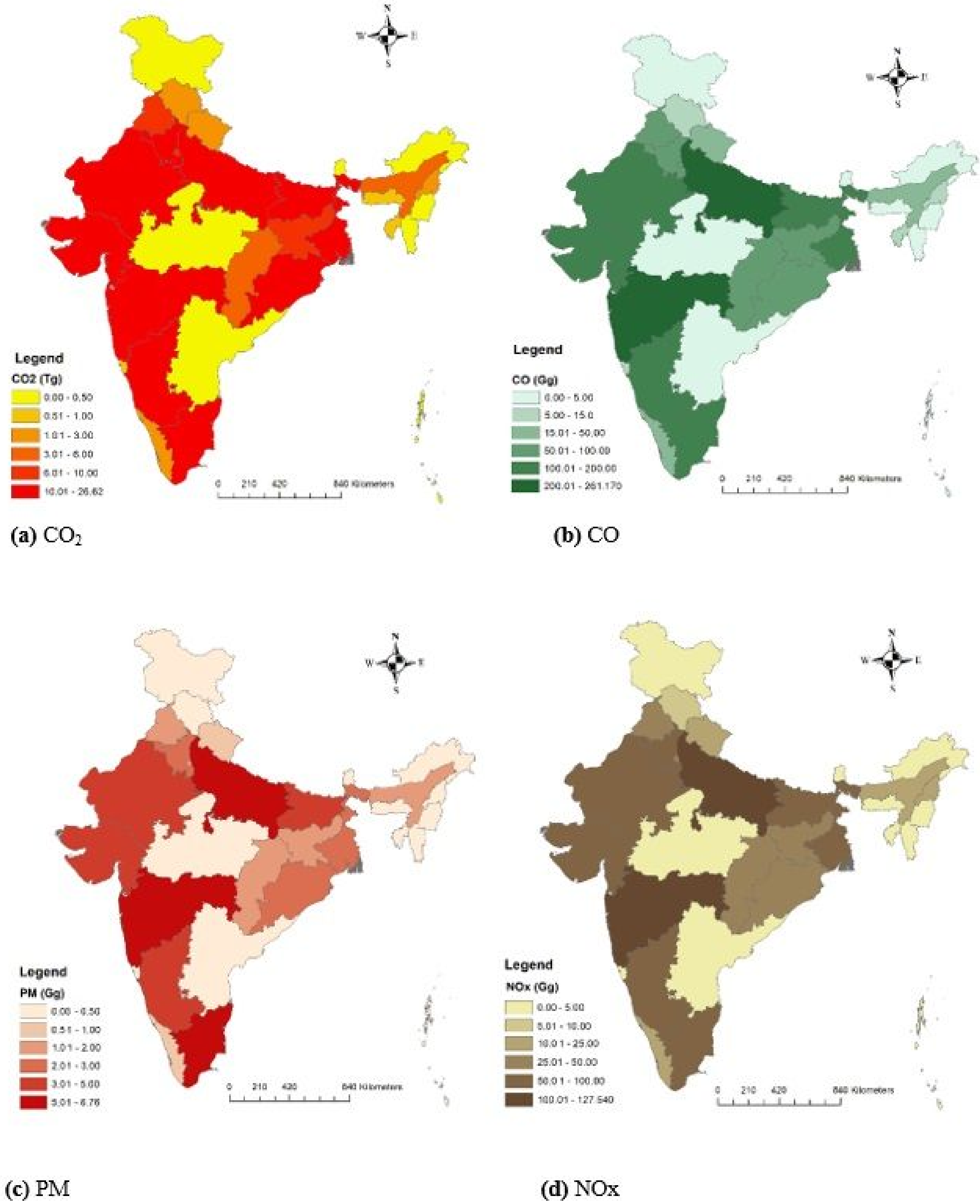


Figure 11

Vehicle emissions from the different states of India (2020)- (a) CO2, (b) CO, (c) PM, (d) NOx

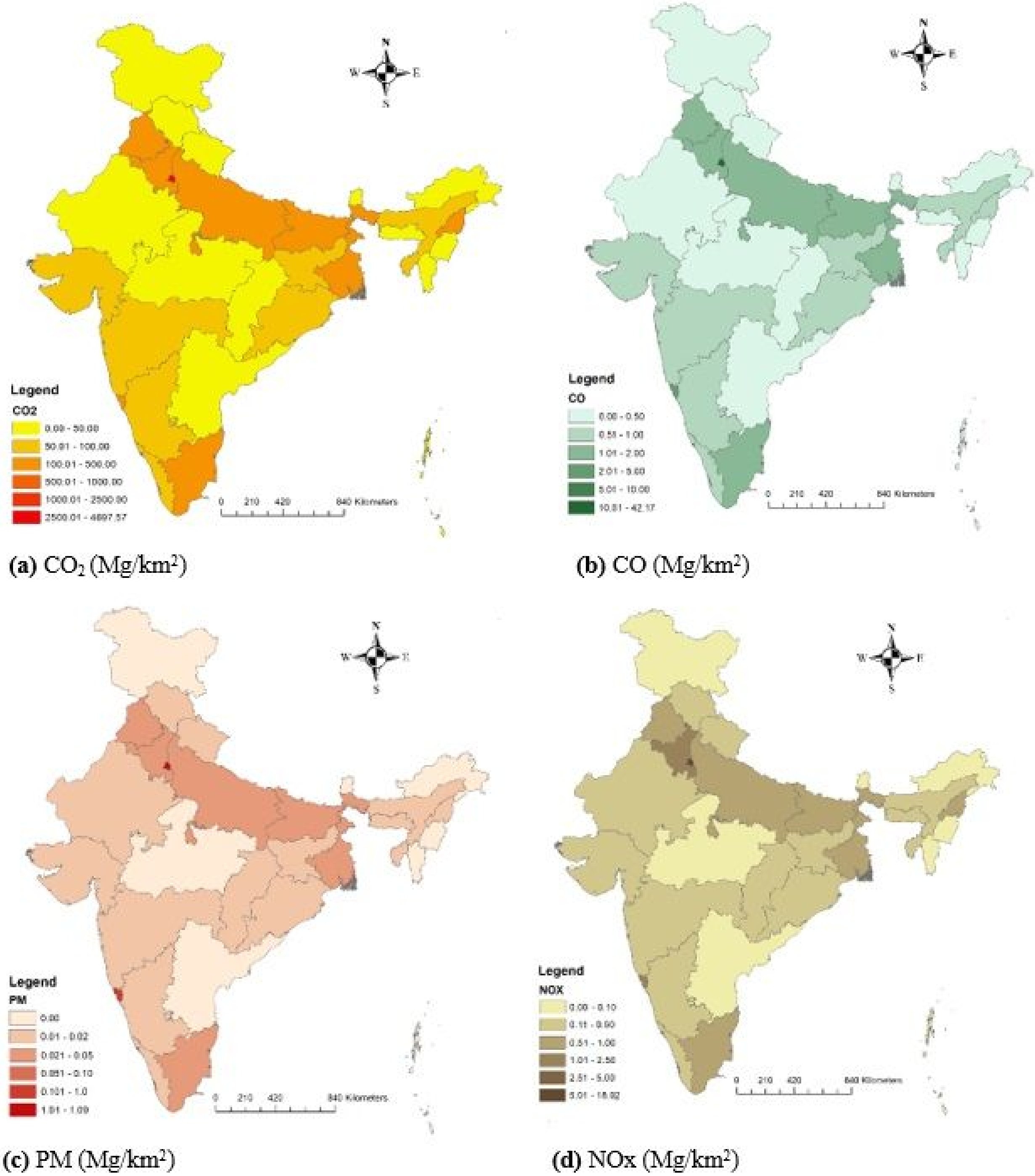


Figure 12

Vehicle emissions per unit area (Mg/km2) from the Indian states for the fleet of 2020- (a) CO2, (b) CO, (c) PM, (d) NOx

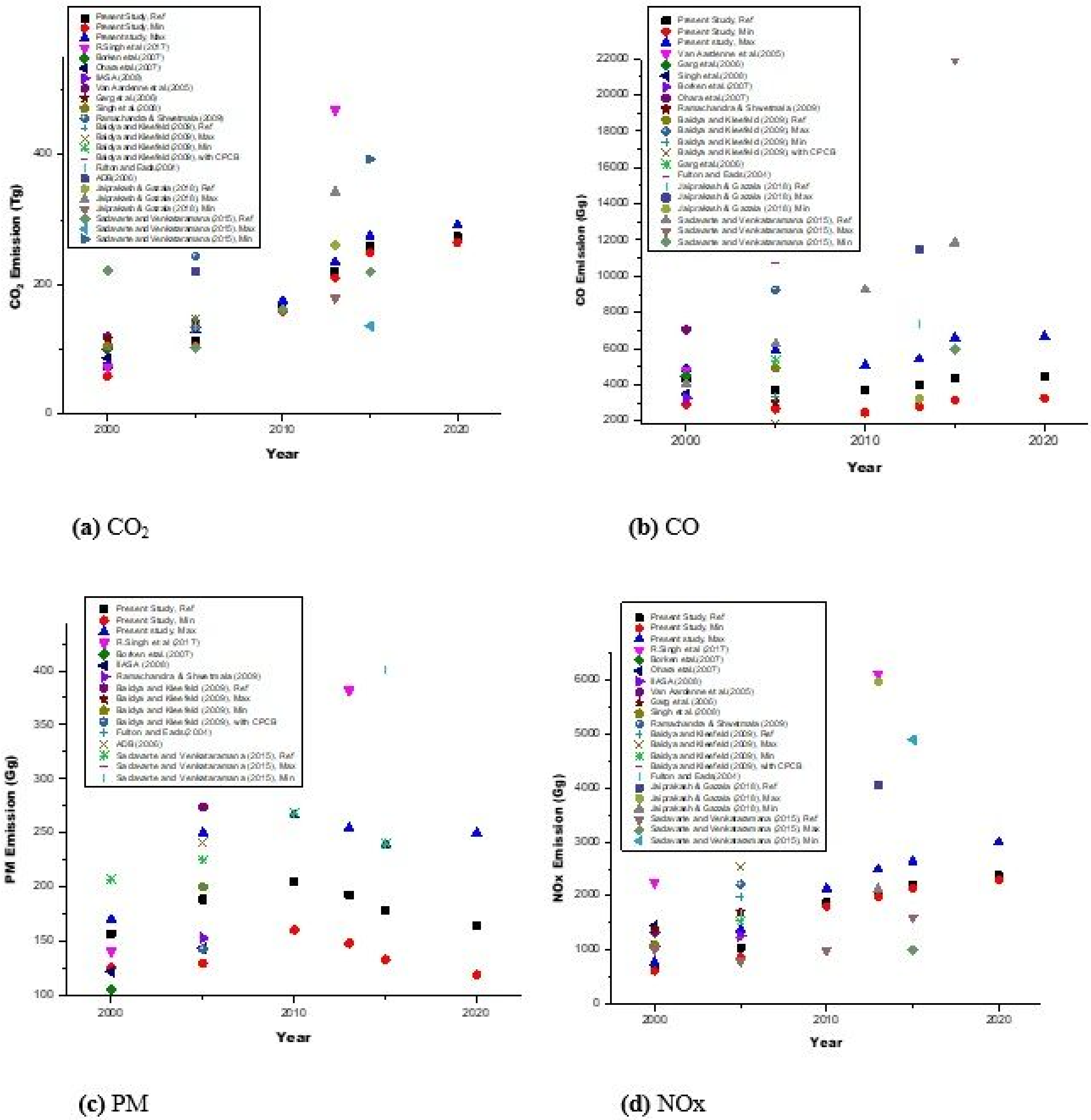


Figure 13

Comparison of Vehicle emissions with the past studies on India- (a) CO2, (b) CO, (c) PM, (d) NOx emission