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Research Article

Vehicular Emission Scenarios in Selected Regions of India as per Vehicular Emission Norms

Sandhiya Lakshmanan* and Anupama Upadhayay

CSIR-National Institute of Science Communication and Policy Research, New Delhi (110 012), India

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Corresponding Author

Sandhiya Lakshmanan

✉: sandhiya@niscpr.res.in

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Abstract

The transport sector is a major contributor to pollution. India has put in place Bharat Stage Emission Standards (BSES) to reduce air pollution caused by the road transport sector. The present study addresses the emission patterns of Light and Heavy Duty Vehicles in India across various BSES (BS-III, IV and VI). The emissions of pollutants such as VOC, NO_x, $PM_{2.5}$, CO and BC for the years 2013-2021 are estimated for both LDV and HDV functioning under BS-III, IV and VI norms. By analyzing variables such as vehicle characteristics and environmental factors, the study determines unique emission trends in selected states in the Plain, Eastern Himalaya and Himalaya and Trans-Himalaya areas. Notably, the Plain region's high population density and commercial activity make it a significant pollution producer. The results revealed that all the regions exhibited an overall increase in emissions till 2018 and after that emissions started declining. Significant reductions in VOC, $PM_{2.5}$, NO_x, CO and BC emissions are revealed by the switch to stringent BS standards, highlighting the benefits of cleaner fuels and cutting-edge engine technologies.

Keywords: BSES, HDV, LDV, Pollutant estimation, Vehicular emissions

Introduction

Ambient air pollution is the serious environmental risk factor worldwide with 3.4 million premature deaths annually due to lung and heart diseases (IHME, 2017). As the population of megalopolis cities in India has increased, as have the number of vehicles, the amount of gasoline they consume and air pollution (Ghose *et al.*, 2004; Sen Gupta, 2015). Among other things, the two main sources of emissions are industrial and motor vehicle emissions (Singh *et al.*, 2021). Globally, there were 700 million motor vehicles on the road in 2000 and now according to the report of the International Energy Agency (IEA) which predicted that the number of vehicles on the world's roads will increase from 1.2 billion in 2014 to 2 billion by 2035 (Voelcker, 2014). According to data from AQI India, 2022, seven of the most polluted cities worldwide are located in India (Kumar, 2023). India's vast road network, spanning over 0.4 million kilometers, plays a vital role in the nation's economic growth and mobility. In the 1950s, it already handled 15% of passenger traffic and 14% of freight, laying the foundation for a transportation sector that today contributes a substantial 4.5-5% to the industry and 6.4% to the country's GDP. On the other hand, the automobile market shifted throughout last 20 years into a dominant mode of transportation in terms of both the quantity of automobiles and the size of the road network. This is demonstrated by the fact that, with a network length of 4.7 million km, road transportation carries 86% of passengers and 66% of freight (Malik and Tiwari, 2017). Motor vehicles are responsible for emitting to ~58% of NO_x (nitrogen oxides) and ~73% of $PM_{2.5}$ (particulate matter) (Lapuerta *et al.*, 2017). Exposure to NO_x leads to increase in all-reason death, respiratory and cardio-vascular effects (Faustini *et al.*, 2014; Mills *et al.*, 2015). NO_x is a precursor to ozone and particulate matter ($PM_{2.5}$). Apart of this, weather can have also a significant impact on how air pollution is transported, deposited and altered. Weather conditions can cause extreme pollution even on days when there are fewer emissions overall (Eregowda *et al.*, 2021). Similarly, in our earlier research (Lakshmanan *et al.*, 2023); it was found that incorporating climate factors including height, temperature and relative humidity greatly impacted the emissions.

In relation to curbing the vehicular emission, one of the

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significant step taken by India is leapfrogging from BS-IV to BS-VI fuel standards by April 1, 2020 (ICCT, 2016). The initial standard put forth was called "India 2000," and it required that both passenger cars and commercial trucks adhere to standard that are on par with EURO I rules. After that in 2005, BS-II standard was mandated to all over the country, then the BS-III emission standards were implemented beginning in 2010, thereafter in 2017, BS-IV was applied nationwide. However, due to the worst air quality conditions in Indian cities, the government chose to forgo BS-V requirements and jump straight to BS-VI standards, which is now being implemented nationwide as of April 2020. As per the release of Press Information Bureau, a drop of NO_x and $PM_{2.5}$ emissions by 30% and 80% on moving from BS-III to BS-IV norms, respectively, has resulted in a considerable reduction in tailpipe emissions when switching from one norm to another (PIB, 2019). Therefore, diesel engines could decrease their NO_x levels by 68%, PM levels by 82% and HC (hydrocarbon) + NO_x levels by 43% by applying BS-VI standard (TVS Motor, 2021). The strict BS-VI rules include particle number limits for both light and heavy-duty vehicles, as well as strict limits on emissions for all emissions.

Due to the fact that the severe yet unequal health effects of vehicle emissions differ geographically as well as within the transportation industries, including LDV, HDV, shipping and off-road machinery (Gajbhiye *et al.*, 2023a), this study evaluated the way each of the BS standard stages works as well as how much varying vehicle exhaust emission levels contribute to worsening of air quality in the different geographical area of India as emissions are considerably impacted by meteorology. Because of the exposures described above, this research paper attempts to quantify the effect of various BS norm stages in lowering vehicular emissions in selected meteorological regions of India by estimating changes in volatile organic compounds (VOC), particulate matter ($PM_{2.5}$), nitrogen oxides (NO_x), carbon monoxide (CO) and black carbon (BC) emission from vehicles operating under various norms. The vehicular emissions for the period of 2013-2021 resulting from the LDV and HDV as well as from the vehicles operating under various emission norms are estimated by selecting a few states in the Himalaya and Trans-Himalaya region, Eastern Himalaya region and Plain region. Through this, the impact of BS-III, IV and VI norms in reducing vehicular emissions in these regions is studied.

Materials and Methods

To evaluate the scenario of vehicular emission regulation in different selected geographical regions of India, it is necessary to integrate real-time conditions data on on-road emission trends with the number of vehicles (exhaust, emission control technology and emission norms) and conduct a thorough analysis of emissions of different pollutants, including NO_x, $PM_{2.5}$, VOC, CO and BC. We accessed data on the number of registered vehicles (up to July 2022) using the Ministry of Road Transport and Highways' VAHAN portal, for the calendar years 2013 to 2022. Data is collected for vehicles under the light and heavy-duty vehicle categories and the BS standards they match (BS-I, II, III, IV and VI). The methodology followed is shown in figure 1.

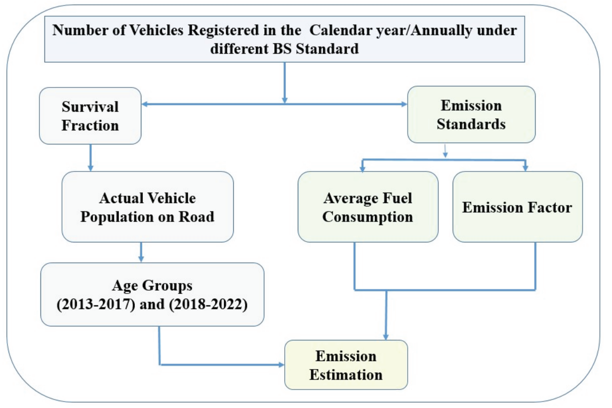

Figure 1: Layout for calculating emissions and analysis of BS regulations

The impact of the emission regulations can be verified by the survivability of automobiles following the proactive execution of strict emission rules. Furthermore, survivability influences the quantity of vehicles on the road (Yan *et al.*, 2014). To figure out the emission of various vehicles functioning under varying BS Standards, a fleet model that takes into account the age-based grouping of the vehicles is necessary. A fleet model has been employed in a number of prior research, including our own (Gajbhiye *et al.*, 2023a), to predict the age-wise survival of vehicles (Pandey and Venkataraman, 2014; Goel *et al.*, 2015; Malik and Tiwari, 2017; Singh *et al.*, 2022a). According to Pandey and Venkataraman (2014) the study calculates the survivability of vehicles using the fleet model that determines the age-wise survival fraction of vehicles for the national fleet of 2020. For the scenario of vehicular emission regulation in different geography, after the calculation of survivability, we get the actual vehicle population of the road. Thereafter employing the average fuel consumption approach (Goel and Guttikunda, 2015; Han *et al.*, 2017; Singh *et al.*, 2022b; Gajbhiye *et al.*, 2023b; Lakshmanan *et al.*, 2023) and emission factor (in g km^{-1}) from the various secondary literature, then estimated the emission scenario for the parameters NO_x, CO, VOC, $PM_{2.5}$ and BC in selected geographical regions. The overall calculation of survivability, emission estimation and emission factor for the parameters is detailed and discussed in our recent study (Lakshmanan *et al.*, 2023).

Results and Discussion

Vehicular Emission Trends

The data of the country is split into three geographical sections the Himalaya and Trans-Himalaya, Plain and the Eastern Himalaya. The topography of India, which comprises the Deccan Plateau, Eastern Ghat, Northern Plains, North East Himalaya, Trans-Himalaya, Himalaya and Western Ghat, serves as the main criterion for selecting states (Lakshmanan *et al.*, 2023). Accordingly, states are chosen from these geographical sections of Indian geography.

States in the Himalaya and Trans-Himalaya area include Himachal Pradesh, Jammu and Kashmir and Uttarakhand; states in the plains include Chhattisgarh, Maharashtra, Tamil Nadu and Uttar Pradesh. States in the Eastern Himalayas comprise Assam, Arunachal Pradesh, Manipur and Tripura. The survivability of the vehicles operating under different norms in these regions is obtained in our earlier study. The survival fraction along with the emission factors collected from the various secondary literature (Lakshmanan *et al*., 2023) are used for estimating the BC, NO_x, CO, VOC and $PM_{2.5}$ emissions.

Black Carbon Emissions in Different Geographical Regions of India

The BC emission trend is shown in figure 2. Himachal Pradesh, Jammu and Kashmir and Uttarakhand are states that are part of the Himalaya and Trans-Himalaya area. In these states, with a few significant exceptions, the figure 2 shows that BC emissions have risen overall in the majority of locations. The results show that from 2013 to 2021, BC emissions in this area were quite modest, ranging from 0.01 kT to 0.18 kT. The peak year for emissions was 2018 and then there was a minor reduction in 2019 and 2020. Emissions rose once more in 2021, reaching 0.20 kT.

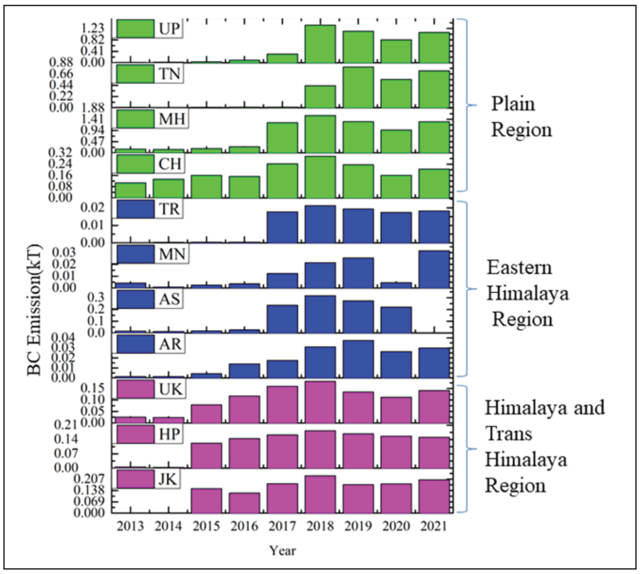

Figure 2: BC emissions from 2013-2021

The states Assam, Arunachal Pradesh, Manipur and Tripura in the Eastern Himalaya areas emit different amounts of BC. With values ranging from 0.01 kT to 0.32 kT, Assam has the highest emissions, which steadily increased from 2013 to 2018 before slightly declining in 2019, 2020 and 2021. In contrast, Arunachal Pradesh has moderate BC emissions, which range from 0.01 kT to 0.06 kT. Whereas, Manipur and Tripura have comparatively low emissions, with maximum values of 0.03 kT and 0.02 kT, respectively and most values being near to zero. According to the research, BC emissions in all four states Arunachal Pradesh through Tripura rose gradually between 2016 and 2021, whereas emissions in Manipur and Assam abruptly decreased in 2020 and 2021, respectively. In this area, Assam has more emissions than Arunachal Pradesh, Manipur and Tripura.

Maharashtra had the greatest emission in the plain area, which includes the states of Maharashtra, Chhattisgarh, Tamil Nadu and Uttar Pradesh. It peaked at 1.57 kT in 2018 and then somewhat decreased in the following years, ranging from 1.31 kT to 0.96 kT. With emission ranges between 1.13 kT and 0.82 kT from 2019 to 2021, Uttar Pradesh's emissions somewhat decreased from their peak of 1.35 kT in 2018. Tamil Nadu's emissions peaked in 2018 and 2019, when they were 0.63 kT and 0.80 kT, respectively. From 2020 to 2021, there was a minor decline in emissions, ranging from 0.55 kT to 0.72 kT. With 0.30 kT of emissions in 2018, Chhattisgarh led the way. There was a decline in future years. The data reveals that from 2013 to 2018, the emission in these four states climbed rapidly and then it somewhat decreased in the years that followed. In comparison to all four states of plain region, Chhattisgarh contributed lower emissions than Maharashtra, Tamil Nadu and Uttar Pradesh. The statistics show that between 2013 and 2021, BC emissions in the plain region ranged from 0.01 to 1.57 kT, more than those in the other two regions (Himalaya and Trans-Himalaya and Eastern Himalaya). 2018 saw the greatest emissions, which were then somewhat lower in 2019 and 2020. Emissions rose once more in 2021, reaching 1.31 kT. The data on BC emissions in the various areas of India from 2013 to 2021 reveals that the Plain region had the highest concentration of emissions, followed by the Eastern Himalaya, the Himalaya and Trans-Himalaya and emissions in the majority of locations climbed continuously before somewhat decreasing after that. According to past studies, traffic emissions are a noticeable source of black carbon and are positively connected with temperature and the height of the mixing layer; they are inversely correlated with rainfall, wind speed and relative humidity (Raju *et al.*, 2020). Therefore, these could be the reasons behind the highest black carbon concentration in the Plains and comparatively lower emissions in the Eastern and Trans-Himalaya.

NO_x Emissions in Different Geographical Regions of India

The NO_x emission trend for the years 2013-2021 is depicted in figure 3. As shown in figure 3, in the Himalayas and Trans-Himalaya, Jammu and Kashmir has the highest NO_x emission in this region, with range from 0.66 kT to 62.82 kT. NO_x emission from Jammu and Kashmir steadily increased from 2016 to 2017 and highest during 2018 with 62.82 kT then decreased significantly from 2019 to 2021. Himachal Pradesh has the highest NO_x emissions in 2017 to 2019, with range from 66.66 kT to 69.66 kT. Similarly, Uttarakhand has the highest NO_x emissions in 2017 to 2018, with range 60.27 kT to 68.76 kT, after that decreased gradually from 2019 to 2021. Jammu and Kashmir is contributing to higher NO_x emissions than Himachal Pradesh and Uttarakhand in Himalayas and Trans-Himalaya. In the Eastern Himalaya area, Assam has the highest NO_x emissions in 2013, with emission of 6.99 kT while, Arunachal Pradesh, Manipur and Tripura having 0.79 kT, 2.53 kT and 2.66 kT NO_x emissions, respectively. However, in 2017, the NO_x emissions from this region increased notably, with 9.01 kT, 3.88 kT and 8.32 kT, respectively in Assam, Arunachal Pradesh, Manipur and Tripura. In 2018, the NO_x emissions from all the four states was higher in comparison to all the other years, that is in Arunachal Pradesh, Assam, Manipur and Tripura, the emission increased remarkably to 9.78 kT, 92.00 kT, 6.13 kT and 11.20 kT, respectively. The NO_x emissions from this region dropped in 2020 and 2021. In this region, Assam has higher emission than Arunachal Pradesh, Manipur and Tripura.

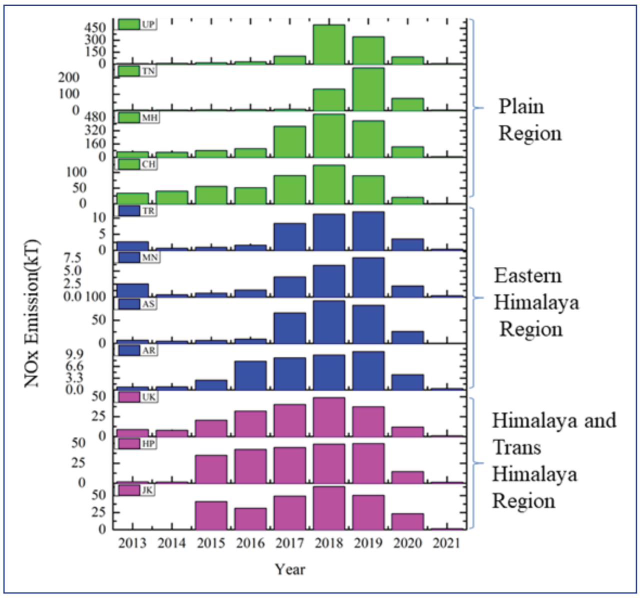

Figure 3: NO_x emissions from 2013-2021

As shown in figure 3, in the Plain region, Maharashtra has the highest NO_x emissions from 2013 to 2017 with range of emission 65.60 kT to 373.03 kT. In 2018, the NO_x emissions jumped on peak to 517.55 kT and then gradually decreased in 2019 to 2021. After Maharashtra, Chhattisgarh has the highest NO_x emission in plain region, from 2013 to 2017 with the emission range 33.89 kT to 89.80 kT. In 2018, the NO_x emissions is on peak at 123.06 kT, then gradually going down from 2019 to 2021 with range of 89.16 kT to 1.26 kT. NO_x emission in other two states Tamil Nadu and Uttar Pradesh gradually increased from 2013 to 2017 with range of 3.32 kT to 98.86 kT. On the other hand, NO_x emission are higher during 2018 and 2019 with range of 130.66 kT to 692.67 kT emission in both states relative to 2013 to 2017, then decreased during 2020 and 2021. The NO_x emission of Maharashtra in 2018, increased remarkably, in comparison to the year 2013. Over the past few years, Maharashtra regularly had the highest NO_x emissions, with Uttar Pradesh close behind. While Chhattisgarh had comparatively low emissions compared to the other three states, Tamil Nadu and Chhattisgarh both had high NO_x emissions. All four states have seen an increase in NO_x emissions over time, although Maharashtra and Uttar Pradesh have seen the noticeable increases, according to trends. Again, in comparison to the all regions, plain region have higher NO_x emission because of higher traffic density and vehicle activity, in plain area which is the major contributor of NO_x emission (Sahu *et al.*, 2022).

$PM_{2.5}$ Emission in Different Geographical Regions of India

The $PM_{2.5}$ emission trend for the years 2013-2021 is shown in figure 4. The $PM_{2.5}$ emissions in the Himalayas and Trans-

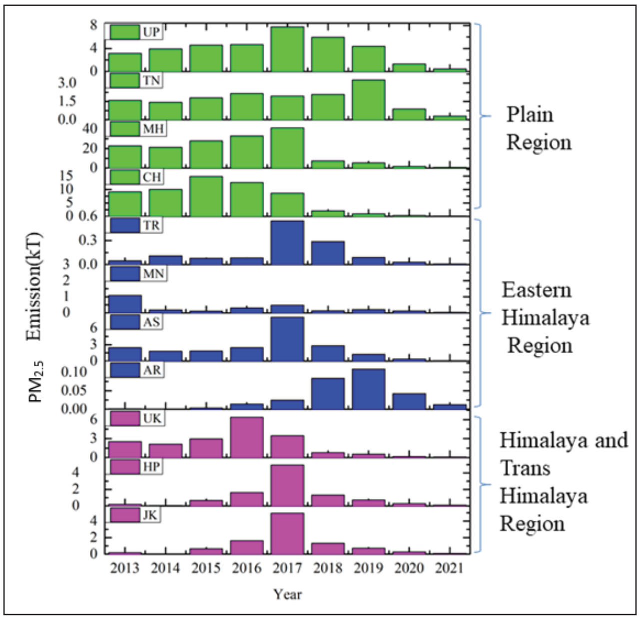

Figure 4: $PM_{2.5}$ emissions from 2013-2021

Himalaya region have been relatively low compared to the other two regions (Eastern Himalaya Region and Plain region). $PM_{2.5}$ emissions in the Himalayas and Trans-Himalaya are higher during the years 2013 to 2017 ranging between 0.03 kT and 6.96 kT in Jammu and Kashmir and Himachal Pradesh, while in Uttarakhand, the $PM_{2.5}$ emissions range from 2.10 kT to 6.39 kT. From 2018 to 2021, this emission trend continuously decreased in subsequent years ranging from 0.71 kT to 0.08 kT in Jammu and Kashmir and Himachal Pradesh; whereas, in Uttarakhand, the corresponding range is 0.56 kT to 0.09 kT. Here, Uttarakhand is showing higher emission as compared with other two states, Jammu and Kashmir and Himachal Pradesh.

The Eastern Himalaya region showing $PM_{2.5}$ emission levels have been relatively stable from 2013 to 2016, with a slight increase in 2017 and a decrease in 2018 and 2020. As shown in figure 4, Arunachal Pradesh is showing very low $PM_{2.5}$ emissions from 2013 to 2018 in the range of 0.01 kT to 0.02 kT, while in the year 2019, the emissions jumped to 0.11 kT after that gradually decreased in 2020 and 2021. However, Arunachal Pradesh has lower emission than other states such as Assam, Manipur and Tripura of this region. Assam is showing higher $PM_{2.5}$ emission amongst all four states of the region, it is gradually increasing from 2013 to 2017 with range of 1.79 kT to 8.03 kT then continuously decreases from 2018 to 2021 with the range of 0.07 kT to 2.79 kT. Manipur and Tripura states are showing almost moderate trend of $PM_{2.5}$ emission. From 2013 to 2017, the $PM_{2.5}$ emissions gradually increases within range of 0.05 kT to 1.09 kT, while from 2018 to 2021 it tend to decrease with the range of 0.29 kT to 0.01 kT. $PM_{2.5}$ emission in the plain area which included the states Maharashtra, Chhattisgarh, Tamil Nadu and Uttar Pradesh, shows highest levels among the three regions. Maharashtra has the highest $PM_{2.5}$ emissions in this region, from 2013 to 2017 with range of emission 21.16 kT to 61.13 kT then it is gradually goes down from 2018 to 2021 with range of 7.30 kT to 0.30 kT. In Maharashtra during 2017, the $PM_{2.5}$ emissions jumped on peak to 61.13 kT then continuously decreased from 2018 to 2021. After that Chhattisgarh is placed on second position among the emission contribution in the plain region and showing the highest $PM_{2.5}$ emissions from 2013 to 2017 gradually increased with range of 8.66 kT to 16.89 kT. In 2015-2016, reached on peak then consistently going down from 2018 to 2021 with range of 2.02 kT to 0.11 kT. Other two states Tamil Nadu and Uttar Pradesh have gradually increased trend of $PM_{2.5}$ emission from 2013 to 2019 within range of 1.62 kT to 7.76 kT, then this trend is decreased during 2020 and 2021. Among all the four states, Maharashtra and Chhattisgarh have had the most noticeable $PM_{2.5}$ emission contribution. While Tamil Nadu has relatively lower $PM_{2.5}$ emissions in comparison to the other three states. Also, the $PM_{2.5}$ emissions are prominent before 2017, where most of the vehicles were operating under BS-III norms. This reveals that the $PM_{2.5}$ emissions from older vehicles are higher in accordance with the earlier study (Pandey and Venkataraman, 2014), which showed that from older vehicles; around 23-45% of $PM_{2.5}$ is emitted.

CO Emission in Different Geographical Regions of India

CO emissions in different Indian regions from 2013 to 2021 are illustrated in figure 5. As shown in the figure, CO emissions show rising overall in the majority of locations over the years. From 2013 to 2021, CO emissions in Himalaya and Trans-Himalaya region showed a peak at 2018 with 31.72 kT emissions. The peak year for emissions was 2017 and 2018 and then there was a minor reduction in 2019 to 2021. Assam, Arunachal Pradesh, Tripura and Manipur in the Eastern Himalayas emit different amounts of CO with values ranging from 0.66 kT to 66.83 kT. Assam has the highest CO emissions amongst the states studied ranging between 5.69 kT to 66.83 kT, while emission turned very low in 2021. As shown in figure 5, CO emissions in all four states Arunachal Pradesh, Assam, Manipur, Tripura is rising gradually between 2016 and 2018 and then emissions are abruptly decreased in 2020 and 2021. Arunachal Pradesh (range from 0.66 kT to 6.06 kT), Manipur (0.25 kT to 3.60 kT) and Tripura (0.06 kT to 3.07 kT) has moderate CO emissions. Maharashtra has the greatest CO emission in the plain region. It peaked at 217.53 kT in 2018 and from 2013 to 2017, the emissions gradually increase ranging from 65.69 kT to 68.63 kT, then decreased with emission ranges between 181.51 kT and 106.66 kT from 2019 to 2021. Uttar Pradesh is showing on second rank after Maharashtra with peak CO emissions at 187.63 kT in 2018 and from 2013 to 2017, emission is gradually rising from 6.32 kT to 67.78 kT and then turned down with emission ranges between 83.75 kT from 2019 to 2021. Similarly in Tamil Nadu, CO emissions is very low from 2013 to 2017 and peaked in 2018 and 2019, where they were 59.85 kT and 110.26 kT, respectively. From 2020 to 2021, there was a minor decline in emissions, ranging from 56.58 kT to 58.82 kT. Chhattisgarh is showing moderate emission in comparison with other states like Maharashtra, Tamil Nadu and Uttar Pradesh. The data reveals that from 2013 to 2019, the emission is almost linear ranging from 32.53 kT to 69.69 kT and then turned down in 2020 and 2021, *i.e.*, ~15.56 kT of emissions. In comparison to all four states of plain region, Chhattisgarh contributes lower CO emission than Maharashtra, Tamil Nadu and Uttar Pradesh.

The statistics show that between 2013 and 2021, CO emissions in the plain region (maximum 217.53 kT), is more than those in the other two regions Himalaya and Trans-Himalaya (maximum 31.72 kT) and Eastern Himalaya region (maximum 66.83 kT). The data on CO emissions in the various areas of India from 2013 to 2021 reveals that the Plain region has the highest concentration of CO, followed by the Eastern Himalaya region, Himalayas and Trans-Himalaya.

VOC Emission in Different Geographical Regions of India

The VOC emissions from different regions of India for the years 2013-2021 is shown in figure 6. As shown in the figure 6, in Himalaya and Trans-Himalaya, Uttarakhand

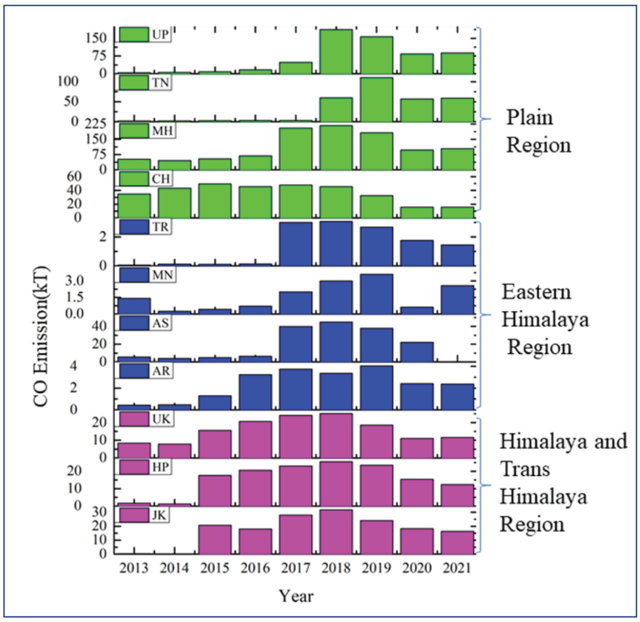

Figure 5: CO emissions from 2013-2021

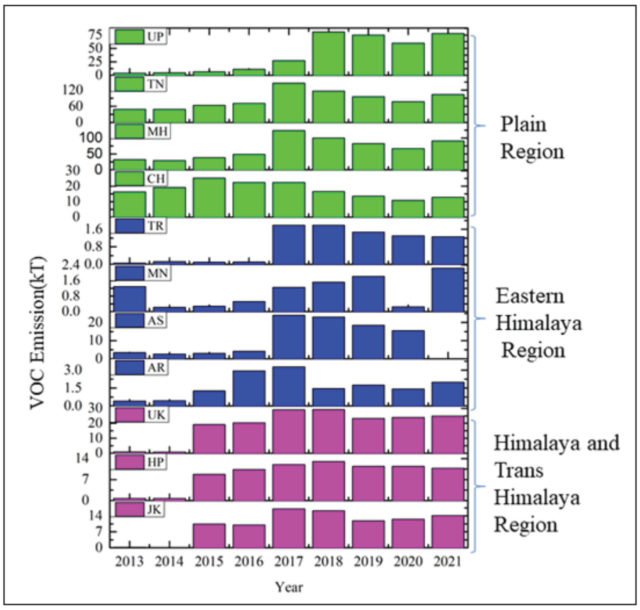

Figure 6: VOC emissions from 2013-2021

is contributing the highest VOC emissions in this region, with range from 0.93 kT to 29.17 kT. VOC emissions from Uttarakhand consistently increased from 2015 to 2021 and highest during 2018 having 29.17 kT, while the emissions were lower during the year 2013 to 2016. Jammu and Kashmir is having second position in this region after Uttarakhand. Jammu and Kashmir has the highest VOC emissions from 2015 to 2018, with range of 10.00 kT to 17.09 kT. After that its trend is going down from 2019 to 2021. Similarly in 2013, Himachal Pradesh has lower VOC emissions then it is gradually raised from 2015 to 2021, with range of 10.76 kT to 12.98 kT. Himachal Pradesh is less contributing to VOC emission than Jammu and Kashmir in Himalaya and Trans-Himalaya.

In the Eastern Himalayan Region, Assam has the highest VOC emissions. But the trend of VOC emission in all states of Eastern Himalaya Region, *i.e.*, Assam, Arunachal Pradesh, Manipur and Tripura are similar; it gradually increases from 2013 to 2016, then showing higher emission during 2017 to 2021. Arunachal Pradesh has VOC emission range within 0.60 kT to 3.27 kT. In Assam, emission range is from 0.13 kT to 26.00 kT. Manipur and Tripura have mix range of emission in between 0.05 kT to 1.81 kT, but Manipur and Tripura are showing lower VOC emission contribution than the other two states.

As shown in figure 6, in the plain region, Tamil Nadu has the highest VOC emissions, from 2013 to 2016 with the range of emission from 68.67 kT to 71.06 kT. In 2017, the VOC emission jumped on peak, *i.e.*, 166.21 kT and then gradually decreased from 2018 to 2020, but in 2021, it is again showing some increment. After Tamil Nadu, Maharashtra has the highest VOC emissions in plain region, from 2013 to 2016 with a gradual increase ranging between 29.36 kT and 68.63 kT. During 2017 and 2018, it jumped on peak with the range of 123.75 kT to 100.10 kT respectively. After 2018, the VOC emissions are gradually going down from 2019 to 2021, with range of 66.59 kT to 90.70 kT. VOC emissions in other two states Chhattisgarh and Uttar Pradesh gradually increased from 2013 to 2017 with range of 3.75 kT to 27.08 kT and then VOC emission has reached higher during 2018 and 2019 in both states relative to 2013-2017. Again in 2020 and 2021, the emissions have decreased. Chhattisgarh has relatively low emissions in comparison to the other three states. In comparison to all three regions, VOC emission from plain region is higher than that from the Eastern Himalaya and Trans Himalaya. This is directly attributed to the abundant vehicle population in the states of plain area when compared to the other region. The above results show that the NO_x, VOC, CO, $PM_{2.5}$ and BC emissions are more prominent in the plain, relative to the Himalayas and Eastern Himalayas. As the plain region generally have factors such as more vehicle density, activity and traffic which co-cordially interacts with other factor like vehicle maintenance, fuel used, ambient temperature and wind speed. After that which result's to the higher pollutant NO_x, VOC, CO, $PM_{2.5}$ and BC emission from vehicle sector (Goel *et al.*, 2016; Raju *et al.*, 2020; Sahu *et al.*, 2022). However, as we have discussed in our earlier research (Lakshmanan *et al.*, 2023), the main factor influencing the emissions is meteorology.

Norms-wise Emission Scenario

The emission of NO_x, $PM_{2.5}$, CO, BC and VOC under Bharat Stage norms BS-III, IV and VI is shown in figure 7 for the years 2013 to 2021. Figure 7 illustrates how the emission rules tighten up dramatically from BS-III to BS-VI in terms of the context of NO_x emission. Vehicles that comply with BS-III have lower NO_x emissions than those that comply with BS-IV. However, the BS-VI emissions have significantly reduced NO_x emissions. The adoption of cutting-edge engine technologies and the usage of cleaner fuels may be the main causes of this decrease in NO_x emissions. CO emissions from vehicles that complied with BS-III emission standards jumped to 6.74 million kT from 3.59 million kT under BS-IV emission standards. While CO emissions have remarkably decreased to 2.27 million kT since the BS-VI standards were put into place. A decrease in CO emissions is seen with BS-VI standards with relation to the BS-III and IV standards. Between BS-III and IV regulations, there is a 26% increase in CO emissions on average. When compared to BS-IV regulations, the enforcement of BS-VI norms reduces CO emissions by 52%.

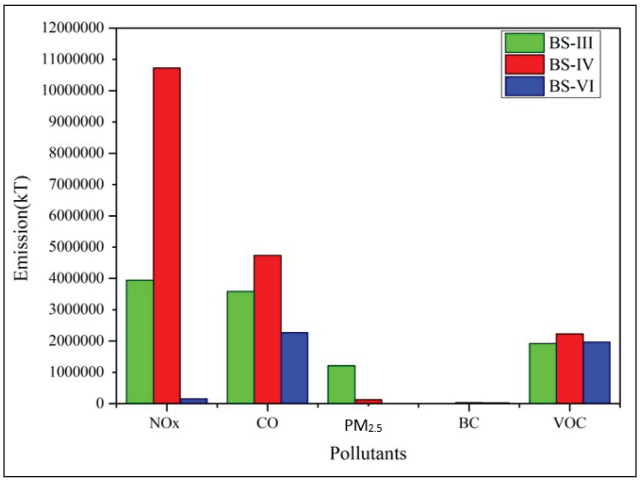

Figure 7: Norms-wise emission scenario for years 2013-2021

In comparison to BS-IV and BS-VI emission limits, $PM_{2.5}$ emissions under BS-III emission standards permit a much greater $PM_{2.5}$ emission. For BS-IV compliance vehicles, the $PM_{2.5}$ emissions are lowered to 30,836 kT from 1.22 million kT for BS-III compliant vehicles. And the $PM_{2.5}$ emissions have been further reduced to 11,099 kT due to the adoption of BS-VI emission standards. With the adoption of BS-VI norms, $PM_{2.5}$ emissions are further reduced by 91%. The reduction in particulate matter ($PM_{2.5}$) from BS-III to BS-IV is almost 89%. BC emissions from vehicles that are BS-III compliance are 10,915 kT, which is notably less than the emissions from vehicles that are BS-IV compliant, which are 36,336 kT. Following the adoption of BS-VI standards, BC emissions dropped to 28,612 kT. Between BS-III and IV norms, BC emissions were reduced by roughly 68%, while with BS-VI requirements, BC emissions were further reduced by 17%. The VOC have grown from 1.92 million kT, with BS-III, to 2.23 million kT under BS-IV emission regulations. The adoption of BS-VI rules, however, has caused a decrease in VOC emissions to 1.96 million kT. From BS-III to BS-IV norms, there is a roughly 16% reduction in VOC emissions and the introduction of BS-VI regulations results in a 12% reduction. Still, currently, BS-III and IV vehicles are also under operation and they are old vehicles, so if they are poorly maintained and the catalytic converter loses some of its functionality, it may lead to higher NO_x and CO emissions (Goel *et al.*, 2016; Tsai *et al.*, 2017), since number of factors, including vehicle age, driving style, servicing, *etc*., are important in determining exhaust emissions (Raparthi *et al.*, 2021). In the meantime, it is evident from these discussions that, under the BS-VI standards, SCR technology controls all emissions; however, VOC emissions are on scale with NO_x and CO emissions. As it was mentioned also in a prior research (Hakkim *et al.*, 2022), NO_x and VOC emissions may play a part in the development of secondary pollutants, greater liability for these emissions is needed. To control all emissions, advanced after-treatment technologies need to operate in an equitable way.

Conclusion and Policy Recommendations

This study aims to understand the trend of emission from HDV and LDV running under BS-III, IV and VI emission norms in different regions of India. The emissions of pollutants such as VOC, NO_x, $PM_{2.5}$, CO and BC for the time period 2013-2021 under different norms are estimated. The study identifies distinct emission patterns across the Himalayas and Trans-Himalaya, the Eastern Himalayas and the Plains. Among these, the Plains region shows a notably high level of emissions. BC emissions peaked in 2018 in the Himalayas and Trans-Himalayan area and then somewhat declined in the years that followed. On the other hand, larger BC emissions were found in the Eastern Himalaya region, especially in Assam. These emissions increased until 2018 before declining. The BC emissions in the Plain region peaked in 2018 and then started to decline. And there were regional differences in the NO_x emissions. The Himalaya and Trans-Himalaya gained considerably from Jammu and Kashmir's contribution, the Eastern Himalaya led by Assam and the Plain region was dominated by Maharashtra. The trends showed that NO_x emissions increased in all regions between 2013 and 2019, then began to fall in the years that followed. Similarly, there were regional differences in $PM_{2.5}$ emissions; Maharashtra and Chhattisgarh in the Plain area recorded the highest values. $PM_{2.5}$ concentrations in the Himalaya and Trans-Himalaya region were comparatively low and exhibited a declining trend between 2018 and 2021. In the Eastern-Himalaya region, Assam contributed to the highest $PM_{2.5}$ emissions. In the Plain area, Maharashtra and Uttar Pradesh led the way in CO emissions. There was a noticeable rise in CO emissions from the Eastern Himalaya region, specifically from Assam, which peaked in 2018 and then began to decline. Every region saw an overall increase in emissions until 2018 before they started to decline. There were regional variations in VOC emissions, in the Himalayas and Trans-Himalaya, Uttarakhand contributed the most, Assam in the Eastern Himalaya region and Tamil Nadu in the Plain region. With the adoption of stricter rules, there was a noticeable reduction in pollutant emissions, on switching from BS-III to BS-IV and BS-VI standard.

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