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Impact of lockdown associated with COVID19 on air quality and emissions from transportation sector: case study in selected Indian metropolitan cities

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Abstract
This study examines the impact of air quality in selected Indian metropolitan cities during the COVID19 pandemic lockdown period. Concentrations of air quality parameters such as $PM_{2.5}$, NO_2, SO_2, and CO during the transition to lockdown and the actual lockdown period were compared with business as usual periods (a period prior to COVID19 lockdown and a corresponding period in 2019) to estimate the reduction in emission in four major IT hubs in India namely Bengaluru, Chennai, Hyderabad and Pune. A 40–45% reduction in $PM_{2.5}$ concentration was observed, in these cities, during the lockdown compared to the corresponding period in 2019 and a 20–45% reduction was observed compared to business as usual period in 2020. A vehicle kilometer traveled (VKT)-related questionnaire survey-based study in Hyderabad revealed that, with 48% of population utilizing work-from-home during the transition to lockdown period, vehicular $PM_{2.5}$ emission in Hyderabad reduced by 54% compared to usual traffic emissions prior to COVID19 lockdown. Furthermore, it was estimated that emission of up to 3243, 777, 113, and 54 tons/year of CO, NOx, $PM_{2.5}$, and SO_2, respectively, could be avoided in Hyderabad alone, if work-from-home is implemented on a 2 days/week basis. The experience from this study can be used to develop policies favoring reduced use of private vehicles or implementation of work-from-home to combat air pollution and reduce carbon emissions.

Keywords Nitrogen dioxide · $PM_{2.5}$ · Carbon monoxide · SO_2 · Transport-related emissions · Work from home

1 Introduction

India is in a severe environmental and health risk by harboring 21 among 30 cities with worst air quality (Pant et al. 2019; World Health Organisation 2018). According to a report published jointly by Indian Council of Medical Research (ICMR), Public Health Foundation of India (PHFI), and Ministry of Health and Family Welfare, air pollution causes 26% of premature deaths in India in 2017 (Balakrishnan et al. 2019). Among other sources, transportation sector is the fastest growing contributor to air pollution in urban centers. A recent study by Guttikunda et al. (2019a) on emission inventory in 20 Indian cities (excluding Delhi) revealed that transportation accounts for 18% of total particulate matter (PM) emissions. Furthermore, in cities like Bengaluru, Chennai, and Pune, 24–26% of the ambient emissions are attributed to transportation (Rastogi et al. 2019). More than 60% of PM_{10} pollution over Hyderabad city comes from direct vehicular exhaust and road dust (Guttikunda and Kopakka 2014). Policy decisions and countrywide change of fuel type have reduced SO_2 emissions from transportation (Sabapathy 2008). Despite extensive efforts, the pace of air quality improvement remains slow in India due to several natural and anthropogenic reasons. For example, a recent study by Singh et al. (2020) revealed

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that air pollution is relatively higher for inland cities and lower for coastal cities. Transitioning to renewable and green energy (e.g., electric vehicles) to curb transportation-related pollution is a prime and much endorsed option. It has been shown by Chowdhury et al. (2019), that a transition from bad fuel to clean fuel in the household has the potential to significantly reduce the $PM_{2.5}$ levels at the national level. Purohit et al. (2019) have reported that the air pollution control measures implemented until June 2018, should deliver an overall decline of ambient $PM_{2.5}$ levels of about 14% by 2030, and stabilize the pollution levels despite economic growth. However, the option of reducing the need of vehicular transportation must be explored.

The recent outbreak of the severe acute respiratory syndrome coronavirus 2 (COVID19), first detected in Hubei province of China, has sent the globe into frenzy since the beginning of 2020 (Sohrabi et al. 2020). The Government of India (GoI) acted swiftly by recommending seclusion during the period 15/03/2020 to 24/03/2020, denoted in this study as transition to lockdown (TLD) (Table 1). In the TLD period, private companies initiated the work-from-home (WFH) option in order to ensure social distancing and the public started to voluntarily avoid travel. GoI called for a one-day nation-wide curfew on 22/03/2020 ("Coronavirus: Nationwide 'Janta curfew' begins on PM Modi's appeal," 2020). Considerable improvement in air quality was observed due to Janta curfew. The average AQI in Bengaluru on 23/03/2020 was 99 as compared to 135 on 21/03/2020 and 137 on 23/03/2019 (https://aqicn.org/sources/). Eventually, a nation-wide complete lockdown of the commercial and non-essential service sector was announced for the period of 24/03/2020 to 15/04/2020 (Karan Deep Singh et al. 2020b), which was further extended in various phases with different regulations.

In addition to the distressing effects on human health, COVID19 has vastly decelerated the transportation system. The data released by Google revealed that the work trips reduced by 47% and travel for retail and recreation reduced by 77% during the transition to lockdown in India (Google mobility report 2020). The decrease in travel can be quantitatively measured using the reduction in vehicle kilometers traveled (VKT). VKT is an important metric in transportation planning and provides a measure of total travel in a selected region and change in travel over time, which further can be used to understand the environmental impact.

Amidst the nation-wide COVID19-related lockdown, the work operations of IT (Information Technology) sector were undoubtedly the least affected compared to other commercial sectors, since WFH was a viable option. The Indian IT and Information Technology Enabled Service (ITeS, which covers diverse service-based operations including finance, HR, administration, health care, telecommunication, manufacturing, business, and knowledge processing) industry leads the sourcing terminal across the world. Up to 75% global digital talent is located in India, and India accounted for 55% market share of the global services sourcing business in 2017–18 (IBEF 2019). With a total value of US$ 177 billion in 2019 and witnessing a growth of 6.1% per year, the IT/ITES sector is expected to grow to US$ 350 billion by 2025 (IBEF 2019). In 2017, IT/ITES hubs viz., Bengaluru (Silicon Valley of India), Hyderabad (Bioinformatics hub), Chennai (infrastructure and Business Processes Outsourcing, BPO, hub), and Mumbai (Financial capital) employed up to 4 million as direct employees (ICSI 2018). The transportation of the ITeS workforce to commute to work contributes substantially to the air emissions. In order to explore the scope of reduction in transportation-related air emissions, COVID19-related lockdown presented an ideal opportunity and Indian metropolitan cities that predominantly host the IT and ITeS companies were considered for examination in this study.

With millions of Indians on WFH during the COVID19 lockdown, correlating VKT statistics to atmospheric emissions makes intuitive sense. Few studies suggest improvement in air quality in Indian cities such as Delhi and Kolkata to COVID19-related lockdown (Singh et al. 2020). However, a direct correlation between the reduction in VKT and improvement in air quality has not been examined. Total emissions from vehicles are directly proportional to the total kilometers traveled. Despite the belief that suspending the transportation sector played a key role in reducing air emissions, it is unknown whether the contribution is significant. Moreover, meteorology could play an important role in air pollution, transport, deposition, and transformation and can bring severe pollution on days even when the total emission is reduced. For example, a recent study by Chauhan and

Table 1 Description of the study phases during COVID19 lockdown

Study phase code	Study phases name	Duration	Phase description
BaU	Business as Usual	01/03/2020 to 14/03/2020	Usual operation of all sectors along with regular travel
TLD	Transition to lock down	15/03/2020 to 24/03/2020	Private companies initiated the work-from-home (WFH) option in order to ensure social distancing, where people voluntarily avoided travel
LD	Lockdown period	25/03/2020 to 15/04/2020	Phase-1 of nation-wide complete lockdown

Singh (2020a) showed a 35% and 14% decline in atmospheric $PM_{2.5}$ concentration in Delhi and Mumbai, respectively, in March 2020, compared to March 2019 and attributed the decline to COVID19, wherein a complete lockdown was observed throughout the world with practically no traffic on the roads. Briz-Redón et al. (2021) in Spain revealed that while the lockdown had reduced the air pollution in some of the cities, some other cities were unaffected due to varying meteorological parameters. Distinct diurnal, seasonal, and monthly variations are observed in air quality due to local meteorology with the highest and lowest concentrations in the winter and monsoon months, respectively (Singh et al. 2021). Therefore, it is important to quantify the emission reduction due to reduced transportation for further policy decisions and identify economic sectors that do not essentially rely on work-related mobility.

Accordingly, the objectives of this study were (a) to compare the air quality during business as usual (BaU) scenario (01/03 to 14/03/2020), transition to lockdown (15/03/2020 to 24/03/2020), and lockdown phase (25/03 to 15/04/2020) with respective periods in 2019 (01/03 to 14/03; 15/03 to 24/03; 25/03 to 15/04/2019) for Indian metropolitan cities that dominate the IT markets, namely, Bengaluru, Chennai, Hyderabad, and Pune, and (b) to estimate the transportation-related emissions during BaU, transition to lockdown and lockdown period.

2 Methodology

2.1 Study period and study area

The air quality trend in Indian metropolitan cities namely Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Jaipur, Kolkata, Navi Mumbai, Mumbai, Pune, Surat, and Visakhapatnam during the period 2012 to 2018 was analyzed based on the air quality parameters such as particulate matter of size < 2.5 µm ($PM_{2.5}$), carbon monooxide (CO), sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). Based on the air quality trend, Bengaluru (population: 12.95 million and population density: 4381 persons/km^2), Chennai (population: 10.64 million and population density: 14,350 persons/km^2), Hyderabad (population: 12.25 million and population density: 18,480 persons/km^2) and Pune (population: 7.13 million and population density: 603 persons/km^2) (https://worldpopulationreview.com) that predominantly host the IT and ITeS companies were selected as study area to explore the reduction in transportation-related air emissions by comparing the air quality parameters, viz., NO_2, SO_2, PM_{10}, and $PM_{2.5}$. The daily (average) ambient concentration data were obtained from the air quality database by Central Pollution Control Board (CPCB), India, under the National Air Quality Monitoring Programme (NAMP) (www.app.cpcbccr.com).

For the case study in the four selected cities, the study periods considered (Table 1) were pre-lockdown or Business as Usual (BaU) period, referred as BaU, between 01/03/2020 and 14/03/2020, transition to lockdown (TLD) between 15/03/2020 and 24/03/2020 and lockdown period (LD) between 25/03/2020 and 15/04/2020. Although the lockdown was extended in phases beyond 15/04/2020 by the Indian Government, 25/03/2020 to 15/04/2020 was selected indicatively. To minimize the influence of meteorological parameters, data from the previous year during the same intervals (01/03 to 14/03; 15/03 to 24/03; 25/03 to 15/04/2019) were compared with that of 2020.

2.2 Transportation related emissions

In developing nations like India, acquiring household travel pattern data is difficult. The Indian census does not provide a cross-tabulated data on individual travel pattern (Bansal et al. 2016). Unavailability of travel pattern data creates difficulty in calibrating actual emissions through vehicles. To understand the commuter's choice of mode for work trip and its characteristics, an online questionnaire survey was designed to gather information about the travel behavior of commuters before and during the transition to lockdown period of COVID19 outbreak for Hyderabad city.

The questionnaire enquired about the commuters' socio-economic characteristics (age, income, and city of residence), travel characteristics (preferred mode of transport, type of vehicle owned, fuel type, distance from work to home, travel time, frequency of traveling to work) and travel behavioral changes due to COVID19 outbreak. The survey hyperlink was circulated through personal communications, social media platforms, and public forums. The participation in the study was anonymous, voluntary, and confidential. Nearly 550 responses obtained from Hyderabad are used in this study to understand the average VKT by different vehicle types for work trips and other visits before and after the lockdown period due to COVID19 pandemic. Table 2 shows the summary statistics of work trip characteristics. Based on the vehicle and fuel type, distance traveled, and frequency of travel, average VKT was calculated using Eq. (1):

$$VKT_{(x,y)} = \frac{\sum_1^n \mu \times d}{7 \times n}, \tag{1}$$

where μ = frequency of travel to work place, d = distance to work place, x x = type of vehicle (car or motorized 2-wheeler), y = type of fuel (petrol or diesel), and n = sample size.

The VKT for other modes of transport such as bus and auto-rickshaw was calculated based on the daily average

Table 2 Descriptive statistics of work trip characteristics

Attributes	Category	Percentage
Distance to workplace from home	Less than 5 km	37
	5–10 km	21
	10–20 km	12
	20–30 km	15
	More than 30 km	15
Travel time between home and work	0–15 min	36
	15–30 min	19
	30–60 min	22
	1–2 h	14
	More than 2 h	9
Frequency of travel per week	Whole week	11
	Six days	25
	Five days	46
	Less than 5 days	18
Common mode of travel between work and home	Walk	14
	Bicycle	2
	Auto Rickshaw	5
	BUS	16
	Car	30
	Metro/Train/Suburban	9
	Two wheeler	24
Fuel type	Diesel	23
	Petrol	77

operated length. The daily operated length for Telangana State Regional Transport Corporation (TSRTC) buses in Hyderabad metropolitan is approximately 482,280 km (TSRTC 2020). The total average projected distance traveled by shared auto/taxi operators was ~ 83 km/d and total average trips made per day were approximately 9 (CTS 2013). The distances estimated were converted into emissions by multiplying with a distanced-based emissions factor. In this study, the distanced-based emission factor used was sourced from a study on atmospheric emissions from road transportation by Baidya and Borken-Kleefeld (2009).

3 Results

3.1 Air quality trend in Indian metropolitans

The annual air quality parameters (NO_2, SO_2, PM_{10}, and $PM_{2.5}$) for Indian metropolitans viz., Ahmedabad, Bengaluru, Chennai, Delhi, Hyderabad, Jaipur, Kolkata, Navi Mumbai, Mumbai, Pune, Surat, and Visakhapatnam show a steady increase from 2012 to 2018 (Fig. 1). In most of the metropolitans, concentration of PM_{10} was higher than the Indian National Ambient Air Quality Standards (NAAQS, $NO_2 = 40$, $SO_2 = 50$, $PM_{10} = 60$, $PM_{2.5} = 40$ μg/m^3), which are further higher than the World Health Organization (WHO) guideline values (WHO-GV) ($NO_2 = 40$, $SO_2 = 20$, $PM_{10} = 20$, $PM_{2.5} = 10$ μg/m^3) (www.cpcb envis.nic.in; www.who.int).

The ambient NO_2 concentration in Pune, Delhi, Kolkata, and Navi Mumbai was higher than the NAAQS since 2012–2014, with Pune showing a steep increase from ~ 45 μg/m^3 in 2014 to 70 μg/m^3 in 2018 (Fig. 1a). While the SO_2 concentration in all the metropolitans are below the NAAQS, concentration in Pune and Navi Mumbai is higher that of WHO-GV, with Pune showing an increase from ~ 20 μg/m^3 to ~ 40 μg/m^3 in 2018 (Fig. 1b). The PM_{10} concentrations in all the considered Indian Metropolitans were higher than both NAAQS and WHO-GV with Delhi, Ahmedabad, and Jaipur recording the ambient concentration > 200 μg/m^3. Similarly, the $PM_{2.5}$ concentrations were higher than WHO-GV in all the metropolitans, with concentrations higher than the NAAQS in Bengaluru, Hyderabad, Jaipur, Navi Mumbai, Surat, Ahmedabad, and Pune and a concentration > 100 μg/m^3 in Delhi. Given the high annual average ambient pollutant concentration in Bengaluru, Chennai, Hyderabad, and Pune, which are also the IT/ITeS hubs, these cities were chosen for further investigation.

3.2 Ambient pollutant concentration during the lockdown period

The daily average ambient concentration in the selected cities before the lockdown, during transition and after lockdown, and the corresponding periods in 2019 are shown in Table 3. A clear decrease in NO_2, $PM_{2.5}$, SO_2 and CO concentration was observed during the lockdown period and the ambient concentrations were well within the limit of the NAAQS and WHO-GV.

3.2.1 Nitrogen dioxide concentration

The ambient NO_2 concentrations in Bengaluru gradually decreased from ~ 50 μg/m^3 before lockdown to ~ 10 μg/m^3 during the lockdown (Fig. 2a). The average NO_2 concentration was 11.56 μg/m^3 during the lockdown, compared to 23.0 and 27.3 μg/m^3 during the transition and BaU period, respectively, and in the range of 30–35 μg/m^3 during the corresponding periods in 2019. The NO_2 concentrations were considerably higher before the lockdown in comparison with the same period in 2019. A decreasing trend was observed in other considered cities (Fig. 3b, 3c and 3d) where in the NO_2 concentrations were as low as 8.2, 19.1, and 11.6 μg/m^3 in Chennai, Hyderabad and Pune, compared to 11.5, 27.4, and 16.0 μg/m^3 before the lockdown and > 15, > 30, and > 12 μg/m^3 during 2019, respectively. On an average, a 67.1, 47.6, 39.7, and 6.8% reduction in the NO_2 concentrations were observed, respectively, in Bengaluru, Chennai, Hyderabad,

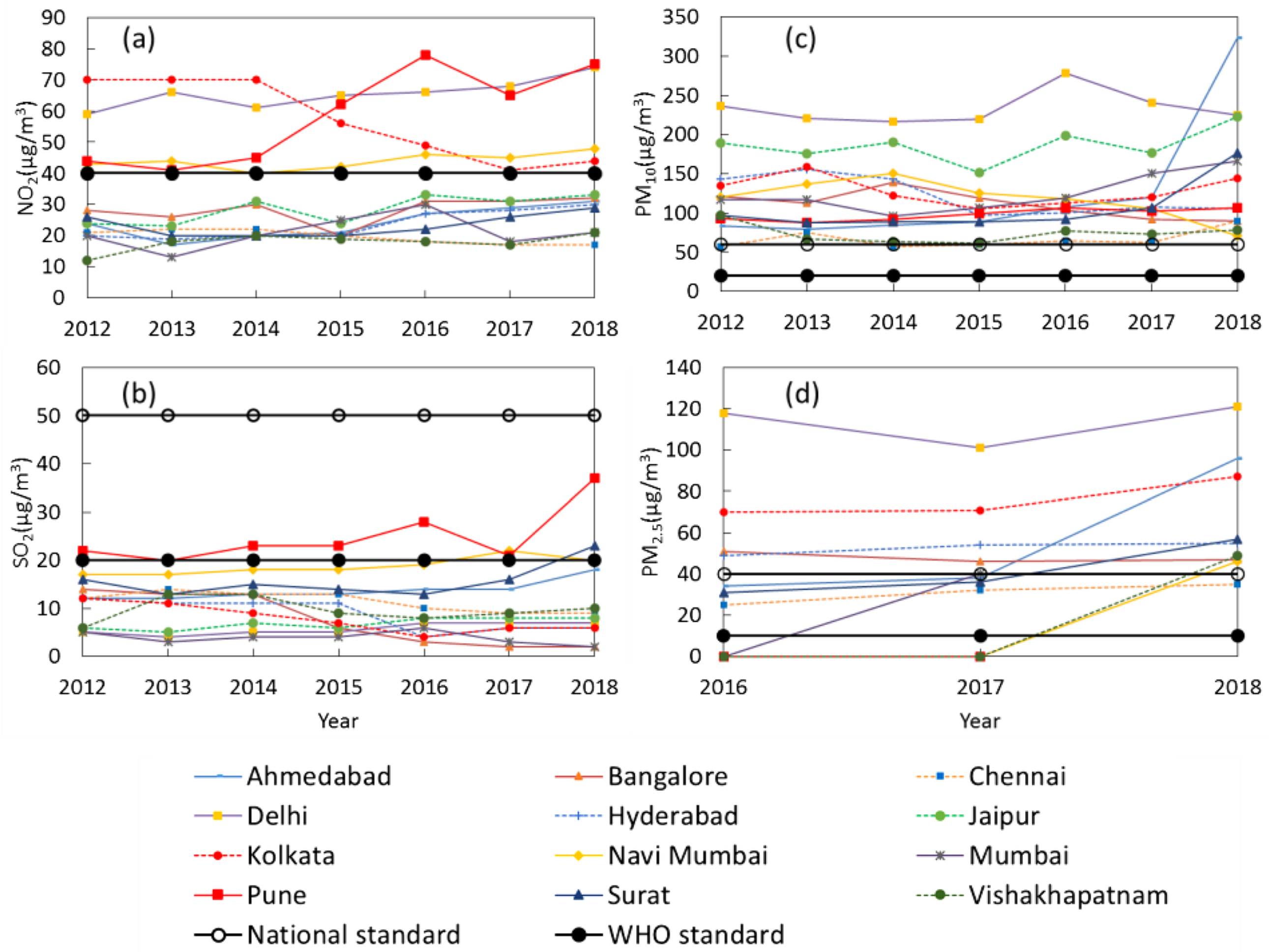

Fig. 1 Yearly ambient concentrations of characteristic pollutants (NO_2, PM_{10}, SO_2 and $PM_{2.5}$) in all the Indian metropolitans

Table 3 Daily average ambient pollutant concentration (the values in parenthesis show the standard deviation)

		Bengaluru		Chennai		Hyderabad		Pune	
		2019	2020	2019	2020	2019	2020	2019	2020
NO_2 (µg/m^3)	Business as usual	32.8 (8.7)	27.3 (4.5)	23.8 (14.7)	11.5 (3.3)	32.3 (7.5)	27.4 (4.3)	14.0 (2.4)	16.0 (2.6)
	Transition phase	32.5 (3.1)	23.0 (4.9)	21.9 (5.8)	8.6 (1.5)	28.0 (2.4)	26.0 (5.8)	12.5 (1.4)	14.2 (4.1)
	Lockdown phase	35.2 (5.3)	11.6 (2.1)	15.6 (3.2)	8.2 (2.2)	31.7 (4.3)	19.1 (5.2)	12.4 (1.1)	11.6 (6.4)
$PM_{2.5}$ (µg/m^3)	Business as usual	48.7 (10.0)	51.8 (25)	45.1 (12.5)	30.8 (7.4)	46.5 (9.2)	38.0 (9.1)	51.5 (9.4)	50.6 (8.4)
	Transition phase	45.5 (5.9)	34.5 (6.9)	46.7 (9.6)	30.6 (5.2)	39.7 (3.3)	32.7 (6.2)	49.0 (7.3)	44.6 (13.2)
	Lockdown phase	51.7 (5.1)	28.4 (8.8)	40.5 (9.6)	22.0 (7.1)	41.1 (8.1)	33.4 (7.6)	52.5 (12.9)	30.4 (16.9)
SO_2 (µg/m^3)	Business as usual	5.9 (1.6)	7.0 (0.5)	11.5 (6.7)	8.9 (4.5)	9.4 (5.8)	5.7 (1.9)	28.8 (4.9)	44.7 (7.4)
	Transition phase	5.7 (0.6)	6.9 (0.6)	8.4 (3.0)	8.8 (5.7)	6.9 (1.8)	5.6 (1.0)	25.8 (2.9)	39.6 (11.4)
	Lockdown phase	6.4 (1.8)	6.3 (1.6)	6.5 (0.4)	6.0 (2.2)	7.4 (1.4)	6.7 (1.7)	25.4 (2.0)	24.5 (4.8)
CO (µg/m^3)	Business as usual	0.97 (0.2)	1.05 (0.1)	0.77 (0.1)	0.67 (0.1)	0.61 (0.1)	0.51 (0.1)	0.78 (0.1)	1.70 (0.1)
	Transition phase	0.91 (0.1)	0.94 (0.1)	0.76 (0.1)	0.85 (0.1)	0.65 (0.1)	0.52 (0.1)	0.70 (0.1)	1.84 (0.3)
	Lockdown phase	0.98 (0.1)	0.76 (0.1)	0.96 (0.1)	0.58 (0.1)	0.61 (0.1)	0.46 (0.1)	0.62 (0.1)	1.07 (0.1)

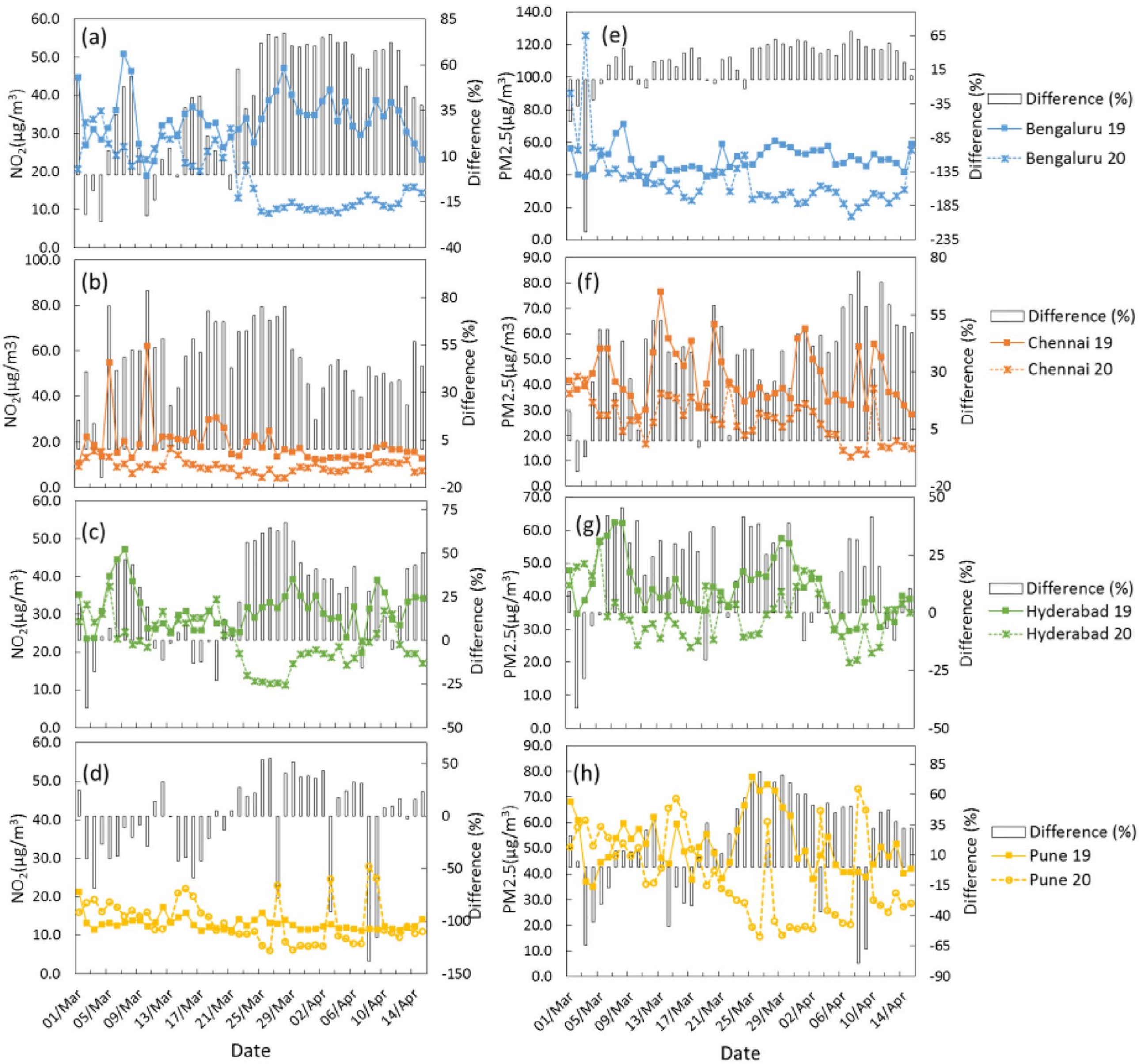

Fig. 2 NO_2 and $PM_{2.5}$ ambient concentration in Bengaluru, Chennai, Hyderabad and Pune during the study periods of 1st March to 15th April for the years 2019 and 2020. Difference (%) indicates the percentage difference in the ambient pollutant concentration during the study periods in 2020 compared to 2019

and Pune during the lockdown period compared to the corresponding duration in 2019 and a 57.1, 28.7, 30.1, and 27.9% decrease, respectively, compared to the BaU period (Table 4).

3.2.2 $PM_{2.5}$ concentration

The ambient concentration of $PM_{2.5}$, the most significant parameter in determining air quality (Pant et al. 2019), showed a steep decrease in all the four cities during lockdown (Fig. 2e, 2f and 2g). The concentrations during the lockdown period were, respectively, 28.4, 22.0, 33.4, and 30.4 µg/m^3 in Bengaluru, Chennai, Hyderabad, and Bengaluru, compared to 27.3, 11.5, 27.4, and 16.0 µg/m^3 before the lockdown (Table 3). Up to 45.1, 45.7, 18.9, and 42% reduction of $PM_{2.5}$ concentration occurred in Bengaluru, Chennai, Hyderabad, and Pune, respectively, during the lockdown period compared to the corresponding period in 2019 and a 45.2, 28.7, 12.3, and 39.9% reduction compared to the BaU period (Table 4).

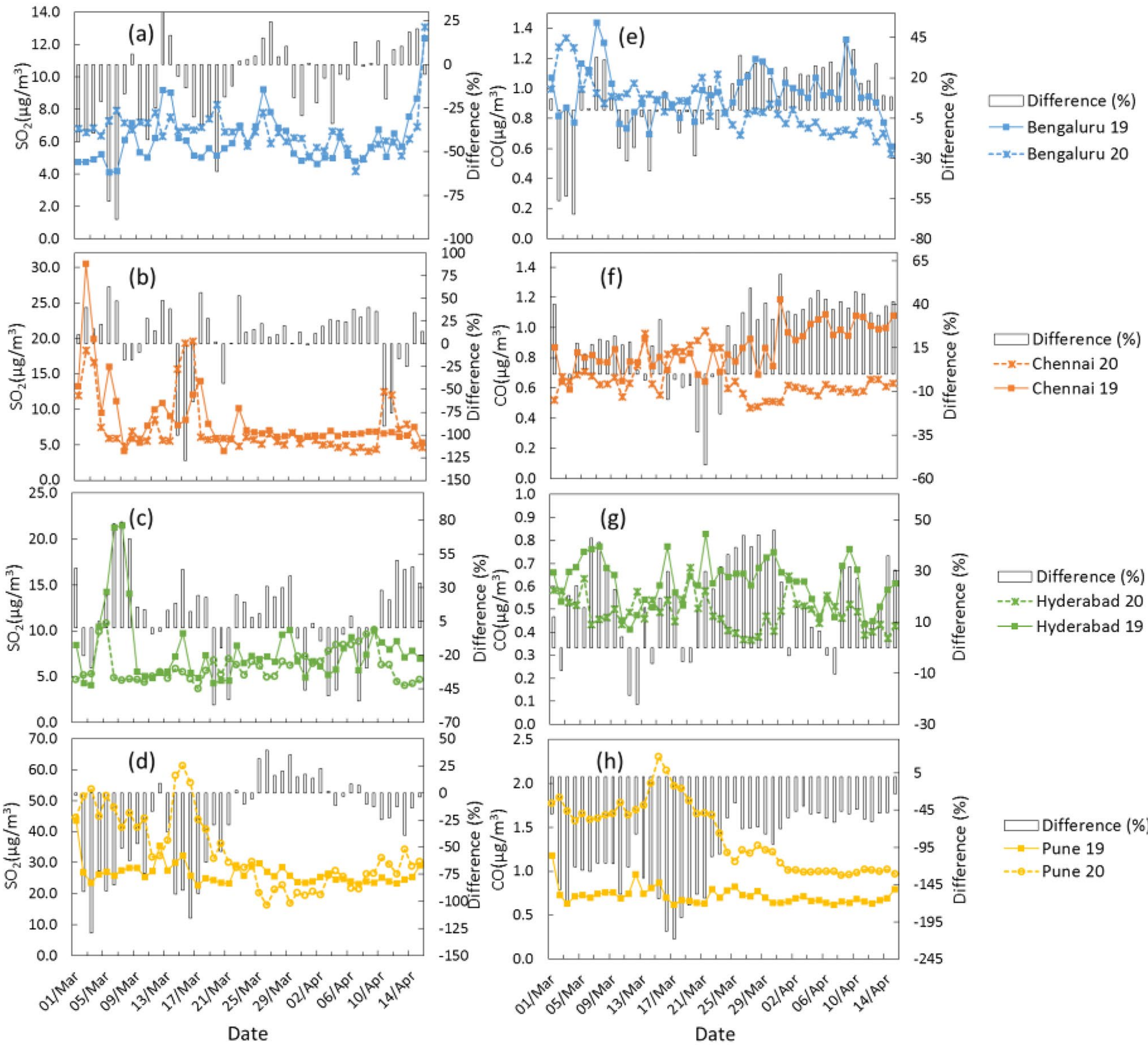

Fig. 3 SO_2 and CO ambient concentration in Bengaluru, Chennai, Hyderabad and Pune during the study periods of 1st March to 15th April for the years 2019 and 2020. Difference indicates the percentage difference in the ambient pollutant concentration during the study periods in 2020 compared to 2019

3.2.3 Sulfur dioxide concentration

The overall ambient SO_2 concentration in Pune was very high (30–60 μg/m^3) compared to that in other cities (< 20 μg/m^3). Furthermore, the SO_2 concentration in Bengaluru and Pune during the study periods in 2020 was higher than in 2019 (Fig. 3a, 3d). The SO_2 concentrations during the lockdown were 6.3, 6.0, 6.7, and 24.5 μg/m^3, respectively, in Bengaluru, Chennai, Hyderabad and Pune, compared to 7.0, 8.9, 5.7, and 44.7 μg/m^3 before the lockdown (Fig. 3a, 3b, 3c and 3d; Table 3). Contrary to the usual decreasing trend, the SO_2 concentration in Hyderabad seemed to increase during the lockdown (Fig. 3c), while a small reduction of 1.7, 8.2, 9.4, and 3.4%, respectively, was observed in Bengaluru, Chennai, Hyderabad, and Pune during the lockdown period compared to the corresponding period in 2019. Furthermore, a 10.7, 33.0, and 45.2% decrease in SO_2 concentration compared to the BaU period occurred, respectively, in Bengaluru, Chennai, and Pune (Table 4) while a 17.2% increase was observed in Hyderabad. While concentration of majority of pollutants decreases with minimal reduction in emission sources, reduction of ambient SO2 concentration requires a prolonged inactive period for the

Table 4 Percentage reduction in emission during the lockdown (25/03/2020 to 15/04/2020) compared to other time periods

Percentage reduction in emission during the lockdown (25/03/2020 to 15/04/2020) compared to		Bengaluru	Chennai	Hyderabad	Pune
NO_2	Duration in 2019 corresponding to the lockdown period (24/03 to 15/04, 2019)	67.1	47.6	39.7	6.8
	Business as usual (BaU) (01/03/2020 to 15/03/ 2020)	57.7	28.7	30.1	27.9
$PM_{2.5}$	duration in 2019 corresponding to the lockdown period (24/03 to 15/04, 2019)	45.1	45.7	18.9	42.0
	Business as usual (BaU) (01/03/2020 to 15/03/2020)	45.2	28.7	12.3	39.9
SO_2	duration in 2019 corresponding to the lockdown period (24/03 to 15/04, 2019)	1.7	8.2	9.4	3.4
	Business as usual (BaU) (01/03/2020 to 15/03/2020)	10.7	33.0	-17.2	45.2
CO	duration in 2019 corresponding to the lockdown period (24/03 to 15/04, 2019)	23.2	39.6	24.6	-55.1
	Business as usual (BaU) (01/03/2020 to 15/03/ 2020)	27.6	13.4	9.8	37.1

emission sources (Briz-Redón et al. 2021). However, the actual reason for this possible increase and also why this increase was observed only in Hyderabad require further analysis of correlation between meteorological variables and air quality.

3.2.4 Carbon monooxide concentration

A clear increase in the ambient CO concentrations in 2020, compared to 2019, was observed in Bengaluru, Chennai, and Pune (Fig. 3e, 3f and 3h), indicating an increase in the overall CO emission. However, a clear decrease in CO concentration was observed during the lockdown. The CO concentrations were as low as 0.76, 0.58, 0.46, and 1.07 µg/m^3 during the lockdown in Bengaluru, Chennai, Hyderabad, and Pune, respectively, in contrast to concentrations of 1.05, 0.67, 0.51, and 1.70 µg/m^3 before the lockdown (Table 3). During the lockdown period, a decrease of 23.2, 39.6, and 24.6% in the CO concentration, compared to the corresponding period in 2019 and a decrease in 27.6, 13.4, and 9.8% compared to the BaU period were, respectively, seen in Bengaluru, Chennai, and Hyderabad. While in Pune, a 37.1% decrease compared to the BaU phase and a 55.1% increase compared to the corresponding period in 2019 were observed.

3.3 Impact of vehicular traffic on atmospheric emissions: a case study in Hyderabad

Table 4 depicts the vehicle kilometers traveled (VKT) for personalized mode of transport, i.e., two-wheeler and car. The VKT for car and motorized two-wheeler is calculated using Eq. (1), as explained in Sect. 2.2. The VKT during BaU period for other modes of transport such as bus and auto-rickshaw was calculated based on the fleet size and the daily average operated length as mentioned in Sect. 2.2. The comprehensive transportation study (CTS 2013) for Hyderabad metropolitan area, conducted at 52 locations, revealed that the Hyderabad traffic comprises 57–62% two-wheelers, 11 to 18% cars, and 10 to 12% auto-rickshaws, 3% buses, and 6% trucks, respectively. The traffic survey was conducted at 52 locations within Hyderabad Metropolitan area. According to a report released in 2018 by Urban Emissions, mobile emissions account for 74%, 60%, 9%, and 17% of total emissions of CO, NOx, PM_{10}, and SO_2, respectively (UE info 2020) (Table 5).

Figure 4 illustrates the trends of vehicular emissions in the city of Hyderabad during BaU and the transition to

Table 5 VKT calculations for personalized mode of transport, i.e., two-wheeler and car

Vehicle type	VKT (on business as usual)		VKT (during transition to lock-down)		VKT (during lockdown)	
	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel
Car (km)	12.3	15.34	4.27	5.46	1.2	1.5
TW (km)	7.58	NA	2.85	NA	0.75	NA

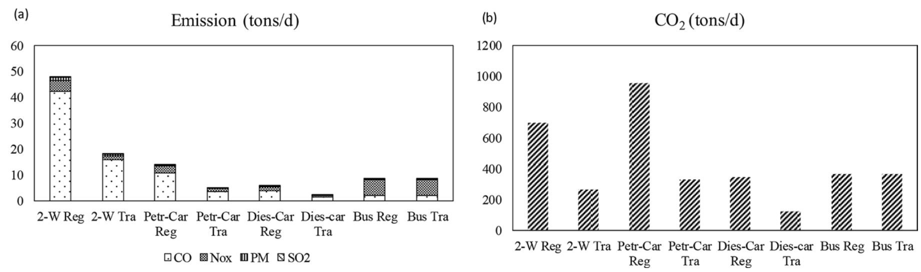

Fig. 4 Average traffic emission in Hyderabad during business as usual and transition to lockdown phase *(Reg: business as usual scenario, Tra: transition to lockdown)*

lockdown phases. With 48% of population utilizing the WFH during the transition to lockdown period, vehicular emission reduced by 61%, 38%, 54%, and 50% for CO, NOx, PM and SO_2, respectively, compared to usual traffic emissions. A 54% reduction in vehicular CO_2 emission was predicted during the transition to lockdown. Individual CO_2 emissions of each vehicle mode are given in Fig. 4b. It can be noted here that India has signed the Paris Agreement and pledged to reduce the carbon dioxide levels to 30–35% by 2030, starting from 2020, as compared to 2005 (1.21 billion tons).

With a predicted 27,90,381 two-wheelers plying on the Hyderabad roads, compared to 4,14,505 cars in 2020 (CTS 2013), emission from two-wheelers is higher. This study estimated that two-wheelers contributed 71%, 30%, 61%, 23%, and 30% of CO, NOx, PM, SO_2, and CO_2, respectively. Public transport like buses are the main source of NOx by emitting ~ 41% of the total NOx emissions, and more than 50% of SO_2 emission was attributed to personal cars.

Estimating the actual transport emissions is a complex task since it is difficult to calculate the actual number of vehicles traveling on the road every day and it tends to vary on a daily basis. The questionnaire survey was used as a base for the required travel behavior data during the transition phase. During the transition to lockdown, the trucks that continued to operate to sustain industrial and construction activities as well as the transport of food and general cargo were the main contributors of PM_{10} and NOx. The fleet of passenger cars, 2-W, and auto-rickshaw circulations had a 70–80% decrease in the transition phase (23/03/2020 to 29/03/2020). Therefore, a clear decrease in CO and NOx concentration in the ambient air was observed (Sect. 3.2). The decrease in PM_{10} and NOx, however, was not directly proportional to the vehicular flux reduction, due to the effect of air masses and meteorological parameters. For example, concentration of pollutants increases with sunlight hours, ambient air temperature while an increase in wind speed reduces ambient pollutant concentration. At the same time, very low wind speed can reduce PM concentration in the air due to higher deposition. Similarly, high pressures increase PM concentration, as particulates cannot disperse properly and tend to concentrate (Briz-Redón et al. 2021).

4 Discussion

In this section, the status of air quality in selected Indian cities, along with scope for emission reduction in Bangalore, Chennai, Pune, and Hyderabad is discussed. Further, estimation of emission reduction in Hyderabad city based on questionnaire survey is depicted.

4.1 Air quality in Indian cities

The air quality trend based on $PM_{2.5}$, CO, SO_2, and NO_2 concentration during the period 2012–2018, in Ahmedabad, Bangalore, Chennai, Delhi, Hyderabad, Jaipur, Kolkata, Navi Mumbai, Mumbai, Pune, Surat, and Visakhapatnam showed a rapid deterioration and started to get higher than both WHO and national air quality standards. Amidst the prime focus on economic growth and prioritizing urban development, the overall state of environment in India is among the worst in the world. Considering the annual average ambient concentration of the critical parameters (NO_2, SO_2, CO, and $PM_{2.5}$) in Indian metropolitans (Fig. 1), newer urban agglomerates such as Ahmedabad and Pune are recording a steep decrease in air quality, primarily due to an accelerated urbanization.

With the adoption of Bharat Stage IV norms (equivalent of Euro IV standards) since 2010 for both vehicles and fuels, a reduction in the SO_2 concentration below the NAAQS (except for Pune) has been achieved (Fig. 1b). Bharat stage emission standards are emission standards instituted by the Government of India to regulate the output of air pollutants from internal combustion engines and spark-ignition engines equipment, including motor vehicles (Government of India 2019). Furthermore, the implementation of Bharat Stage IV resulted in a decrease in NO_2 concentration (Fig. 1a) due to the efficient catalytic conversion of NO_2 to N_2 and O_2 in the vehicles in the presence of low sulfur fuel (Thakur 2017). The emissions are expected to further reduce with the implementation of Bharat Stage VI norms throughout India in 2020 (Purohit et al. 2019).

In order to reduce the ambient emissions at both the regional and urban scale, the National Clean Air Programme (NCAP) was launched in 2019 as a national-level strategy.

The national-level target of NCAP is a 20–30% reduction of $PM_{2.5}$ and PM_{10} concentrations by 2024 (Government of India 2019). Although several programs have been launched to reduce the ambient missions, the effective implementation of the strategies is a challenge.

4.2 Scope for the emission reduction in Bengaluru, Chennai, Hyderabad, and Pune by normalizing the work-from-home option

Transportation sector accounts for 56% and 70% of the total $PM_{2.5}$ and PM_{10} emissions in the form of vehicle exhaust and on-road dust resuspension (Guttikunda et al. 2019b). A comprehensive study by Guttikunda et al. (2019b) showed that the vehicular exhaust alone contributed up to 40.1% of $PM_{2.5}$, 24.5% SO_2, 42.4% NO_x, and 70.7% of CO to the overall annual emissions in the greater Bengaluru region and estimated the annual emission (in tons/year) from vehicular exhaust as follows: 12,550 of $PM_{2.5}$, 13,200 of PM_{10}, 1300 of SO_2, 24,100 of NO_x, and 237,300 of CO for the year 2015. Furthermore, > 70% of the $PM_{2.5}$ emissions originate from a small fraction of diesel operated vehicles (few taxis, buses, HDVs and LDVs) (Guttikunda et al. 2019b). The emissions contributed, estimated by Guttikunda et al. (2019b), by the transportation sector (without considering the resuspension of the road dust) for Bengaluru, Chennai, and Pune in 2015 and for Hyderabad in 2018 are as shown in Table 6.

The emission of the considered components (NO_2, $PM_{2.5}$, SO_2 and CO) in the study area (Bengaluru, Chennai, Hyderabad and Pune) are much higher than the NAAQ standard and there is an immediate concern for the reduction of emissions. In order to achieve the national target of the NCAP, i.e., a reduction of 20–30% of $PM_{2.5}$ and PM_{10} emissions, regularizing the WFH option is a prospective option.

The recent lockdown period, imposed in India due to the COVID19 pandemic, provided a pivotal opportunity to study the reduction of emissions caused by the transportation sector. Arbitrarily attributing 25% of the transport-related emissions to the IT/ITeS sector in the metropolitans considered in this study and assuming that 30% of the IT/ITeS employees could avail a WFH option without affecting the work efficiency, up to 7.5% reduction in emissions could be achieved by normalizing the WFH option. To put this in to perspective, considering the emissions in 2015 for Bengaluru, Chennai, and Pune and in 2018 for Hyderabad (Table 6), respectively, emission of up to 878, 826, 507, and 434 tons/year of $PM_{2.5}$; 1687, 1463, 2565, and 773 tons/year of NOx; and 16,611, 12,372, 23,439, and 7735 tons/year of CO could be avoided. The COVID19 lockdown was a first of its kind situation in India, and since no study focused on the impact of the lockdown on different economic sectors and effectiveness of WFH, it is difficult to precisely estimate the scope of emission reduction in the transportation. Furthermore, it is challenging to calculate the percentage of employees working in IT/ITeS sectors in each of the considered cities since no focused study has been carried out and reliable data are not available.

4.3 Estimate of emission reduction in Hyderabad based on the questionnaire survey

From the questionnaire survey in Hyderabad, it was observed that ~ 75% of motorbike users and ~ 70% of car users had an option of voluntary work from home for 2 or more days. With a conservative assumption that commuters who availed > 4/week voluntary WFH option during pandemic is likely to have 2 d/week of WFH in regular time, an emission of up to 3243, 777, 113, 54, and 129 tons of CO, NOx, $PM_{2.5}$, SO_2, and CO_2 could be avoided. The 2d/week of WFH accounted for a 15% reduction of $PM_{2.5}$ emissions from transportation compared to 5.73% reduction of $PM_{2.5}$, predicted by the odd–even driving scheme earlier implemented in Delhi (Mishra et al. 2019). The overall CO_2 emissions in India are projected to rise up to 2.91 billion tons by 2020 (Amarpuri et al. 2019). Reduction of 129 tons in Hyderabad alone is considerable to meet the country's target of achieving a 30–35% reduction in the CO_2 emissions by 2030 relative to 1.21 billion tons in 2005.

Table 6 Total estimated emissions from the transportation sector for 2015 (2018 for Hyderabad) and the predicted reduction in emissions in a scenario with 30% WFH prevalence

	$PM_{2.5}$ tons/year (Guttikunda et al., 2019b)	NO_X tons/year (Guttikunda et al., 2019b)	SO_2 tons/year (Guttikunda et al., 2019b)	CO tons/year (Guttikunda et al., 2019b)	Reduction in emission under the presumed WFH prevalent scenario			
					$PM_{2.5}$ (tons/year)	NO_X (tons/year)	SO_2 (tons/year)	CO (tons/year)
Bengaluru	12,550	24,100	1,300	237,300	878	1687	91	16,611
Chennai	11,800	20,900	1,050	176,750	826	1463	73	12,372
Hyderabad	7,250	36,650	850	334,850	113	778	55	3243
Pune	6,200	11,050	500	110,500	434	773	35	7735
Total	25,250	92,700	3700	859,400	2645	6488	258	60,157

The estimates in this study provide a practical insight on possible reduction of emissions in the transportation sector. Monitoring and research with real-time data on the vehicle travel pattern, actual reduction in emission, and WFH supporting regulations are required to achieve a substantial emission reduction. The transition to lockdown is comparable to a hypothetical WFH prevalent situation. However, the study has a few limitations: (a) The survey data were collected using an online questionnaire which is susceptible to have non-responder bias which may have affected the study results. (b) The analysis of questionnaire survey is based on self-reported data, which rarely can be independently verified. (c) The study did not collect data related to ridesharing services, and therefore, associated implications on emissions are not considered. Future studies shall investigate the effect of non-work-based trips on air quality.

WFH holds a huge potential in reducing the traffic congestion, noise emission, consumption of energy, infrastructure, and work facilities in service-based and IT/ITeS sectors. Besides, the time spent by the employees on work-related travel could be put to better use. Furthermore, Delventhal et al., (2020) suggest a movement of companies to the core cities and residents to the periphery can lead to; drop in travel time and easing of traffic congestion; drop in real estate prices in metropolitan cities; and overall welfare of the employees (Delventhal et al,. 2020). Although the WFH option appears to be promising and practical in terms of curbing the ambient emissions and offsetting the carbon emissions and postpone the climate change consequence, few aspects that need scrutiny are (a) impact of working in isolation on the employee psychology and strategies to reduce the work pressure, (b) ergonomic optimization of the home-office since IT/ITeS-based jobs demand long hours of sitting in-front of the workstation, (c) maintain team integrity among the co-workers amidst limited physical interaction, (c) measures to avoid over-exploitation of the employees under the circumstance of non-containment of physical 'work-space,' (c) development of safe and secure online portals to avoid data theft, hampering, and piracy, and (d) alternative work options for IT/ITeS-dependent employees (cleaning, housekeeping, retailers, etc.).

5 Conclusions

The lockdown enforced due to COVID19 pandemic and subsequent option of work-from-home have resulted in a reduced dependency on transportation. Indicating a reduction in the emission of NO_2, SO_2, $PM_{2.5}$, and CO during COVID19-related lockdown in Indian metropolitan cities (Bengaluru, Chennai, Hyderabad, and Pune) due to the confinement of population and reduction of road traffic compared to both pre-lockdown period and corresponding period in 2019, the findings of this study are of value. Air pollution being a major concern in India, findings from this study suggest that work-from-home option can be an effective tool to reduce the transportation-related ambient emissions. Although further research is required to examine the long-term improvement in air quality, the findings from the study can be used to understand the effect of controlled scenarios on air quality improvement and to formulate policies that support work-from-home in service-based sectors.

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Compliance with ethical standards

Conflicts of interest No conflict of interest.

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