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Impact of the COVID-19 lockdown on roadside traffic-related air pollution in Shanghai, China

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A R T I C L E   I N F O

Keywords:
COVID-19
Traffic-related air pollution (TRAP)
Lockdown
Roadside

A B S T R A C T

The outbreak of COVID-19 has significantly inhibited global economic growth and impacted the environment. Some evidence suggests that lockdown strategies have significantly reduced traffic-related air pollution (TRAP) in regions across the world. However, the impact of COVID-19 on TRAP on roadside is still not clearly understood. In this study, we assessed the influence of the COVID-19 lockdown on the levels of traffic-related air pollutants in Shanghai. The pollution data from two types of monitoring stations—roadside stations and non-roadside stations were compared and evaluated. The results show that NOx, PM 2.5 , PM 10 , and SO 2 had reduced by ~30–40% at each station during the COVID-19 pandemic in contrast to 2018–2019. CO showed a moderate decline of 28.8% at roadside stations and 16.4% at non-roadside stations. In contrast, O 3 concentrations increased by 30.2% at roadside stations and 5.7% at non-roadside stations. This result could be resulted from the declined NOx emissions from vehicles, which lowered O 3 titration. Full lockdown measures resulted in the highest reduction of primary pollutants by 34–48% in roadside stations and 18–50% in non-roadside stations. The increase in O 3 levels was also the most significant during full lockdown by 64% in roadside stations and 33% in non-roadside stations due to the largest decrease in NOx precursors, which promote O 3 formation. Additionally, Spearman’s rank correlation coefficients between NOx and other pollutants significantly decreased, while the values between NOx and O 3 increased at roadside stations.

1. Introduction

The novel outbreak of Coronavirus Disease 2019 (COVID-19), which was declared a pandemic by the World Health Organization [1], has become significant global health and socio-economic crisis [2,3]. A cumulative confirmed count of over 27.9 million COVID-19 cases and nearly 905 thousand fatalities across 200 countries have been recorded as of 12 September 2020, with numbers continuing to rise (https://www.who.int/emergencies/diseases/novel-coronavirus-2019/situation-reports). To orient on flattening the epidemic curve and effectively protect the health and safety of the general public, the governments have released unprecedented levels of lockdown measures, including social distancing and mandated face covering [4].

According to previous experimental and observational studies, the lockdown measures were highly successful in breaking the chain of COVID-19 transmission and preventing the infection of vulnerable populations [4], and the strict measures also caused significant and rapid environmental improvement [5–13]. Various studies have reported a significant reduction in criteria air pollutants levels (e.g., NOx, SO 2 , PM 2.5 , PM 10 , and CO) during the COVID-19 lockdown period across the world’s most polluted cities (e.g. Wuhan, Bangalore, Beijing, Bangkok, Delhi, Nanjing, New York, and Milan), due to the absence of motor vehicle traffic and suspended manufacturing within lockdown restrictions [14–27]. For instance Ref. [16], observed the significant reduction in ambient PM 10 , PM 2.5 , NOx and SO 2 levels in Delhi and Mumbai cities during post-lockdown phase in comparison with the same time span in 2019 (by almost 55%, 49%, 60% and 19%, and 44%, 37%, 78% and 39%, respectively). In another study, over 300 cities in China experienced a huge decrease in the concentrations of critical air pollutants (PM 2.5 , PM 10 , CO, SO 2 , and NOx) and the Air Quality Index (AQI) obtained through a function of these pollutants concentration during the city control periods in comparison with the same span in 2019, could be
resulted from reduced emissions from the transportation and secondary industrial sectors [17]. Furthermore, some studies reported the dynamic response of air pollutants to the emission reduction and recovery related to COVID-19 lockdown in the Pearl River Delta and the Yangtze River Delta region, by applying the Community Multi-scale Air Quality model and WRF-CAMx modelling system [28,29]. There have been some efforts reporting constant/increased levels of PM and O₃ during the pandemic period in China and Europe, due to the complex interplay between emission, atmospheric chemistry, and meteorological conditions [30–33]. For example [33], attributed a surprising PM exacerbation in northern China during COVID-19 period to the unfavorable meteorological conditions (particularly high relative humidity), invigorated heterogeneous chemistry, and enhanced secondary aerosol formation with the elevated ozone oxidation capacity by NOx reduction. Additionally, it underscored a more comprehensive regulation of precursor gases and meteorological factors when developing a stringent emission controls strategy. Another study [30], observed amplified O₃ pollution in four Southern European cities (Nice, Rome, Valencia and Turin) and Wuhan (China), which highlighted that decreased traffic emissions during COVID-19 lockdown cannot offset the severe O₃ pollution, due to the strong reduction in local NO emissions by alleviating O₂ titration from transport sector. Besides, the aerosol radiative effect on the photochemistry of O₃ formation as well as an increase of O₃ precursors emissions from home and garden activities also were responsible for the enhanced concentration of O₃. Furthermore, a number of epidemiological studies have indicated probable association between the airborne transmission of coronavirus and the concentrations of air pollutants, and chronic exposure to high-level air pollutants possibly leads to more severe and lethal forms of COVID-19 and delay/s/complifies the recovery of patients of COVID-19 [4,34–37]. Therefore, it is of great significance to deeply evaluate air quality responses to a marked emissions reduction, especially in the pollution hotspots.

Traffic emissions are a crucial source of atmospheric pollution in urban regions. According to the United Nations, the health of about 600 million people in urban areas is under threat from ambient traffic pollutants [38]. Small and medium-sized enterprise production, industrial processes, and construction operations were suspended during the COVID-19 pandemic. Traffic activities also followed the minimisation mode and only included the transport for basic necessities and medical supplies. This scenario provided a unique opportunity to investigate the impact of the COVID-19 lockdown on traffic-related air pollution (TRAP). To our knowledge, most existing work has focused on the global to city/country scales and used air quality data from the National Environmental Monitoring Center to macroscopically compare the environmental impacts between the COVID-19 year and previous years. However, the air quality impacts of the COVID-19 lockdown in traffic-related roadside environments still remain unclear.

To fill these research gaps, we utilised hourly air quality data (including NO₂, CO, PM2.5, PM10, SO₂, and O₃) at roadside and non-roadside stations to evaluate the impacts of the COVID-19 lockdown on TRAP in Shanghai, China. To quantify the effects of COVID-19 on air quality, we analysed and compared the temporal variations (including diurnal change, and daytime and night-time change) of the six criteria pollutants in the study stations between a normal year (2018–2019) and the pandemic year (2020). The impacts of different levels of lockdown measures on six key pollutants in the study stations were also estimated. Finally, we conducted a correlation analysis between the ambient air pollutants to determine the inter-relationships between the different air pollutants. Our findings elucidate the role of traffic on air quality changes during the COVID-19 pandemic and provide guidance towards improving air quality following the pandemic recovery.

2. Material and methods

2.1. Description of the study area

Fig. 1. Locations of the Shanghai air quality monitoring stations. The red circles represent the roadside stations, and the purple circles represent the non-roadside stations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

This study was conducted in Shanghai—a megacity located in east China. Air pollution has become one of the most severe issues in the city due to the growth of the economy, population, and number of motorised vehicles. According to the latest data from the Statistical Yearbook (http://tjj.sh.gov.cn/), Shanghai has 24.28 million inhabitants within an area of 6340.5 km², which is divided into 16 districts. The city has a car parc of 4.158 million, and a GDP of approximately 3815.532 billion RMB, ranking first in China and second in Asia.

To further understand the role of traffic sources on airborne pollution during the COVID-19 pandemic, fourteen air quality monitoring stations in Shanghai were selected as data sources and classified into two categories: 1) roadside stations and 2) non-roadside stations. Four air sampling stations were distributed in urban roadsides with busy traffic, and ten air sampling stations were distributed in urban non-roadside areas with dense populations. Generally, the roadside stations represent the atmospheric pollution caused by public transport and reflect the impact of urban traffic sources. The non-roadside stations represent the air pollution status of the central city and reflect the regional background pollution level. The location distribution of the monitoring stations is shown in Fig. 1.

2.2. COVID-19 in Shanghai

According to the National Public Health Emergencies Response Plan, public health emergency warning levels in Shanghai are divided into four levels: Level I (special serious), Level II (serious), Level III (heavy), and Level IV (general). In Shanghai, the Level I and Level II public health emergency response mechanisms were respectively activated on 23 January and 24 March 2020. Considering the effect of the resumption of work on 10 February 2020, the data were divided into four stages to finely assess the impacts of varied lockdown measures on air quality: 1) pre-lockdown (1–22 January), 2) full lockdown (23 January–9 February), 3) partial lockdown (10 February–23 March), and 4) recovery (24 March–12 April).
The strictest prevention and control lockdown measures were implemented during the full lockdown period. Access to roads between streets and communities were temporarily banned (except for epidemic prevention and the transportation of goods for population livelihoods). Public transportation was also suspended, including the closure of railway stations and national and provincial highways. Other external traffic was also temporarily closed. In addition, large-scale public gatherings were cancelled to reduce the risk of cross-infection, and non-essential enterprises, businesses, and shopping malls were shutdown. Schools were postponed, and residents were only permitted to leave their homes to purchase necessities. All residential areas and units throughout the city were under closed management (https://tech.sina.com.cn/roll/2020-01-25/doc-iihnzhha4640599.shtml). Under this mode, the number of people, private cars, and buses in the roadside environment as well as emissions from industrial enterprises, buildings, and other sectors all significantly decreased. The number of infected people had notably reduced in response to the first stage of scientific prevention and control. During the partial lockdown period, some enterprise departments, the industry sector, and traffic operations (except the Wuhan line) had resumed, with the increasing flow of pedestrians and other modes of transport. 

We analysed the data to assess the temporal variations in pollutants between the roadside and non-roadside stations during 2018–2019 and 2020. Furthermore, we assessed the pollutant variability in each station under different lockdown measures and compared their values to that of the same periods in previous years. A correlation analysis is a statistical technique that determines the strength and direction of correlations between variables. In this study, we used a Spearman’s correlation analysis to evaluate the inter-relationships between the different air pollutants over the historical and current periods.

3. Results and discussions

3.1. Comparing the air quality changes between the roadside and non-roadside stations during the COVID-19 pandemic

We compared the air quality changes between the roadside and non-roadside stations to quantitatively evaluate the impacts of the COVID-19 lockdown on TRAP in Shanghai. Fig. 2 present the quantitative comparisons between the diurnal variations in NO2, CO, PM2.5, PM10, SO2, and O3 during the COVID-19 pandemic from 23 January to 12 April 2018–2020.

NO2 and CO are traffic-related pollutants and show a bimodal distribution at each station, with double peaks occurring at 8:00–9:00 and 19:00–20:00 (Fig. 2a and b). The morning and evening peaks in ground-level NO2 and CO were consistent with traffic activity rush hours [44]. During the COVID-19 pandemic, the diurnal variation of NO2 and CO showed a sharp reduction at all stations in Shanghai due to restrictions in vehicular movement—especially during peak traffic hours. The percentage decrease of CO was higher at roadside stations, which suggests that the COVID-19 lockdown had more of an influence on CO concentrations at roadside locations. In contrast, no significant difference in NO2 reduction was observed between the roadside and non-roadside stations, which may be related to the complex chemical reactions between NO2 and O3.

The diurnal variation of PM2.5 and PM10 exhibited a bimodal distribution: two peaks were observed in the morning and evening at each station but were not prominent (Fig. 2c and d). The hourly PM variation significantly reduced during the COVID-19 lockdown, but the ratio reduction of 30–40% remained the same. Based on the analysis results, the decrease in PM2.5 levels at roadside stations was slightly higher than that at non-road stations while PM10 shows opposite trend. It could be due to the different source of particles in varied size. Generally, the local road traffic sources have been suggested to be the dominate contributor to fine particle of PM2.5 on the road of heavy traffic [45]. In contrast to PM2.5, the coarse particle of PM10 is dominated not only by traffic activities, but also by the road dust, industry activities and so on [45,46]. The analysis results based on the original data are consistent with these conclusions. The diurnal variation of SO2 displayed a unimodal distribution, with a higher peak at non-roadside stations (Fig. 2e). Furthermore, the peak in the non-roadside stations preceded that in the roadside stations by ~2 h. The effect of the COVID-19 lockdown on the reduction of SO2 was significant in non-roadside monitoring stations, due to its strong association with the industry sector and weak association with traffic flow [17].

As illustrated in Fig. 2f, the diurnal variation of O3 showed the

| Periods | Temperature (°C) | Pressure (mm) | Wind speed (ms⁻¹) | Relative humidity (%) |
|---------|-----------------|---------------|-------------------|----------------------|
|         | Average | SD | Average | SD | Average | SD | Average | SD |
| 2018-2019 | 9.32 | 6.1 | 766.21 | 4.78 | 2.6 | 1.38 | 72.25 | 18.66 |
| 2020 | 10.44 | 4.81 | 766.76 | 4.18 | 2.64 | 1.33 | 72.21 | 19.92 |

Table 1
Changes in meteorological parameters between a normal year and the pandemic year.
opposite trend to that of NO$_2$ at each station. As NO$_2$ is the key precursor in the chemical reactions of O$_3$ formation, the hourly variation of O$_3$ is closely associated with NO$_2$. Moreover, O$_3$ production occurs in NO$_x$-saturated regions of urban areas [39,47]. Thus, O$_3$ concentrations were negatively correlated with NO$_2$. O$_3$ levels tended to decrease during the morning, reaching a minimum value at 08:00. This finding is due to the accumulation of NO from traffic emissions, which prevented the accumulation of O$_3$ due to the titration reaction (NO + O$_3$ → NO$_2$ + O$_2$). O$_3$ concentrations then gradually increased until 15:00 due to the increase in solar radiation, which facilitated O$_3$ formation via photochemical reactions (NO$_2$ + O$_2$ + h$_\nu$ → NO + O$_3$) [41]. Subsequently, O$_3$ concentrations began to decline under decreasing sunlight and maintained a lower level at night. During the epidemic, the O$_3$ ground concentrations were unexpectedly enhanced, especially in roadside stations. This may be caused by the combined effects of favourable meteorological conditions and a reduction in titration reactions [48,49]. Solar radiation is a key meteorological condition for O$_3$ formation via photochemical reactions. Thus, the increase in solar radiation favoured O$_3$ production. Additionally, the reduction in NO emissions from road transport alleviated O$_2$ titration, which promoted the rise in O$_3$. Previous studies also found that lower fine particle concentrations enhanced O$_3$ levels. O$_3$ is a secondary atmospheric pollutant, and its formation process also depends on the concentration of atmospheric hydroperoxide radicals (HO$_2$). However, a decrease in PM$_{2.5}$ reduces the amount of HO$_2$ absorbed by PM$_{2.5}$, which likely promoted the increase in O$_3$ [17, 43].

The percentage change in ambient pollutants was further calculated to accurately quantify the difference in each monitoring station (Fig. 3). The total effect of the COVID-19 lockdown on the emissions reduction of NO$_2$, PM$_{2.5}$, PM$_{10}$, and SO$_2$ was significant at all stations (~30–40%), while a moderate decline in CO was observed in roadside (28.8%) and non-roadside stations (16.4%). The O$_3$ trends in Shanghai were station-specific, with an increase rate of 30.2% in roadside stations and 5.7% in non-roadside stations. As multiple precursors and meteorological conditions influence O$_3$ concentrations, the complex chemistry and physical processes (i.e., accumulation or dispersion) led to a high nonlinearity between O$_3$ and NO$_2$ [39,41]. As a result, the enhancement of O$_3$ was not consistent with the decrease in NO$_2$.

3.2. Comparison of daytime and night-time air quality change during the COVID-19 pandemic

We observed significant differences between the daytime and night-time changes based on the diurnal variation of air pollutants. The daytime and night-time changes in TRAP during the COVID-19 pandemic from 23 January to 12 April are shown in Fig. 4. An obvious reduction in most pollutants was observed during the daytime and night-time in all stations, but we identified notable differences between each pollutant. The reduction in gaseous pollutants (except for O$_3$) during the day had exceeded the reduction during the night in all monitoring stations due to the notable decrease in vehicle miles traveled, small and medium-sized enterprise production, and factory processing during the daytime of the
epidemic. In contrast, particulate pollutants showed the opposite behaviour to that of gaseous pollutants. The mean levels of PM$_{2.5}$ and PM$_{10}$ respectively declined by 33.3% and 31.5% during the daytime and 36.8% and 32.9% during the night-time at roadside stations; and 29.6% and 36.4% during the daytime and 33.1% and 38.8% during the night-time in non-roadside stations. The slightly higher percentage reduction in PM during the night-time at each station is more than expected, which requires deep investigation. Assuming that home (e.g. cleaning and fireplaces) and garden activities (e.g. barbeques and biomass burning) have either not changed or increased marginally, the reduction in the night time may be attributed to the decrease in traffic emissions and coal-based tandoors in restaurants/hotels and street food [43].

The average NO$_2$ concentration decreased by 22.47 μg/m$^3$ (−35.3%) in the daytime and 11.98 μg/m$^3$ (−25.0%) in the night-time at roadside stations, and 15.24 μg/m$^3$ (−34.0%) in the daytime and 12.66 μg/m$^3$ (−28.3%) in the night-time at non-roadside stations. The reduction during the day had exceeded that of the night at all stations, especially at roadside monitoring stations. However, minor differences in CO were observed between the daytime and night-time. Compared to non-roadside stations, the reduction in both daytime and night-time was stronger at roadside stations. In contrast, O$_3$ levels showed station-specific characteristics, with an increase of 15.90 μg/m$^3$ (36.5%) in the daytime and 8.04 μg/m$^3$ (17.7%) in the night-time at roadside stations, and 4.08 μg/m$^3$ (5.4%) in the daytime and 3.66 μg/m$^3$ (6.2%) in the night-time at non-roadside stations. The NO$_2$ levels at roadside stations decreased by roughly 1.5 times that at non-roadside stations during the daytime, while O$_3$ increased by nearly 4 times, which infers a non-linear relationship between O$_3$ and NO$_2$. The highest rise in O$_3$ occurred during the day at roadside stations, which was mostly related to the largest decline in NO$_2$ during the day. In contrast, non-roadside monitoring stations showed a slightly higher increase during the night, which may be linked to the decrease in nitrogen oxide production in non-roadside areas. This phenomenon would have decreased nitric acid concentrations and hydrocarbon oxidation, leading to a reduction in O$_3$ consumption at night [50]. As an industrial sector pollutant, we observed significant differences in SO$_2$ between the daytime and night-time at roadside stations (33.5% vs. 24.5%). However, the percentage decrease at non-roadside areas was almost the same (39% vs. 38.5%).

3.3. Comparison of air quality changes under different lockdown measures during the COVID-19 pandemic

To further understand the impact of different lockdown measures on TRAP during the COVID-19 epidemic, the temporal variations of six key air pollutants in each station were compared in Fig. 5 and Table 2. In general, the concentrations of NO$_2$ followed a decreasing trend under the different lockdown measures during the COVID-19 pandemic at all stations (even with the same time span in 2018–2019), could be a result of the higher atmospheric mixing height in the warmer months of the year, which leads to lower concentration of air pollutants. However, besides of atmospheric condition, the pollution source is the dominated factor on pollutant variation. In China, the Spring Festival always appear in February and most of the traffic activities will cease in urban area
especially in Shanghai. After the festival, more and more workers begin to move back to city again and traffic activities begin to increase. Maybe it is the major reason for the increase of pollutant during the period of March 25 to April 8. The minimum value of NO\textsubscript{2} occurred during the full lockdown phase in 2020 at all monitoring stations, presumably due to the stringent lockdown measures, and leading to the significant reduction of traffic activities. The values gradually rebounded during the partial lockdown and recovery period but were still lower than pre-lockdown levels. This trend was consistent with the temporal variation in traffic activities. During the full lockdown period, a sharp reduction in road bans was imposed, public transport and private cars were restricted, and only necessary transport activities (e.g., food and medical supplies) were permitted. As the road measures weakened, vehicular movement on the road increased, leading to an increase in NO\textsubscript{2} from traffic emissions. NO\textsubscript{2} declined sharply, especially in the full lockdown phase, and the percentage reduction of CO was much lower than that of NO\textsubscript{2}. However, the O\textsubscript{3} rebounded under all response policies at all monitoring stations, especially in the full lockdown phase.

Compared with the same periods in 2018–2019, the concentrations of NO\textsubscript{2}, CO, PM\textsubscript{2.5}, PM\textsubscript{10}, and SO\textsubscript{2} at all monitoring stations significantly reduced during the full lockdown, partial lockdown, and recovery periods by \textasciitilde33.7–47.7%, \textasciitilde20.4–31.6%, and \textasciitilde24.3–42.8% at roadside stations, respectively; and \textasciitilde17.9–50.3%, \textasciitilde12.9–31.6%, and \textasciitilde23.6–43.3% at non-roadside stations (Table 2). Air quality showed the largest improvement during the full lockdown phase, especially for the roadside monitoring stations. Additionally, the reductions in CO and PM\textsubscript{2.5} emissions during the full lockdown phase were more prominent at roadside stations, indicating the high contribution of full lockdown measures on the air quality of roadside microenvironments. However, the percentage reduction in NO\textsubscript{2} between roadside and non-roadside stations was almost equal (\textasciitilde48%), which was expected due to the complex chemical reactions and atmospheric dynamics. The increase in O\textsubscript{3} concentration was the most significant during the full lockdown period, with a growth ratio of 64% and 33% at roadside and non-roadside stations, respectively. The change was mainly related to VOC restrictions in Shanghai. For example, in term of "VOC-limited" conditions, a reduction in VOCs emission reduces the O\textsubscript{3} formation, but a reduction in NOx emission increases the O\textsubscript{3} formation [30]. Thus, the strongest decrease in NO\textsubscript{2} precursors promoted O\textsubscript{3} formation. Similar increases in O\textsubscript{3} concentrations during the pandemic were also observed in other urban areas around the world, including Nice, Rome, Wuhan, Chongqing, and Beijing-Tianjin-Hebe [30,51,52]. These results indicate that the strictest lockdown control measures significantly improved TRAP. However, the increase in O\textsubscript{3} was unexpected and therefore requires coordinated VOC control.

3.4. Comparisons of air quality correlations during the COVID-19 pandemic

Table 3 compares the correlation matrices of the six air pollutants between the roadside and non-roadside stations during the study period (23 January to 12 April 2018–2020). Spearman’s rank correlation coefficients were calculated to quantify the correlation direction and intensity between pollutants. We observed significant positive correlations between NO\textsubscript{2}, CO, PM\textsubscript{2.5}, PM\textsubscript{10}, and SO\textsubscript{2} during the previous period at each station (\(p < 0.01\)) due to the primary emission sources. This result reveals the dominant impact of traffic compared with other primary emissions to criteria air pollutants, and in general PM\textsubscript{2.5} [53]. The
Spearman’s rank correlation coefficients between most of pollutants significantly decreased during the COVID-19 pandemic, especially between NO\textsubscript{2} and other pollutants (except for O\textsubscript{3}) at roadside stations. These results suggest that controlling NO\textsubscript{2} traffic emissions would be an effective method reducing CO, PM\textsubscript{2.5}, PM\textsubscript{10}, and SO\textsubscript{2} emissions but would not prevent a rise in O\textsubscript{3} due to the adverse effects of NO\textsubscript{2}.

Compared with other pollutants, PM\textsubscript{2.5} concentrations were more closely related to CO concentrations in each period at both non-roadside and roadside stations, with high Spearman’s rank correlation coefficients of 0.76 and 0.73, respectively, during 2020 (p < 0.01). As CO is not a precursor of secondary aerosols, the positive association between CO and PM\textsubscript{2.5} was mainly attributed to the similar source between CO and fine particles. NO\textsubscript{2} and SO\textsubscript{2} concentrations play an important role in the formation of secondary aerosols [48]. Table 3 shows that the NO\textsubscript{2} concentrations were highly correlated with PM\textsubscript{2.5} and PM\textsubscript{10} at each station during the previous periods (p < 0.01), with high Spearman’s rank correlation coefficients of respectively 0.58 and 0.51 at non-roadside stations, and 0.50 and 0.53 at roadside stations. However, the concentrations of PM\textsubscript{2.5} and PM\textsubscript{10} were more affected by SO\textsubscript{2} during the pandemic, with high Spearman’s rank correlation coefficients of respectively 0.47 and 0.64 at non-roadside stations, and 0.54 and 0.50 at roadside stations. Similar results were also observed in

Table 2

|                  | Pre-lockdown\textsuperscript{a} | Full lockdown\textsuperscript{b} | Partial lockdown\textsuperscript{c} | Recovery\textsuperscript{d} | %   |
|------------------|---------------------------------|---------------------------------|----------------------------------|----------------------------|-----|
| non-roadside     |                                 |                                 |                                  |                            |     |
| NO\textsubscript{2} | 51.4 ± 16.7                     | –11                             | 25.4 ± 12.0                      | –48                        | 31.1 ± 15.0               | –27 |
| CO               | 0.9 ± 0.4                        | –1                              | 0.7 ± 0.2                        | –18                        | 0.6 ± 0.2                 | –13 |
| PM\textsubscript{2.5} | 57.4 ± 41.4                     | 9                               | 39.3 ± 24.0                      | –26                        | 31.7 ± 19.3               | –25 |
| PM\textsubscript{10} | 47.0 ± 30.1                      | –25                             | 34.7 ± 19.0                      | –48                        | 39.1 ± 24.6               | –28 |
| SO\textsubscript{2} | 6.9 ± 2.3                       | –37                             | 5.9 ± 1.9                        | –50                        | 6.2 ± 2.7                 | –32 |
| O\textsubscript{3}     | 42.2 ± 21.9                      | 6                               | 71.6 ± 18.5                      | 33                         | 73.4 ± 26.7               | 7   |
| road side        |                                 |                                 |                                  |                            | 76.7 ± 29.2               |     |
| NO\textsubscript{2} | 55.8 ± 15.1                     | –17                             | 29.9 ± 15.0                      | –48                        | 38.3 ± 16.8               | –32 |
| CO               | 0.8 ± 0.3                        | –7                              | 0.6 ± 0.2                        | –34                        | 0.5 ± 0.2                 | –26 |
| PM\textsubscript{2.5} | 62.6 ± 37.2                     | 13                              | 35.4 ± 23.3                      | –35                        | 30.4 ± 19.2               | –29 |
| PM\textsubscript{10} | 55.1 ± 31.9                      | –19                             | 37.5 ± 18.9                      | –46                        | 42.9 ± 25.4               | –23 |
| SO\textsubscript{2} | 6.0 ± 1.8                       | –29                             | 5.6 ± 2.0                        | –38                        | 5.9 ± 3.3                 | –20 |
| O\textsubscript{3}     | 27.4 ± 17.5                      | 23                              | 61.5 ± 21.7                      | 64                         | 58.1 ± 24.0               | 30  |
| The values are presented as mean ± standard deviation. Unit: μg/m\textsuperscript{3} (except for CO mg/m\textsuperscript{3}). Percentage represents the variation compared to the same period in 2018–2019.\textsuperscript{a} From 1 January to 22 January.\textsuperscript{b} From 23 January to 9 February.\textsuperscript{c} From 10 February to 23 March.\textsuperscript{d} From 24 March to 12 April.
other studies [15]. The strong correlation between PM$_{2.5}$ and PM$_{10}$ (0.66) was expected, as PM$_{2.5}$ is a component of PM$_{10}$ both exist in the form of particulate matter, and their formation processes are similar. O$_3$ was significantly negatively correlated with NO$_2$ and CO (p < 0.01), especially with NO$_2$ at roadside stations. This result was expected because NO$_2$ is a precursor of photochemical reactions, and the increase in O$_3$ concentrations coincides with the decrease in NO$_2$. However, O$_3$ levels showed no correlation with PM$_{2.5}$ and PM$_{10}$ in 2020 at all stations, with low and insignificant correlation coefficients (p > 0.05).

4. Conclusions

Previous studies have demonstrated the significant impact of the COVID-19 outbreak on air quality. In this study, we conducted multiple comparisons to determine the contribution of traffic and assess the impact of lockdown on air quality. To further investigate this issue, the pollution data from roadside and non-roadside stations in Shanghai were collected and analysed. We came to the following three conclusions:

(1) The air quality at both roadside and non-roadside stations improved drastically during the COVID-19 pandemic, with a sharp reduction in the pollution levels of NO$_2$, PM$_{2.5}$, PM$_{10}$, and SO$_2$. The corresponding CO level declined by 28.8% and 16.4% at roadside and non-roadside locations, respectively. In contrast, O$_3$ pollution levels respectively increased by 30.2% and 5.7% at roadside and non-roadside stations, as the reduced NO emissions from lower road transport and higher temperatures likely decreased O$_3$ titration. Moreover, due to the stricter restrictions on vehicle movement, most of pollutants (except particulate matter) showed more notable variability during the daytime.

(2) The full lockdown control measures resulted in the highest decrease in NO$_2$, CO, PM$_{2.5}$, PM$_{10}$, and SO$_2$ by ~33.7–47.7% at roadside stations and ~17.9–50.3% at non-roadside stations. However, the most notable improvement in O$_3$ concentrations occurred during the full lockdown period, especially at roadside monitoring stations. These results suggest that minimising traffic emissions can significantly improve air quality in Shanghai, especially for primary pollutants in roadside microenvironments. However, such the stringent lockdown achieves only limited effects on O$_3$ levels, as higher VOC-NOx ratio. To effectively control O$_3$ pollution at city scale, the ratio of VOCs to NOx concentrations needs to be further taken into account [30].

(3) The Spearman’s rank correlation coefficients between most pollutants drastically reduced during the epidemic period but were still significant—especially between NO$_2$ from traffic emissions and other pollutants on roadside locations (except O$_3$). This finding suggests that the contribution of motor vehicle emissions to Shanghai’s primary pollutant sources decreased during the epidemic. In addition, particulate matter was more affected by NO$_2$ in 2018–2019 and SO$_2$ in 2020.

Our research provides novel insights on air quality changes during the COVID-19 pandemic and improves the understanding of the relationship between traffic and the environment. Additionally, this study also elucidates the impact of Shanghai’s lockdown measures on TRAP, which can be used by local authorities to implement effective environmental policies. One limitation of our research is that the dataset only consists of fourteen air monitoring stations across Shanghai. Broader target regions could provide more accurate results and deeper insights. Future studies should consider more urban traffic stations to further assess the impact of traffic restrictions on air quality through randomised experiments.

CRediT authorship contribution statement

Cui-Lin Wu: Conceptualization, Methodology, Visualization, Investigation, Writing – review & editing. Hong-Di He: Conceptualization, Visualization, Investigation, Writing – review & editing. Hong-Wei Wang: Formal analysis, Writing – review & editing. Wan-Jin Cai: Formal analysis, Writing – review & editing. Zhong-Ren Peng: Formal analysis, Writing – review & editing. An-Ning, Ni: Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was partially funded by the National Natural Science Foundation of China (No. 12072195), the National Planning Office of Philosophy and Social Science (No. 16ZDA048) and the National Key R&D Program of China (No. 2016YFC0200500). We also acknowledged the support of the Shanghai Environmental Monitoring Center for providing the roadside monitoring data.

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