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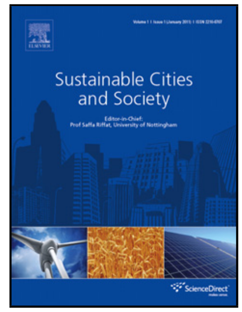

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COVID-2019 Lockdown in Beijing: A Rare Opportunity to Analyze the Contribution Rate of Road Traffic to Air Pollutants

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Highlights:

- In Beijing, the lockdown has led to a sharp drop in road traffic.
- Road traffic reduced by 46.9%, while PM2.5 and NO_2 reduced by 5.6% and 29.2% respectively.
- The Maximum Possible Contribution Rate of road traffic to PM2.5 and NO_2 are 11.9% and 62.3%, respectively.

Abstract

In Beijing, the lockdown imposed to curb the spread of COVID-2019 has led to a sharp drop in road traffic. This provides an opportunity to quantify the contribution rate of road traffic to PM2.5 and NO_2 concentrations. This paper creatively puts forward the concept of the Maximum Possible Contribution Rate (MPCR) and estimates the MPCR of road traffic to PM2.5 and NO_2 by analyzing the daily air pollution data and road traffic data in Beijing from January 24 to March 31, 2020 and the same period in 2019. The findings of this paper include: The decrease in SO_2 concentration during the lockdown indicates a reduction in pollutant emissions from industry and households. During the lockdown, road traffic in Beijing reduced by 46.9%, while the concentrations of PM2.5 and NO_2 in the atmosphere reduced by 5.6% and 29.2% respectively. The MPCR of road traffic to PM2.5 and NO_2 concentrations are 11.9% and 62.3%, respectively. The concentration of O_3 did not increase significantly with the decrease of PM2.5 and NO_2 concentrations. The findings of this paper provide a reference for city managers to evaluate the contribution rate of Beijing's road traffic to air pollutants and to formulate reasonable emission reduction policies.

Keywords: COVID-2019; Lockdown; Road traffic; MPCR; PM2.5; NO_2

1. Introduction

Since 2009 the World Health Organization (WHO) has declared six international public health emergencies. These emergencies are: the swine influenza virus (H1N1) in 2009; the resurgence of the poliovirus in May 2014; the spread of the Ebola virus in West Africa in August 2014; the Zika virus outbreak in 24 countries and regions in 2016; ather Ebola virus outbreak in the Democratic Republic of the Congo in 2019; the COVID-2019 outbreak in 2019. As of 16:00 on November 5, 2020 (Beijing time), 48438926 people have been infected with COVID-2019, and 1231014 people have died (Baidu Real Time Big Data Report of COVID-2019, see https://voice.baidu.com/act/newpneumonia/newpneumonia/). COVID-2019 has become the most serious public health incident since the establishment of the WHO. To curb the spread of COVID-2019, the government imposed an unprecedented lockdown on Wuhan from January 23, 2020 (Chong et al., 2020; Wu et al., 2020). Since then, similar lockdowns have been introduced in many cities, which have included limits on nonessential movement in and out of cities, suspension of all transport, and closure of industries, thus reducing personal contact and effectively suppressing the spread of COVID-2019 (Chinazzi et al., 2020; Kraemer et al., 2020; Tian et al., 2020).

Another effect of the lockdown has been, to a certain extent, the improvement in air quality (Wyche et al., 2021; Bao et al., 2020). Ou et al. (2020) found that the lockdown severely affected gasoline demand in the United States. This leads to a reduction in pollutant emissions. In China, lockdown produced a 25% drop in CO_2 (Carbon Brief 2020, see https//www.carbonbrief.org), a 63% drop in NO_2 and a 35% drop in PM2.5 (Cole et al., 2020). Laurent et al. (2020) found that throughout Western Europe the concentration of NO_2 decreased by 30%-50% during the lockdown, and the concentration of fine particulate matter dropped by 5%-15%. Kumar et al. (2020) observed substantial reductions in PM2.5 concentrations during lockdown, from 19 to

43% (Chennai), 41-53% (Delhi), 26-54% (Hyderabad), 24-36% (Kolkata), and 10%-39% (Mumbai). Similarly, Latif et al. (2021) found that in Klang Valley there were significant reductions in the concentrations of PM10, PM2.5, NO_2 and CO during the lockdown.

As China's capital, its political and cultural center and a hub for international communication, Beijing has a permanent population of more than 20 million. A large number of local emissions and geographical conditions (as shown in Figure 1) result in serious air pollution in Beijing. In order to control the air pollution problem, Beijing has adopted a series of measures, including the use of electricity for heating in rural areas instead of coal (Xu et al., 2020), and the replacement of coal-fired with gas-fired thermal power plants. This has improved Beijing's air quality, but there are still certain gaps with the air quality guidelines specified by the WHO. For example, the average PM2.5 concentration in Beijing in 2017 was 58 $\mu g/m^3$, which was 35% lower than 89.5 $\mu g/m^3$ in 2013, but this concentration level is still much higher than the 10 $\mu g/m^3$ air quality guideline specified by the WHO. Further measures are needed to reduce the concentration of pollutants in the atmosphere.

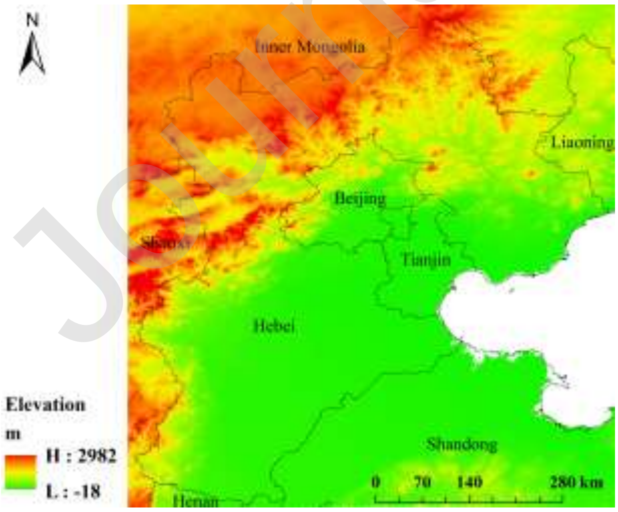

Fig. 1 Topography of Beijing and surrounding cities

In cities, particulate matter with an aerodynamic diameter lower than 2.5 μm (PM2.5), nitrogen dioxide (NO_2) and tropospheric ozone (O_3) are among the most threatening air pollutants in terms of harmful effects on human health associated with respiratory and cardiovascular diseases and mortality (Weinmayr et al., 2010; Pascal et al., 2013; Stafoggia et al., 2013; Cohen et al., 2017; Nuvolone et al., 2018). Road traffic is considered an important source of PM2.5 and NO_2 (Wang et al., 2020a; Shekarrizfard et al., 2017; Tang et al., 2020), and it has an important impact on the concentration of O_3. Zhang et al. (2020a) found that secondary aerosols, solid fuel combustion, dust and marine aerosols are the principal pollution sources of PM2.5, accounting for about 46.1%, 22.4% and 13.0% respectively, and vehicle emissions could be the main anthropogenic source of secondary aerosols in Beijing. Hua et al. (2020) found that heating is the main source of PM2.5 and vehicles are the main source of NO_2 in Beijing. Because of the lockdown, road traffic in Beijing has dropped sharply, which provides us with a rare opportunity to study the impact of road traffic on atmospheric pollutants through experiments. This will provide a natural, experimental basis for Beijing to formulate reasonable road traffic policies and ultimately realize the sustainable development of the city.

This paper creatively puts forward the concept of the MPCR and estimates the Maximum Possible Contribution Rate (MPCR) of road traffic to PM2.5 and NO_2 by analyzing the daily air pollution data and road traffic data in Beijing from January 24 to March 31, 2020 and the same period in 2019. The results show that the PM2.5 concentration during the lockdown dropped by 5.6% compared with the same period last year, and the NO_2 concentration dropped by 29.2%. This, combined with the road traffic data obtained on Baidu, finally infers that the MPCR of road traffic to PM2.5 and NO_2 are 11.9% and 62.3%, respectively. In addition, we found that the O_3 concentration did not increase significantly during the lockdown. The reason for this phenomenon may be due to more rainfall and snowfall during the lockdown and the decrease in the concentration of CO, a precursor of O_3.

2. Related works

The concentration of pollutants in the atmosphere is affected by many factors. Different cities have different types and scales of pollution sources, climatic conditions, topographical conditions, etc. Whether it is to predict the concentration of pollutants in the future (Doreswamy et al., 2020; Chang et al., 2020), figure out the contribution rate of pollution sources to pollutants or for other research purposes, it is often necessary to conduct specific research on this city (Table 1). It is impossible to copy the research results of other cities.

There are many studies on Beijing’s air pollution, which are related to the domestic and international influence of Beijing. Many of these studies use a simulation method (Xu et al., 2018; Ji et al., 2019). In addition, when important events such as APEC are held in Beijing, studies are also carried out to take advantage of the on-site monitoring method to conduct analysis (Fontes et al., 2018; Xu et al., 2019). At such times, the government will often take some measures to limit the number of vehicles. The lockdown has imposed greater restrictions on road traffic. Many articles have used the impact of the lockdown to study the air pollution in some cities (Patel et al., 2020; Maria et al., 2020a; Aiymgul et al., 2020; Wang et al., 2020b; Saadat et al., 2020; Ramachandran et al., 2020). At present, there is no research to analyze the contribution rate of Beijing's pollution sources through the lockdown.

We found that those studies using experimental methods usually only draw qualitative conclusions on the contribution rate of a certain pollution source. Quantitative conclusions are often drawn by using simulation methods. This is related to the fact that the influencing factors related to air pollution are too complicated and uncontrollable in real life. Usually, we only need to know the approximate value of a certain pollution source's contribution rate to guide the formulation and implementation of policies, and it is not necessary to accurately calculate the contribution rate. Therefore, this paper creatively puts forward the concept of the MPCR. When a major change occurs in a pollution source, and other influencing factors have a positive impact on a pollutant, the change in the concentration of this pollutant can be regarded as having been completely caused by this pollution source. The MPCR of this pollution source to the pollutant can be obtained. Although this method cannot obtain an accurate contribution rate, it greatly simplifies the calculation process. The MPCR can prevent us from overestimating the impact of a certain pollution source, and has a strong reference value for the formulation and implementation of emission reduction policies. At the same time, as long as the conditions for the use of this method can be met, other cities in the world can also use this method to calculate the MPCR of a certain pollution source to pollutants, so as to guide the city to formulate a reasonable emission reduction policy.

Table 1 Summary of recent studies on air pollution

Research	Region	Analyzing	Method	Key findings
Fontes et al., 2018	Beijing	The impact of road traffic on air pollution	Check the impact of road traffic measures on the concentration of air pollutants under similar weather conditions	Traffic restriction measures are important to reduce the concentration of air pollutants
Xu et al., 2018	Beijing	Sources of air pollution	Determine the main sources of PM2.5 through PMF model	Industrial and traffic contribute 17% to PM2.5
Zhao et al., 2018	Langfang	The impact of road traffic on air pollution	Analyze the impact of traffic restrictions on air pollution by monitoring the changes in the concentration of pollutants in three different periods	The traffic restriction policy did effect the concentrations of PM2.5-bound nitrated polycyclic aromatic hydrocarbons (nPAHs) and oxygenated polycyclic aromatic hydrocarbons (oPAHs)
Xu et al., 2019	Beijing	The impact of road traffic on air pollution	Detect changes in Beijing's air pollutant concentrations before and during APEC	Reducing road traffic NH_3 emissions may be an effective way to reduce atmospheric NH_3 and secondary NH_4^+ salt in PM2.5
Ji et al., 2019	Beijing	The impact of heating on air pollution	Use LUR model to analyze the spatial distribution and influencing factors of	The difference in PM2.5 concentration between heating and non-heating

Table 1 (continued)

Research	Region	Analyzing	Method	Key findings
			PM2.5 concentration in Beijing heating season and non-heating season	seasons is greatest in the south and east of Beijing, and smallest in the north and west
Song et al., 2019	Xiamen	The impact of traffic on air pollution	Estimate the impact of traffic through deep learning technology	Cars and motorcycles are the main sources of traffic-related pollutants
Zhang et al., 2020	Beijing	Changes and influencing factors of PM2.5	Analyze the changes and influencing factors of PM2.5 concentration in Beijing from 2013 to 2018 through data released by 35 monitoring stations in Beijing	The PM2.5 concentration decreased year by year during 2013-2018; relative humidity and wind speed is the main meteorological factor affecting the distribution of PM2.5 concentration
Patel et al., 2020	Auckland	The impact of road traffic on air pollution	Analyze the impact of lockdown on air quality through monitoring data	Once road traffic is reduced, the air quality in Auckland will be greatly improved
Menut et al., 2020	Western Europe	The impact of road traffic on air pollution	Eliminate the influence of weather conditions through the WRF-CHIMERE modeling suite	Traffic mainly affects NO_2 concentrations and has a small impact on Particulate Matter (PM) concentrations

3. Methodology

Before studying the MPCR of road traffic on PM2.5 and NO_2 in the atmosphere, it is necessary to first determine the weather conditions in Beijing in 2020 and the concentration of pollutants from other sources of PM2.5 and NO_2 (industry and households) compared to the same period in the previous year. If these effects are positive, we can calculate the MPCR of road traffic on PM2.5 and NO_2 through the changes in road traffic and the changes in PM2.5 and NO_2 concentrations during the lockdown. The flowchart of the research methodology is shown in Figure 2.

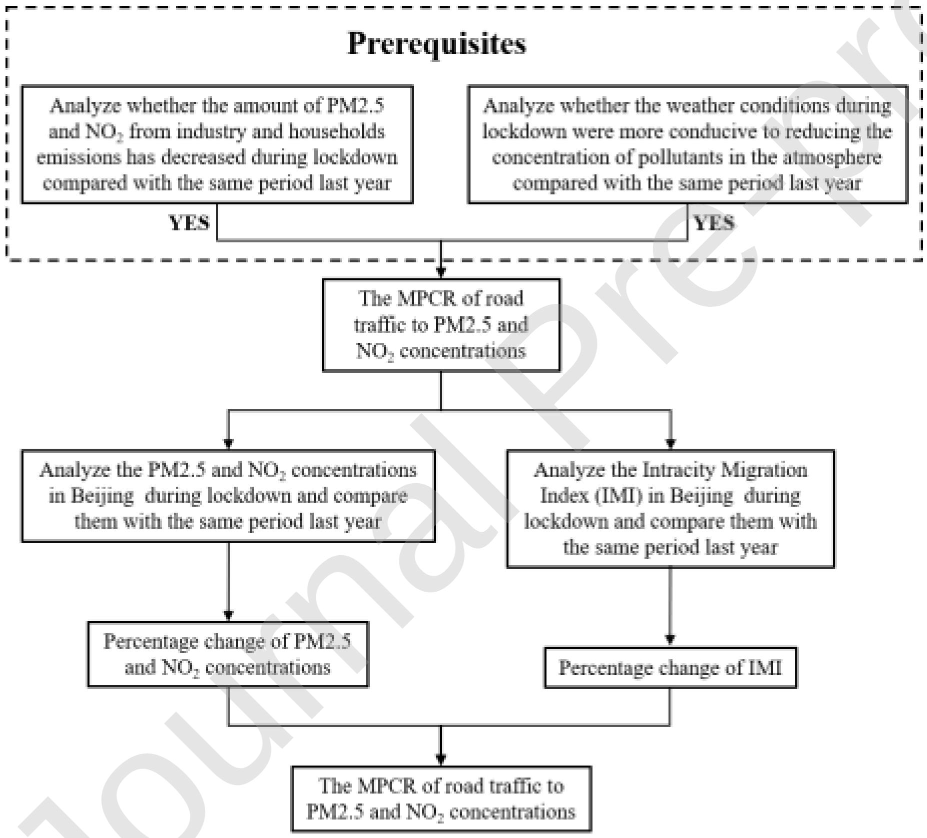

Fig 2. Flowchart of research methodology

Considering the effects of heating, Spring Festival and lockdown on atmospheric pollutant concentration, this paper selects data from January 24 to March 15, 2020 and the same period in 2019 for analysis (Figure 3). In addition, special factors such as fireworks during Spring Festival and unfavorable meteorological diffusion conditions often cause the concentration of pollutants in the atmosphere to rise sharply, which is not conducive to making a correct judgment on the trend of changes in the concentration of atmospheric pollutants. Therefore, this paper excludes special dates, when the PM2.5 concentration is greater than 100 μg/m3, during the period from January 24 to March 15.

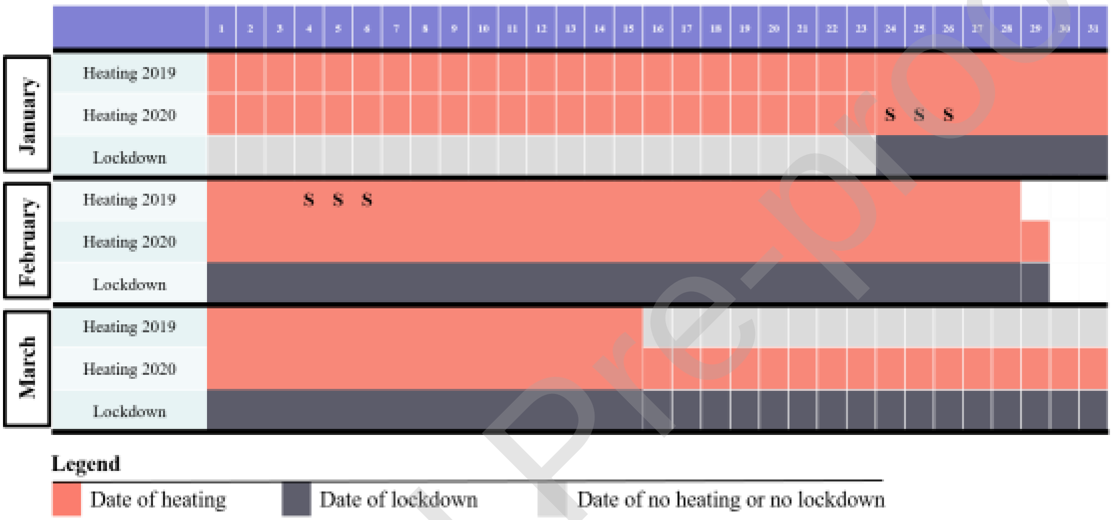

Fig. 3. Heating and lockdown dates for the first three months of 2020 and the heating dates for the first three months of 2019. S: Spring Festival

In this study, the concentration data of atmospheric pollutants in Beijing, which include PM2.5, NO_2, O_3, SO_2 and CO, were obtained from the China Air Quality Online Monitoring and Analysis Platform (see http://www.aqistudy.cn). On this platform, all test items are updated every hour.

The "Baidu Maps Spring Festival Population Migration Big Data" (see http://qianxi.baidu.com) project launched by Baidu provides us with data on the Migration Scale Index (MSI) and the Intracity Migration Index (IMI) for Beijing. MSI is the indexation result of the ratio of the number of people who have moved into Beijing to the total number of residents in Beijing. IMI is the indexation result of the ratio of the number of people traveling in Beijing to the total resident population in Beijing.

Weather conditions influence the formation and diffusion of air pollutants (Kallos et al., 1993; Yen et al., 2013). Monitoring data on the outdoor ambient temperature, relative humidity, wind speed and days of rainfall and snowfall (Table 2) are obtained from the website http://rp5.kz. The weather station is located at the Beijing Capital International Airport, 116.36 east longitude, 40.04 north latitude, 30.4 m above sea level.

Table 2 Meteorological monitoring data from Beijing Capital International Airport

	Average temperature (ºC)	Average relative humidity (%)	Average wind speed (m/s)	Rainfall and snowfall (days)
January 24 to March 15, 2020	2.2	54.2	3.0	10
January 24 to March 15, 2019	1.4	31.1	3.4	5

It can be seen that the average temperature and average wind speed from January 24 to March 15, 2020 and the same period in 2019 are similar. The number of days of rainfall and snowfall (10 days) from January 24 to March 15, 2020 is double that of the same period in 2019. The cleansing effect of rainfall and snowfall can reduce the concentration of pollutants in the atmosphere. Therefore, the weather conditions in 2020 were more conducive to reducing the concentration of pollutants in the atmosphere compared with the same period in 2019.

4. Results

4.1 Impact of the lockdown on industry and households

According to the "Beijing Environmental Statistics Annual Report of 2018" issued by the Beijing Municipal Bureau of Ecology and Environment, atmospheric pollution sources mainly come from three areas: industry, households and road traffic (see http://sthjj.beijing.gov.cn/). As shown in Table 3, SO_2 mainly comes from industry and households, while PM2.5 and NO_2 mainly come from industry, households and road traffic.

Table 3 Sources of different atmospheric pollutants in Beijing

Types of Pollutants	SO_2	PM2.5	NO_2
Pollution Sources	Industry Households	Industry Households Road traffic	Industry Households Road traffic

By analyzing the concentration of SO_2 in the atmosphere, the average concentration of SO_2 in the atmosphere from January 24 to March 15, 2020 was 37.4% lower than the same period in 2019. This change is mainly caused by the reduction of industrial and residential emissions. As shown in Figure 4, according to the statistics of the National Bureau of Statistics (see http://data.stats.gov.cn), the industrial output value of Beijing in February and March 2020 decreased by 2.8% and 2.9% in comparison with the same period last year. It can be seen that the impact of the lockdown on industry is not significant, which means that the reduction in SO_2 concentration during the lockdown may relate more to households. Many people chose to leave Beijing to go home for the Spring Festival, and many people were unable to easily return to Beijing because of the lockdown. As shown in Figure 5, the number of people entering Beijing from January 24 to March 15, 2020 decreased by 75.5% compared with the same period in 2019.

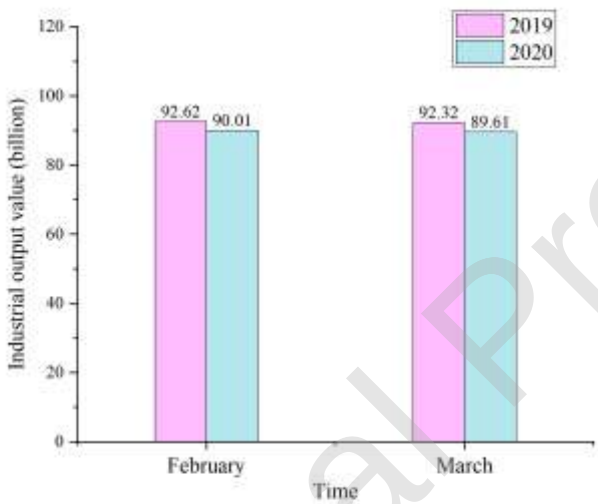

Fig. 4. Industrial output value in Beijing in February and March 2020 and in the same period in 2019

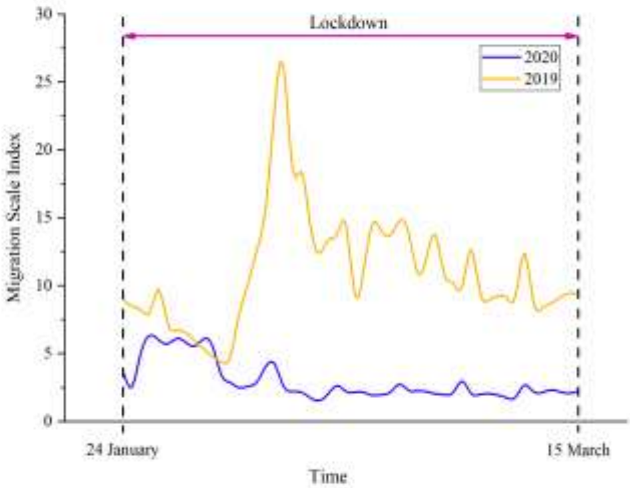

Fig. 5. The trend of MSI in Beijing from January 24 to March 15, 2020 and in the same period in 2019

4.2 MPCR of road traffic to PM2.5 and NO_2

Figure 6 shows the trend of IMI in Beijing from January 24 to March 15, 2020 and in the same period in 2019. Affected by the Spring Festival and the lockdown, the IMI in Beijing decreased by 46.9% compared with the same period in 2019.

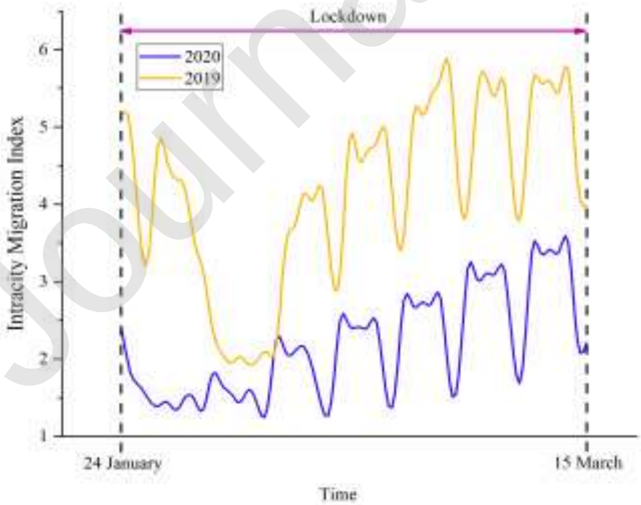

Fig. 6. The trend of IMI in Beijing from January 24 to March 15, 2020 and in the same period in 2019

Table 4 lists the average concentrations of PM2.5 and NO_2 from January 24 to March 15, 2020 and in the same period in 2019. Compared with the same period last year, the average PM2.5 concentration and the average NO_2 concentration during the lockdown have decreased by 5.6% and 29.2%, respectively.

Table 4 Variations of concentrations of PM2.5 and NO_2 from January 24 to March 15, 2020 and the same period in 2019

	PM2.5 (μg/m^3)	NO_2 (μg/m^3)
January 24 to March 15, 2020	36.9	22.3
January 24 to March 15, 2019	39.1	31.5
Percentage change	-5.6%	-29.2%

From Section 4.1, it can be seen that air pollutants from industry and residential buildings have decreased during the lockdown. Therefore, the reduction in concentrations of PM2.5 and NO_2 are not only caused by the decline in road traffic, but are also related to their reduction from industry and households. If it is assumed that the reduction of concentrations of PM2.5 and NO_2 are caused solely by less road traffic, the MPCR of road traffic to the concentrations of PM2.5 and NO_2 are 11.9% and 62.3% (Figure 7), respectively.

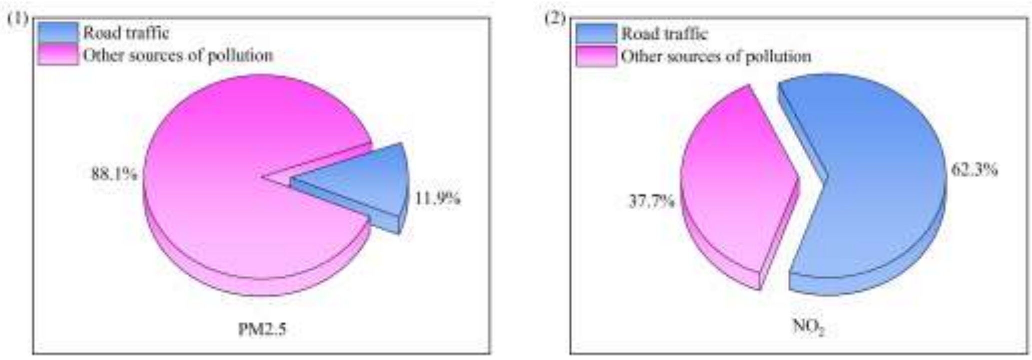

Fig. 7. MPCR of road traffic: (1) PM2.5; (2) NO_2

4.3 Concentrations of O_3

Some studies have found that the impact of lockdown on the environment is not entirely positive. It not only reduces the concentrations of PM2.5 and NO_x, but also increases the concentration of O_3 (Sharma et al., 2020; Pierre et al., 2020; Maria et al., 2020b). This is because the reduction of NO_x concentration will weaken the titration effect of O_3, which leads to the increase of O_3 concentration. In this paper's research findings, the O_3 concentration in Beijing from January 24 to March 15, 2020 only increased by 1.0% compared with the same period last year (Table 5).

Table 5 Variations of concentrations of O_3 and CO from January 24 to March 15, 2020 and the same period in 2019

	O_3 (μg/m^3)	CO (mg/m^3)
January 24 to March 15, 2020	68.56	0.60
January 24 to March 15, 2019	67.85	0.66

Percentage change	+1.0%	-9.1%

5. Discussion

According to the research results in Section 4.2, the contribution rate of road traffic to PM2.5 and NO_2 in Beijing will not exceed 11.9% and 62.3%. Road traffic is the most important pollution source of NO_2, but not the most important pollution source of PM2.5. Some studies have found that road traffic emissions account for 10%-20% of total PM2.5 emissions of the city (Huang et al., 2014; Li et al., 2015; Yang et al., 2016). This is consistent with the MPCR of Beijing road traffic to PM2.5 obtained in this paper. In addition, some studies have found that the contribution rate of road traffic to NO_2 is about 50% (Frey et al., 2010; Shon et al., 2011), which is also close to the MPCR of Beijing traffic to NO_2 obtained in this paper. This shows that the conclusions drawn in this paper are reasonable.

In this paper's research findings, the O_3 concentration in Beijing increased during the lockdown and the same phenomenon also appeared in other cities that implemented the lockdown. This may be related to the reduction of PM and NO_x concentration (Laurent et al., 2020; Pierre et al., 2020). The concentration of O_3 did not increase significantly may be caused by the following reasons: (1) there was more rain and snow during lockdown, and the cleansing effect of rain and snow would reduce the O_3 concentration in the atmosphere; (2) during the lockdown, the CO concentration dropped by 9.1% compared with the same period in the previous year's (Table 5). As one of the important precursors of O_3, the decrease of CO concentration will inhibit the production of O_3.

6. Conclusion

This article creatively puts forward the concept of MPCR. When a major change occurs in a pollution source, if other influencing factors have a positive impact on a pollutant, the change in the concentration of this pollutant can be regarded as having been completely caused by this pollution source. The MPCR of this pollution source to the pollutant can be obtained. Using this method and taking advantage of the rapid decline in the number of road traffic in Beijing during the lockdown, this paper studied the MPCR of Beijing's road traffic on PM2.5 and NO_2.

In order to minimize the impact on climatic conditions, this paper chose to compare the concentration of atmospheric pollutants during the lockdown with the same period in 2019. However, the climatic conditions in both years were not exactly the same. Compared with the same period in 2019, the weather conditions in 2020 were more conducive to reducing the concentration of pollutants in the atmosphere. In addition, during the lockdown, the SO_2 concentration dropped by 37.4%. Through the analysis of pollution sources, it is inferred that the pollutants discharged into the atmosphere by industry and households during the lockdown have been reduced.

During the lockdown period of this study, travel intensity in Beijing was reduced by 46.9%, while the PM2.5 concentration and NO_2 concentration in the atmosphere were reduced by 5.6% and 29.2%, respectively. When it is assumed that the decrease of PM2.5 and NO_2 concentrations is caused entirely by the decrease of road traffic, the MPCR of road traffic to PM2.5 and NO_2 concentrations is 11.9% and 62.3%, respectively. Road traffic is the most important pollution source of NO_2, but not the most important pollution source of PM2.5.

In addition, this paper also found that although the concentration of PM and NO_x decreased significantly during the lockdown, the concentration of O_3 only increased by 1.0%. Therefore, reducing the concentration of PM and NO_x does not necessarily cause a substantial increase in the O_3 concentration, but it also depends on the weather conditions and changes in the concentration of O_3 precursors.

The research results of this paper provide an important reference for Beijing to formulate reasonable emission reduction policies. At the same time, the research method adopted in this paper has good versatility and is suitable for carrying out research on the contribution rate of pollutants in different cities. It greatly simplifies the calculation process, and can prevent cities from overestimating the impact of a certain pollution source in the process of formulate emission reduction policies.

Declaration of interests

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.

References

Aiymgul, K., Nassiba, B., Olga, P.I., Bauyrzhan, B., Bulat, K., Pavel, P., Ferhat, K., (2020). Assessing air quality changes in large cities during COVID-19 lockdowns: The impacts of traffic-free urban conditions in Almaty, Kazakhstan. *Science of Total Environment*. 730, 139179. https://doi.org/10.1016/j.scitotenv.2020.139179.

Bao, R., Zhang, A., (2020). Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *Science of the Total Environment*, 731, 139052. https://doi.org/10.1016/j.scitotenv.2020.139052.

Baidu Real Time Big Data Report of COVID-2019. https://voice.baidu.com/act/newpneumonia/newpneumonia/ Accessed 5 November 2020.

Baidu Maps Spring Festival Population Migration Big Data. http://qianxi.baidu.com/ Accessed 23 November 2020.

Beijing Environmental Statistics Annual Report of 2018. http://sthjj.beijing.gov.cn/ Accessed 5 November 2020.

Chinazzi, M., Davis, J.T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Pastore Y Piontti, A., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H., Halloran, M.E., Longini, I.M., Vespignani, A., (2020). The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. *Science*, 368, 395-400. https://doi.org/10.1101/2020.02.09.20021261.

Carbon Brief 2020. https//www.carbonbrief.org/ Accessed 5 November 2020.

China Air Quality Online Monitoring and Analysis Platform. https://www.aqistudy.cn/ Accessed 5 November 2020.

Chong, K.C., Cheng, W., Zhao, S., Ling, F., Mohammad, K,N., Wang, M.H., et al., (2020). Monitoring disease transmissibility of 2019 novel coronavirus disease in Zhejiang, China. *International Journal of Infectious Diseases*, 96, 128-130. https://doi.org/10.1016/j.ijid.2020.04.036.

Cole, M., Elliott, R., & Liu, B., (2020). The impact of the Wuhan Covid-19 lockdown on air pollution and health: A machine learning and augmented synthetic control approach. *Environmental and Resource Economics*, 76, 553-580. https://doi.org/10.1007/s10640-020-00483-4.

Chang, F., Chang, L., Kang, C., Wang, Y., Huang, A., (2020). Explore spatio-temporal PM2.5 features in northern Taiwan using machine learning techniques. *Science of the Total Environment*, 736, 139656. https://doi.org/10.1016/j.scitotenv.2020.139656.

Cohen, A.J., Brauer, M., Burnett, R., Anderson, H.R., Frostad, J., Estep, K., et al., (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet*, 389, 1907-1918. https://doi.org/10.1016/S0140-6736(17)30505-6.

Doreswamy., Harishkumar, KS., Yogesh, KM., Ibrahim, G., (2020). Forecasting Air Pollution Particulate Matter (PM2.5) Using Machine Learning Regression Models. *Procedia Computer Science*, 171, 2057-2066. https://doi.org/10.1016/j.procs.2020.04.221.

Fontes, T., Li, P., Barros, N., Zhao, P., (2018). A proposed methodology for impact assessment of air quality traffic-related measures: The case of PM2.5 in Beijing. *Environmental Pollution*, 239, 818-828. https://doi.org/10.1016/j.envpol.2018.04.061.

Frey, H.C., Zhang, K., Rouphail, N.M., (2010). Vehicle emissions modeling using on-road vehicle emissions measurements systems (PEMS). *Environmental Science and Technology*, 44, 3594-3600. https://doi.org/10.1021/es902835h.

Hua, J., Zhang, Y., Foy, B., Mei, X., Shang, J., Feng, C., (2020). Competing PM2.5 and NO_2 holiday effects in the Beijing area vary locally due to differences in residential coal burning and traffic patterns. *Science of the Total Environment*, 750, 141575. https://doi.org/10.1016/j.scitotenv.2020.141575.

Huang, R., Zhang, Y., Bozzetti, C., et al., (2014). High secondary aerosol contribution to particulate pollution during haze events in China. *Nature*, 514, 218-222. https://doi.org/10.1038/nature13774.

Ji, W., Wang, Y., Zhuang, D., (2019). Spatial distribution differences in PM2.5 concentration between heating and non-heating seasons in Beijing, China. *Environmental Pollution*, 248, 574-583. https://doi.org/10.1016/j.envpol.2019.01.002.

Kraemer, M.U.G., Yang, C., Gutierrez, B., Wu, C., Klein, B., Pigott, D.M., du Plessis, L., Faria, N.R., Li, R., Hanage, W.P., Brownstein, J.S., Layan, M., Vespignani, A., Tian, H., Dye, C., Pybus, O.G., Scarpino, S.V., (2020). The effect of human mobility and control measures on the COVID-19 epidemic in China. *Science*, 368, 493-497. https://doi.org/ 10.1126/science.abb4218.

Kumar, P., Hama, S., Omidvarborna, H., Sharma, A., Sahani, J., Abhijith, K., E. Debele, S., C. Zavala-Reyes, J., Barwise, Y., Tiwari, A., (2020). Temporary reduction in fine particulate matter due to 'anthropogenic emissions switch-off' during COVID-19 lockdown in Indian cities. *Sustainable Cities and Society*, 62, 102382. https://doi.org/10.1016/j.scs.2020.102382.

Kallos, G., Kassomensos, P., Pielke, R.A., (1993). Synoptic and Mesoscale Weather

Conditions during Air Pollution Episodes in Athens, Greece. *Transport and Diffusion in Turbulent Fields*, 62, 163-184. https://doi.org/10.1007/978-94-011-2749-3_9.

Latif, M.T., Dominick, D., Hawari, N., Mohtar, A., Othman, M., (2021). The concentration of major air pollutants during the movement control order due to the COVID-19 pandemic in the Klang Valley, Malaysia. *Sustainable Cities and Society*, 66, 102660. https://doi.org/10.1016/j.scs.2020.102660.

Laurent, M., Bertrand, B., Guillaume, S., Sylvain, M., Romain, P., Arineh, C., (2020). Impact of lockdown measures to combat Covid-19 on air quality over western Europe. *Science of Total Environment*, 741, 140426. https://doi.org/10.1016/j.scitotenv.2020.140426.

Li, X., Zhang, Q., Zhang, Y., et al., (2015). Source contributions of urban PM2.5 in the Beijing-Tianjin-Hebei region: changes between 2006 and 2013 and relative impacts of emissions and meteorology. *Atmospheric Environment*, 123, 229-239. https://doi.org/10.1016/j.atmosenv.2015.10.048.

Maria, C., Alessandro, A., Giorgio, B., Roberta, P., Paola, R., Marco, C., (2020a). Lockdown for CoViD-2019 in Milan: What are the effects on air quality?. *Science of Total Environment*, 732, 139280. https://doi.org/10.1016/j.scitotenv.2020.139280.

Maria, Z., Roxana, S., Dan, S., Marina, T., (2020b). Assessing the relationship between ground levels of ozone (O_3) and nitrogen dioxide (NO_2) with coronavirus (COVID-19) in Milan, Italy. *Science of Total Environment*, 740, 140005. https://doi.org/10.1016/j.scitotenv.2020.140005.

Menut, L., Bessagnet, B., Siour, G., Mailler, S., Pennel, R., Cholakian, A., 2020. Impact of lockdown measures to combat Covid-19 on air quality over western

Europe. *Science of the Total Environment*, 741, 140426. https://doi.org/10.1016/j.scitotenv.2020.140426.

National Bureau of Statistics. http://data.stats.gov.cn/ Accessed 5 November 2020.

Nuvolone, D., Petri, D., Voller, F., (2018). The effects of ozone on human health. *Environmental Science and Pollution Research International,* 25, 8074-8088. https://doi.org/10.1007/s11356-017-9239-3.

Ou, S., He, X., Ji, W., Chen, W., Sui, L., Gan, Y., Lu, Z., Lin, Z., Deng, S., Przesmitzki, S., Bouchard, J., (2020). Machine learning model to project the impact of COVID-19 on US motor gasoline demand. *Nature Energy*, 5, 666-673. https://doi.org/10.1038/s41560-020-0662-1.

Pierre, s., Alessandra, D., Evgenios, A., Feng, Z., Xu, X., Elena, P., Jose, J., Vicent, C., (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *Science of Total Environment*, 735, 139542. https://doi.org/10.1016/j.scitotenv.2020.139542.

Patel, H., Talbot, N., Salmond, J., et al., (2020). Implications for air quality management of changes in air quality during lockdown in Auckland (New Zealand) in response to the 2020 SARS-CoV-2 epidemic. Science of the Total Environment, 746, 141129. https://doi.org/10.1016/j.scitotenv.2020.141129.

Pascal, M., Corso, M., Chanel, O., Declercq, C., Badaloni, C., Cesaroni, G., et al., (2013). Assessing the public health impacts of urban air pollution in 25 European cities: results of the Aphekom project. *Science of Total Environment*. 449, 390-400. https://doi.org/10.1016/j.scitotenv.2013.01.077.

Ramachandran, S., Rupakheti, M., & Lawrence, M. G., (2020). Wu *Scientific Reports*, 10, 20091. https://doi.org/10.1038/s41598-020-76936-z.

Reliable Prognosis. http://rp5.kz/ Accessed 5 November 2020.

Saadat, S., Rawtani, D., & Hussain, C. M., (2020). Environmental perspective of COVID-19. *The Science of the Total Environment*, 728, 138870. https://doi.org/10.1016/j.scitotenv.2020.138870.

Sharma, S., Zhang, M., Anshika., Gao, J., Zhang, H., Kota, S., (2020). Effect of restricted emissions during COVID-19 on air quality in India. *Science of Total Environment*, 728, 138878. https://doi.org/10.1016/j.scitotenv.2020.138878.

Song, J., Zhao, C., Lin, T., Li, X., Prishchepov, A., (2019). Spatio-temporal patterns of traffic-related air pollutant emissions in different urban functional zones estimated by real-time video and deep learning technique. *Journal of Cleaner Production*, 238, 117881. https://doi.org/10.1016/j.jclepro.2019.117881.

Shekarrizfard, M., Faghih-lmani, A., Tetreault, L., Yasmin, S., Reynaud, F., Morency, P., Plante, C., Drouin, L., Smargiassi, A., Eluru, N., Hatzopoulou, M., (2017). Regional assessment of exposure to traffic-related air pollution: Impacts of individual mobility and transit investment scenarios. *Sustainable Cities and Society*, 29, 68-76. https://doi.org/10.1016/j.scs.2016.12.002.

Stafoggia, M., Samoli, E., Alessandrini, E., Cadum, E., Linares, C., (2013). Shortterm associations between fine and coarse particulate matter and hospitalizations in southern Europe: results from the MED-PARTICLES project. *Environmental Health Perspectives*, 121, 1026-1033. https://doi.org/10.1289/ehp.1206151.

Shon, Z.H., Kim, K.H., Song, S.K., (2011). Long-term trend in NO_2 and NOx levels and their emission radio in relation to road traffic activities in East Asia. *Atmospheric Environment*, 45, 3120-3131. https://doi.org/10.1016/j.atmosenv.2011.03.009.

Tian, H., Liu, Y., Li, Y., Wu, C., Chen, B., Kraemer, M.U.G., Li, B., Cai, J., Xu, B., Yang, Q., Wang, B., Yang, P., Cui, Y., Song, Y., Zheng, P., Wang, Q., Bjornstad, O.N., Yang, R., Grenfell, B.T., Pybus, O.G., Dye, C., (2020). An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science*, 368, 638-642. https://doi.org/10.1126/science.abb6105.

Tang, J., McNabola, A., Misstear, B., (2020). The potential impacts of different traffic management strategies on air pollution and public health for a more sustainable city: A modelling case study from Dublin, Ireland. *Sustainable Cities and Society*, 60, 102229. https://doi.org/10.1016/j.scs.2020.102229.

Wyche, K. P., Nichols, M., Parfitt, H., Beckett, P., Gregg, D. J., Smallbone, K. L., et al.,(2021). Changes in ambient air quality and atmospheric composition and reactivity in the South East of the UK as a result of the COVID-19 lockdown. *The Science of the Total Environment*, 755, 142526. https://doi.org/10.1016/j.scitotenv.2020.142526.

Wang, X., Yang, X., Wang, X., Zhao, J., Hu, S., Lu, J., (2020a). Effect of reversible lanes on the concentration field of road-traffic-generated fine particulate matter (PM2.5). *Sustainable Cities and Society*, 62, 102389. https://doi.org/10.1016/j.scs.2020.102389.

Wang, Q., Li, S., (2020b). Nonlinear impact of COVID-19 on pollutions from January 1 to October 30-Evidence from Wuhan, New York, Milan, Madrid, Bandra, London, Tokyo and Mexico City. *Sustainable Cities and Society*, 102629. https://doi.org/10.1016/j.scs.2020.102629.

Wu, J., Gamber, M., & Sun, W., (2020). Does Wuhan need to be in lockdown during the Chinese Lunar New Year?. *International Journal of Environment Research Public Health*, 17, 1002. https://doi.org/10.3390/ijerph17031002.

Weinmayr, G., Romeo, E., De Sario, M., Weiland, S.K., Forastiere, F., (2010). Shortterm effects of PM10 and NO_2 on respiratory health among children with asthma or asthma-like symptoms: a systematic review and meta-analysis. *Environmental Health Perspectives*, 118, 449-457. https://doi.org/10.1289/ehp.0900844.

Xu, Z., Liu, F., Xu, W., Wang, Z., Yang, Y., Xu, C., Wu, P., Li, X., (2020). Atmospheric air quality in Beijing improved by application of air source heat pump (ASHP) systems. *Journal of Cleaner Production*, 257, 120582. https://doi.org/10.1016/j.jclepro.2020.120582.

Xu, W., Liu, X., Liu, L., Dore, A., Tang, A., et al., (2019). Impact of emission controls on air quality in Beijing during APEC 2014: Implications from water-soluble ions and carbonaceous aerosol in PM2.5 and their precursors. *Atmospheric Environment*, 210, 241-252. https://doi.org/10.5194/acp-15-12667-2015.

Xu, X., Zhang, H., Chen, J., Li, Q., et al., (2018). Six sources mainly contributing to the haze episodes and health risk assessment of PM2.5 at Beijing suburb in winter 2016. *Ecotoxicology and Environmental Safety*, 166, 146-156. https://doi.org/10.1016/j.ecoenv.2018.09.069.

Yang, H., Chen, J., Wen, J., et al., (2016). Composition and sources of PM2.5 around heating periods of 2013 and 2014 in Beijing: implications for efficient mitigation measures. *Atmospheric Environment*, 124, 378-386. https://doi.org/10.1016/j.atmosenv.2015.05.015.

Yen, M.C.,Peng, C.M., Chen, T.C.,Chen, C.S.,Lin,N.H., Tzeng, R.Y.,Lee,Y.A., Lin, C.C., (2013). Climate and weather characteristics in association with the active fires in northern Southeast Asia and spring air pollution in Taiwan during 2010 7SEAS/Dongsha experiment. *Atmospheric Environment*, 78, 35-50. https://doi.org/10.1016/j.atmosenv.2012.11.015.

Zhang, X., Zhang, K., Liu, H., Lv, W., Aikawa, M., Liu, B., Wang, J., (2020a). Pollution sources of atmospheric fine particles and secondary aerosol characteristics in Beijing. *Journal of Environment Science*, 95, 91-98. https://doi.org/10.1016/j.jes.2020.04.002.

Zhang, L., An, J., Liu, M., Li, Z., Liu Y., et al., (2020b). Spatiotemporal variations and influencing factors of PM2.5 concentrations in Beijing, China. *Environmental Pollution*, 262, 114276. https://doi.org/10.1016/j.envpol.2020.114276.

Zhao, J., Zhang, J., Sun, L., Liu, Y., Lin, Y., Li, Y., Wang, T., Mao, H., (2018). Characterization of PM2.5-bound nitrated and oxygenated polycyclic aromatic hydrocarbons in ambient air of Langfang during periods with and without traffic restriction. *Atmospheric Research*, 213, 302-308. https://doi.org/10.1016/j.atmosres.2018.06.015.