How Effective Is Traffic and Production Restriction for Air Pollution? Evidence From a Quasi-natural Experiment in China

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Research Article

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Posted Date: August 17th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-705406/v1>

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How effective is traffic and production restriction for air pollution? Evidence from a quasi-natural experiment in China

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Abstract: Air pollution seriously affects human health. The traffic and production restriction is widely used for controlling heavy air pollution. However, the effectiveness of these two policies has not been scientifically verified through a city-level study. COVID-19 pandemic caused lockdowns in many cities, which makes it possible to verify the effectiveness of these two policies. Taken Wuhan as the study area, this study firstly verifies the existence of lockdown effect on air pollution and analyzes the evolution rule of six air pollutants (PM_{2.5}, PM₁₀, NO₂, SO₂, CO and O₃) using statistical methods. Then the structural break points in six air pollutants are detected with the regression discontinuity design model. Because Spring Festival overlapping COVID-19 may also affect the air pollution, in order to avoid the disturbance of Spring Festival on the results, the Spring Festival effect is also validated. The results illustrate that the effects of traffic and production restriction on six air pollutants are obviously different, in which the concentrations of PM_{2.5}, PM₁₀ and NO₂ decrease significantly, while traffic and production restriction has no apparent effects on SO₂, CO and O₃. Moreover, the structural break points are verified in the four air pollutants (PM_{2.5}, PM₁₀, NO₂ and CO), and the structural break points are caused by lockdown instead of Spring Festival. This study revealed how the traffic and production restriction affected the air pollution at a city level, and provided strong implementation basis to the air pollution control policy.

Keywords: traffic and production restriction, air pollution, COVID-19, Spring Festival effect, structural break points

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How effective is traffic and production restriction for air pollution? Evidence from a quasi-natural experiment in China

Abstract: Air pollution seriously affects human health. The traffic and production restriction is widely used for controlling heavy air pollution. However, the effectiveness of these two policies has not been scientifically verified through a city-level study. COVID-19 pandemic caused lockdowns in many cities, which makes it possible to verify the effectiveness of these two policies. Taken Wuhan as the study area, this study firstly verifies the existence of lockdown effect on air pollution and analyzes the evolution rule of six air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 , CO and O_3) using statistical methods. Then the structural break points in six air pollutants are detected with the regression discontinuity design model. Because Spring Festival overlapping COVID-19 may also affect the air pollution, in order to avoid the disturbance of Spring Festival on the results, the Spring Festival effect is also validated. The results illustrate that the effects of traffic and production restriction on six air pollutants are obviously different, in which the concentrations of $PM_{2.5}$, PM_{10} and NO_2 decrease significantly, while traffic and production restriction has no apparent effects on SO_2 , CO and O_3 . Moreover, the structural break points are verified in the four air pollutants ($PM_{2.5}$, PM_{10} , NO_2 and CO), and the structural break points are caused by lockdown instead of Spring Festival. This study revealed how the traffic and production restriction affected the air pollution at a city level, and provided strong implementation basis to the air pollution control policy.

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1. Introduction

In the past several decades, the acceleration of urbanization and rapid economy development not only bring enormous benefits to people, but also cause lots of air pollution problems. The correlation between air pollution and many adverse human respiratory and cardiovascular diseases has been verified by previous researches (Danesh Yazdi et al., 2019; Hao et al., 2019; Yu et al., 2020). Lots of cities located in north part of China have suffered from serious air pollution for many years, and many air pollution control policies have been implemented in the past ten years. Some scholars have illustrated that the air pollutants mainly derived from industry and traffic (Alahmad et al., 2021; Choi and Myong, 2018; Miao et al., 2019). Therefore, the production restriction (or suspension) on high-pollution industries such as steel and building material factories and even-odd traffic restriction are often adopted to tackle heavy air pollution incidents. However, these two

measures are often applied in small area for a short time in order to reduce the negative influences on human activities (De La Cruz et al., 2019; Hua et al., 2021; Tao et al., 2021). Thus, the effectiveness of these two measures have not been scientifically verified through a city-level empirical study, which leads to the lack of implementation basis of these two measures. In many cities all over the world, the COVID-19 pandemic caused long-term and large area lockdowns which was equivalent to a strict environmental regulation, namely the traffic and production restriction or suspension, which makes it possible to verify the effectiveness of these two measures on air pollution control at a city level.

Some researchers have investigated the apparent differences of various air pollutants' concentrations before and after lockdown without considering the different evolution rules of air pollutants in different lockdown periods. Nakada and Urban (2020) compared the concentrations of different air pollutants before and after partial lockdown in Sao Paulo, Brazil, and found that the NO, NO₂ and CO concentrations decreased significantly. Chauhan and Singh (2020) found a decline in PM_{2.5} from December 2019 to March 2020 (COVID-19 period) in major cities around the world. Berman and Ebisu (2020) evaluated PM_{2.5} and NO₂ concentrations during the COVID-19 period and the pre-COVID-19 period in the continental United States, the results illustrated remarkable decreases in both PM_{2.5} and NO₂ concentrations. Razzaq et al. (2020) investigated the link between COVID-19 and ozone pollution in the top ten affected states of United States, the results confirmed overall dependence between COVID-19 and ozone pollution. Zangari et al. (2020) examined the air quality changes in New York City based on first 17 weeks' PM_{2.5} and NO₂ concentrations (from January to May) of 2015-2020. Baldasano (2020) investigated the effects of traffic reduction in lockdown on NO₂ concentration and found that NO₂ concentration decreased 50% and 62% in Barcelona and Madrid, respectively. Ali et al. (2021) analyzed the linkage between PM_{2.5} concentration and COVID-19 spread in four major cities located in Pakistan.

In order to prevent the rapid widespread transmission of COVID-19, the restriction policies related traffic and production are continuously adjusted and consequently have a time-varying influence on the air pollution. Therefore, analyzing the effects of traffic and production restrictions on air pollution within different lockdown periods can obtain more reasonable results. Talbot et al. (2021) firstly separated the lockdown period in New Zealand into three phases and then analyzed the modifications of PM_{2.5}, PM₁₀ and NO₂ concentrations within different phases. Yuan et al. (2021) analyzed the lockdown effect on air pollution in Hangzhou by dividing the lockdown period into five stages and found that the air pollutants' concentrations have remarkable declines in the third phase (COVID-Lock). Li et al. (2020) explored the effect of human activities on air pollution during the lockdown over the Yangtze River Delta region through separating the lockdown period

into four stages. Zhang et al. (2021) analyzed the modifications of average air pollutants' concentrations in China by splitting the first quarter of 2020 into four stages.

The contribution and novelty of this study is twofold. (1) The strict and rapid lockdown policies which can be mainly regarded as traffic and production restriction may lead to sharp changes in air pollution. Detecting the sharp changes in different air pollutants can help people understand how the lockdown affect different air pollutants. However, few scholars considered the sharp change detection in their studies. The regression discontinuity design (RDD) model is a widely used method to capture this kind of sudden change. Thus, this study validates the sharp changes in different air pollutants during lockdown period utilizing the RDD model, and found that these sharp changes only existed in the $PM_{2.5}$, PM_{10} , CO and NO_2 , which indicates that the lockdown only affected $PM_{2.5}$, PM_{10} , CO and NO_2 concentrations instead of SO_2 and O_3 concentrations. Moreover, with comparison of the RDD coefficient of $PM_{2.5}$ (-34.46), PM_{10} (-37.11) and NO_2 (-19.15), the coefficient of CO (-0.32) indicates that the traffic and production restriction has less influence on CO concentration compared to that on $PM_{2.5}$, PM_{10} , NO_2 concentrations. (2) In the Spring Festival, a legal holiday in China, most of industries are usually suspended and consequently the air pollution may be influenced in this period. Because the Spring Festival in 2020 overlapped with the COVID-19, ignoring the Spring Festival effect may reduce the reliability of the results. However, the above studies on China have rarely considered the dual effects of Spring Festival and lockdown on air quality. In this study, the Spring Festival effect on the air pollution is investigated based on RDD model through comparing the sharp changes in air pollutants during the Spring Festival in 2019 and 2020, and found that there are no any sharp changes in the air pollutants in 2019, thus we can deduce that the sharp changes in the air pollutants in 2020 are unlikely to be caused by the Spring Festival.

The remainder of this paper is organized as follows. Section 2 introduces the study materials and methods, Section 3 presents the empirical results, Section 4 discusses the implication of the findings, and Section 5 concludes this study.

2. Materials and methods

2.1 Study areas and periods

This study aims to verify the effects of traffic and production restriction on air pollution, therefore, the city adopted in this study should satisfy the following two conditions: (1) the city often suffered from serious air pollution; (2) traffic and production restriction is implemented widely at a city level for a long enough period of time.

Wuhan, a mega-city in central China, is the capital of Hubei Province and has an area of

8569.15 square kilometers and a population of 11.21 million. As a typical industrial and resource-based city, Wuhan not only suffered from the typical aerosol particles (PM_{2.5}, PM₁₀) but also the gaseous pollutants (NO_x, SO₂, O₃, CO) (Al-Qaness et al., 2020; Sulaymon et al., 2021; Yang et al., 2019). As shown in Fig. 1, in China, Wuhan has suffered from the most severe COVID-19 pandemic which caused the strictest lockdown. Wuhan has experienced the complete process from large scale lockdown to recovery in China. Therefore, the traffic and production restriction which is the main lockdown policy was adequately implemented in Wuhan. Thus, Wuhan satisfies the above two conditions and is consequently suitable for verifying the effects of traffic and production restriction on the air pollution.

Fig. 1. Density map of the COVID-19 confirmed cases and associated deaths in Hubei, China

With dispersion of COVID-19, different lockdown policies were implemented, and consequently may have different effects on air pollution. Thus, it is vital to find out the implementation dates of different lockdown policies before analyzing the relationship between lockdown and air pollution. After carefully studying the whole process of lockdown in Wuhan, the following four time nodes can be adopted to represent the adjustments of lockdown policies (see Table 1).

Table 1 Time nodes of important events in the lockdown period

Time nodes	Important events
Jan 23rd	The beginning of China's Spring Festival; The highest public health emergency response was implemented
Feb 13th	The end of Spring Festival
Mar 20th	Enterprises resumed production
Apr 07th	Wuhan officially emerged from lockdown

According to the above four time points, the lockdown period can be divided into the following four phases: pre-lockdown (January 1-January 23); level-I lockdown (January 24-February 13); level-II lockdown (February 14-March 20); level-III lockdown (March 21-April 7). Fig. 2 shows the different restrictions on production and traffic in each phase of lockdown. In lockdown, the strictest traffic restriction was enforced on all outbound routes from Wuhan. International passenger flights, ferries and long-distance passenger transport services in Wuhan were all suspended. Airports and railway stations were closed and intra-city public transport halted in Wuhan. Moreover, all of the non-essential enterprises were suspended.

Note: * The online-hailing service was restricted; # Motor vehicle was banned

Fig. 2. The implementation date of different traffic and production restrictions in lockdown

2.2 Data sources

Daily data of PM_{2.5}, PM₁₀, SO₂, CO, NO₂ and O₃ concentrations from January 1st to April 7th, 2020 in Wuhan were collected from China's online air quality monitoring and analysis platform (<http://www.aqistudy.cn>). In order to evaluate the modification of air pollution in lockdown, the data during the same study period in 2017-2019 were also collected and adopted as the reference data, see Fig. 3.

2.3 Methods

2.3.1 Methods for analyzing air pollution modification

In this study, the Kruskal-Wallis (K-W) test and Kolmogorov-Smirnov (K-S) test were used to compare the air pollution modifications during the same lockdown period (i.e., January 1st -April 7th) for each of the last four years (2017-2020). Moreover, paired t-test was used to verify the air pollution modifications in pre-lockdown, level-I, level-II, and level-III. These three statistical methods are briefly introduced as follows.

(a) Kruskal-Wallis test

The K-W test statistics can be calculated as follows if there are no ties (i.e., there are no equivalent observations):

$$H = \frac{12}{N(N+1)} \sum_{i=1}^k \frac{R_{i+}^2}{n_i} - 3(N+1) \quad (1)$$

where k is the number of samples, n_i means the size of the i th sample and $i=1,2,\dots,k$,

$N=\sum n_i$ is the number of observations in all samples combined, $R_{i+} = n_i \bar{R}_i = \sum_{j=1}^{n_i} R_{ij}$ means the sum of the ranks in the i th sample.

If there are ties, each observation is given the average value of the ranks for which it is tied. H has to be modified so that its expectation is still equal to $k-1$. After averaging the rank, the revised H statistic can be presented as follows:

$$H_a = \frac{H}{1 - \frac{\sum_{t=1}^g (\tau_t^3 - \tau_t)}{N^3 - N}}, H_a : \chi^2(k-1) \quad (2)$$

where g is the number of ties in the combined samples $\{x_{i1}, x_{i2}, \dots, x_{in_i}, i=1,2,\dots,k\}$, τ_t means the length of the i th tie, and $t=1,2,\dots,g$.

(b) Kolmogorov-Smirnov test

We assume that the sample sizes of the two samples are n_1 and n_2 . $F_1(x)$ and $F_2(x)$ are used to represent the cumulative experience functions of the two samples. Let D_j equal to $F_1(X_j) - F_2(X_j)$, and then the K-S statistics can be calculated as follows:

$$Z = \max_j |D_j| \sqrt{\frac{n_1 n_2}{n_1 + n_2}} \quad (3)$$

(c) Paired t-test

The formula of paired t-test was as follows:

$$t = \frac{d}{s / \sqrt{n}} \quad (4)$$

where d was the mean value of the observed differences, and the noise was described using the standard error, which was calculated by dividing the standard deviation of the difference by the square root of the sample size (n).

2.3.2 Methods for validation of Structural break points in six air pollutants

RDD is used to verify the structural break points in six air pollutants. Assuming that before the experiment, the variables x_i and y_i had a linear relationship: $y_i = \alpha + \beta x_i + \varepsilon_i (i=1,\dots,n)$; if the treatment effect for $D_i = 1(x_i \geq c)$ (constant c is the breakpoint) is positive, then the linear relationship between x_i and y_i has a breakpoint at $x=c$. Since there are no systematic

differences between the individuals in all aspects around $x=c$, the reason of the conditional expectation function $E(y_i|x)$ jumping here can only be the treatment effect of D_i . This jump can be regarded as a causal effect on D_i at $x=c$.

Since there was a clear dividing line between the lockdown period and the non-lockdown period, namely there were no systematic differences in the weather conditions on either side of the boundary, the only difference was lockdown implementation. Therefore, the days before and after the lockdown were considered local randomization, thus RDD can be used to identify the causal relationship between the lockdown and the air quality.

$$\ln y_i = \alpha + \delta D_i + \gamma_1(x_i - c) + \gamma_2 D_i(x_i - c) + \varepsilon_i, i = 1, \dots, n \quad (5)$$

where c was the day of the lockdown, and D_i (lockdown period above) defined the dummy variable for the implementation of the lockdown policy; when $x_i \geq c, D_i = 0$; when $x_i < c, D_i = 1$; δ was the air quality jump amplitude measure at the breakpoint.

3. Results

3.1 Air pollution modification under traffic and production restriction

3.1.1 Comparisons of air pollution modifications during the same study periods from 2017 to 2020

Fig. 3 presents the daily concentrations of six air pollutants from January 1st to April 7th over the last four years. As shown in Fig. 3, the concentrations of $PM_{2.5}$, PM_{10} and NO_2 decreased notably after the lockdown was implemented in Wuhan (January 23rd), and declined sharply again after February 10th when the residential communities were on lockdown. Because of the restrictions on traffic and production implemented in lockdown, the concentrations of $PM_{2.5}$, PM_{10} and NO_2 were significantly lower than those in the same periods over the past three years (2017-2019), while the concentrations of O_3 , SO_2 and CO do not have apparent modification trends.

Fig. 3. Daily concentrations of six air pollutants from January 1 to April 7 in 2017-2020

In order to further verify the above findings obtained from descriptive statistics results, the air pollution modifications during the same study periods from 2017 to 2020 are compared using K-W and K-S methods, and the results are shown in Table 2. For each air pollutant, K-W test was used to verify if apparent difference existed in its concentrations during the research period (January 1st – April 7th) over the past four years (2017-2020). The results of K-W test indicated that only the result of O₃ failed to reject the null hypothesis, which revealed that the concentration of O₃ for the past four years has no apparent difference, i.e., the concentration of O₃ has not been affected by the lockdown. The results also illustrated that the results of PM_{2.5}, PM₁₀, NO₂, SO₂ and CO successfully rejected the null hypothesis, indicating that there is at least one year when each above air pollutant's concentration is different from that in other years. Therefore, it is necessary to detect in which year when the air pollutant's concentration is different. It is easy to understand that if one air pollutant concentration during the research period in 2020 is different from all that in 2019, 2018 and 2017, (i.e., all the results of paired difference tests of 2020 vs. 2019, 2020 vs. 2018 and 2020 vs. 2017 reject the null hypothesis), we can conclude that this air pollutant was significantly affected by the lockdown. If one of the above three paired difference tests can not reject the null hypothesis, then the conclusion that the air pollutant was remarkably affected by the lockdown cannot be deduced. For each air pollutant, the results of paired difference tests of 2020 vs. 2019, 2020 vs. 2018 and 2020 vs. 2017 are listed in Table 2. The results of all the three paired difference tests (i.e., 2020 vs. 2019, 2020 vs. 2018 and 2020 vs. 2017) for PM_{2.5}, PM₁₀ and NO₂ rejected the null hypothesis, which means that the concentrations of PM_{2.5}, PM₁₀ and NO₂ were significantly affected by the lockdown. However, there is no concrete evidence to conclude that the concentrations of SO₂ and CO were affected by the lockdown, because there is one paired

difference test (2020 vs. 2018) cannot reject the null hypothesis for SO₂, and there are two paired difference tests (2020 vs. 2018) cannot reject the null hypothesis for CO.

Table 2 The results of K-W test and K-S test for six air pollutants

	Paired comparison	Methods	Difference	P-value
PM _{2.5}	ALL	K-W test	YES	<0.01
	2020 vs. 2019	K-S test	YES	<0.01
	2020 vs. 2018	K-S test	YES	<0.01
	2020 vs. 2017	K-S test	YES	<0.01
PM ₁₀	ALL	K-W test	YES	<0.01
	2020 vs. 2019	K-S test	YES	<0.01
	2020 vs. 2018	K-S test	YES	<0.01
	2020 vs. 2017	K-S test	YES	<0.01
SO ₂	ALL	K-W test	YES	<0.01
	2020 vs. 2019	K-S test	YES	<0.05
	2020 vs. 2018	K-S test	NO	0.11
	2020 vs. 2017	K-S test	YES	<0.01
NO ₂	ALL	K-W test	YES	<0.01
	2020 vs. 2019	K-S test	YES	<0.01
	2020 vs. 2018	K-S test	YES	<0.01
	2020 vs. 2017	K-S test	YES	<0.01
CO	ALL	K-W test	YES	<0.01
	2020 vs. 2019	K-S test	NO	0.15
	2020 vs. 2018	K-S test	NO	0.80
	2020 vs. 2017	K-S test	YES	<0.01
O ₃	ALL	K-W test	NO	0.26
	2020 vs. 2019	K-S test	NO	0.07
	2020 vs. 2018	K-S test	NO	0.96
	2020 vs. 2017	K-S test	NO	0.46

3.1.2 Air pollution modification in different lockdown periods

The descriptive statistics results for six air pollutants during pre-lockdown, level-I, level-II and level-III periods are shown in Table 3. The paired t-test has been conducted for each air pollutant during each of the four lockdown periods, and the results are shown in Fig. 4 and Table 4. The detailed modifications of each air pollutant during different lockdown periods are presented as follows.

(1) Modification of PM_{2.5} and PM₁₀ concentrations

According to Table 3, PM_{2.5} and PM₁₀ concentrations have the similar modification trend in lockdown periods. Their concentrations continuously decreased in all the three lockdown periods, and have largest decline degree in level-III compared with that in pre-lockdown period. Based on

the results shown in Fig. 4, the $PM_{2.5}$ and PM_{10} concentrations in level-I of 2020 have no significant difference with that in other years, while have significant difference in level-II with that in other years. The main reason may be that the lockdown is estimated to show a lag time of about two weeks before causing more complete effects on air pollution. During the level-III, the $PM_{2.5}$ concentration nearly returned to the average level in previous years because of resumption of production and public transportation. However, the concentration of PM_{10} did not increase apparently with resumption in level-III, the reason may be that even though the traffic and some important industries resumed, the main emission sources of PM_{10} such as construction and building material industries were still under restriction because of labor and raw material availability, therefore, the PM_{10} concentration was still in a low level compared to previous years.

Table 3 Descriptive statistics for air pollutants during different lockdown periods in 2020

Air pollutant	Mean	Std Dev.	Max	Min	Number
Pre-lockdown					
$PM_{2.5}$	62.73	31.05	108	12	22
PM_{10}	75.14	36.16	105	19	22
SO_2	6.77	1.85	11	5	22
NO_2	44.05	11.56	76	26	22
CO	1.07	0.22	1.6	0.8	22
O_3	36.82	21.16	73	5	22
level-I					
$PM_{2.5}$	48.27	21.60	97	18	22
PM_{10}	53.73	22.70	103	20	22
SO_2	6.82	1.92	11	5	22
NO_2	22.27	8.49	36	10	22
CO	0.86	0.20	1.3	0.5	22
O_3	71.95	20.61	110	46	22
level-II					
$PM_{2.5}$	35.25	13.88	75	9	36
PM_{10}	51.86	22.19	89	12	36
SO_2	8.47	2.88	17	5	36
NO_2	20.67	5.12	32	10	36
CO	0.95	0.17	1.3	0.6	36
O_3	89.39	23.89	135	39	36
level-III					
$PM_{2.5}$	32.17	14.66	57	8	18
PM_{10}	48.33	23.44	86	13	18
SO_2	8.89	2.97	16	5	18
NO_2	24.06	7.22	43	15	18
CO	0.86	0.23	1.4	0.6	18
O_3	93.5	32.36	157	53	18

Fig. 4. The results of paired t-test for six air pollutants

Note: the red circle indicates $P < 0.05$

(2) Modification of NO_2 concentration

As shown in Fig. 4, the concentration of NO_2 has a rapid decreasing trend as soon as the lockdown is implemented in the level-I period, and kept in a low level in the level-II, while has a quick increase once the lockdown eased in level-III. The rapid response of NO_2 concentration to lockdown indicates that the link between them is tight and apparent. Moreover, During the lockdown period, the reduction of NO_2 concentration was the largest among all the six air pollutants (see Table 4). It has been confirmed by many previous researches that almost all NO_2 derives directly from the exhaust emission. Therefore, once the traffic restriction was implemented, the NO_2 concentration sharply declined without any lag time, oppositely, once the traffic restriction eased, the NO_2 concentration rapidly increase without any delay. These findings remind us that the exhaust emission reduction policies such as promoting electric vehicles, private vehicle transport reduction and encouraging public transport can effectively reduce the NO_2 concentration.

(3) Modification of O_3 , SO_2 and CO concentrations

Among six air pollutants, O_3 was the only pollutant with upward trend during the lockdown period, and this increasing trend also existed in the same periods of the previous three years from 2017 to 2019. As shown in Fig. 4, the mean values of SO_2 and CO have no apparent modification trend during the lockdown period. During the whole lockdown period, SO_2 and CO concentrations in 2020 were not significantly different from that in the past three years, indicating that SO_2 and CO concentrations were barely affected by the lockdown. The reason may lie in the following two

aspects: (1) in fact, in the lockdown, even though the traffic and production are restricted strictly, in order to keep the normal life of citizens, most of the heating and electricity generation industries which are the main sources of SO₂ and CO were not affected; (2) moreover, because of residential lockdown, the time of household stove usage and heating was remarkably extended.

Table 4 The change values of six air pollutants' concentrations during different lockdown periods compared to that in previous three years

	Difference between 2020 and 2017 (% change)	Difference between 2020 and 2018 (% change)	Difference between 2020 and 2019 (% change)
PM _{2.5}			
pre-lockdown	-15.09(19.21%)	-3.39(5.07%)	-30.91(29.57%)
level-I	-29.10(38.36%)	-8.67(15.64%)	-16.29(25.84%)
level-II	-37.53(51.57%)	-13.69(27.97%)	-15.14(30.05%)
level-III	-14.89(31.64%)	-8.11(20.13%)	-4.33(11.86%)
PM ₁₀			
pre-lockdown	-21.17(21.85%)	-15.87(17.32%)	-38.65(33.79%)
level-I	-40.67(43.87%)	-8.81(14.48%)	-21.47(29.20%)
level-II	-48.50(48.33%)	-42.53(45.06%)	-34.31(39.82%)
level-III	-38.61(44.41%)	-25.11(34.19%)	-19.78(29.04%)
SO ₂			
pre-lockdown	-6.30(48.46%)	-5.65(45.75%)	-3.65(35.27%)
level-I	-6.62(48.96%)	0.43(6.64%)	0.38(5.83%)
level-II	-4.97(36.98%)	-0.14(1.63%)	-1.36(13.84%)
level-III	-2.44(21.54%)	1.67(23.13%)	-0.61(6.42%)
CO			
pre-lockdown	-0.26(29.55%)	0.13(13.83%)	-0.33(23.57%)
level-I	-0.50(37.04%)	-0.17(16.83%)	-0.07(7.61%)
level-II	-0.26(21.49%)	0.04(4.35%)	-0.06(5.94%)
level-III	-0.28(24.56%)	-0.28(31.46%)	-0.09(9.38%)
NO ₂			
pre-lockdown	-11.91(21.64%)	-11.22(20.64%)	-14.3(24.90%)
level-I	-24.05(51.96%)	-11.05(33.19%)	-8.90(28.58%)
level-II	-40.53(66.24%)	-34.39(62.46%)	-33.33(61.72%)
level-III	-25.72(51.67%)	-16.78(41.10%)	-20.83(46.40%)

	O ₃		
pre-lockdown	-15.00(28.70%)	-23.43(38.6%)	-4.87(13.07%)
level-I	6.76(10.18%)	17.29(30.95%)	28.52(63.92%)
level-II	18.75(26.54%)	2.25(2.58%)	9.97(12.55%)
level-III	5.67(6.46%)	-6.22(6.24%)	-20.00(17.62%)

3.2 Structural break points in six air pollutants

3.2.1 Regression Discontinuity Design results

In this section, the structural break points in six air pollutants during the lockdown period were detected using RDD. After implementation of lockdown, the concentrations of PM_{2.5}, PM₁₀, NO₂ and CO declined considerably because of restrictions on production and traffic (see Fig. 5). Table 5 shows that there were structural break points in PM_{2.5}, PM₁₀, NO₂ and CO, but no structural break points in SO₂ and O₃. With comparison of the RDD coefficients of PM_{2.5} (-34.46), PM₁₀ (-37.11) and NO₂ (-19.15), the coefficient of CO (-0.32) indicates that the traffic and production restriction has less influence on CO concentration compared to that on PM_{2.5}, PM₁₀, NO₂ concentrations. In summary, it can be seen that the lockdown has significant effect on PM_{2.5}, PM₁₀, NO₂ concentrations, less influences on CO, and no influences on SO₂ and O₃.

Fig. 5. RDD results for six air pollutants, 2020

Table 5 Estimation results for RDD

	PM _{2.5}	PM ₁₀	SO ₂	CO	NO ₂	O ₃
2020	-34.46***	-37.11***	-0.62	-0.32***	-19.15***	4.81

2019	-6.27	-10.44	-2.89	0.03	-11.42*	-22.68**
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Note: * $p < .10$, ** $p < .05$, *** $p < .01$

3.2.2 Spring Festival effect on air pollution

Because the Spring Festival overlapped with the COVID-19 in the year 2020, ignoring the Spring Festival effect may reduce the reliability of the results. In this section, the Spring Festival effect on the air pollution is investigated based on RDD model through comparing the sharp changes in air pollutants during the year 2019 and 2020, the results indicated that there are no any sharp changes in the air pollutants in 2019 during the Spring Festival (see Fig. 6), thus we can deduce that the sharp changes in the air pollutants in 2020 are unlikely to be caused by the Spring Festival.

Fig. 6. RDD results for six air pollutants, 2019

3.2.3 Bandwidth sensitivity analysis

Since the bandwidth size could significantly affect the RDD results, to ensure regression robustness, 3-6 days before and after the implementation of the lockdown policy were used as the bandwidth for RDD. Table 6 shows the estimates and significance of the coefficients for different bandwidths. Since there were no significant structural changes in SO_2 and O_3 , these two air pollutants were excluded from the scope of bandwidth sensitivity analysis. Under the different bandwidths, the coefficients of $\text{PM}_{2.5}$, PM_{10} , CO and NO_2 are all significantly negative, which was consistent with the results in section 3.2.1. Therefore, the bandwidth sensitivity analysis revealed that the lockdown had a relatively stable impact on the air pollutants' concentrations and the choice of different bandwidths did not affect the core conclusions of this research.

Table 6 Results of the bandwidth sensitivity analysis

	PM _{2.5}	PM ₁₀	CO	NO ₂
3 days	-31.21***	-33.20	-0.55***	-18.78**
4 days	-30.76***	-32.09***	-0.48***	-18.22**
5 days	-32.65***	-34.70***	-0.40***	-18.59**
6 days	-33.95***	-37.25***	-0.35***	-18.91***

Note: * p<.10, ** p<.05, *** p<.01

4. Discussions

4.1 Equivalence between the lockdown and restriction on traffic & production

The purpose of this study is to investigate the effects of traffic and production restriction on air pollution at a city level, however, these two measures have never been implemented in a large area like a city for long enough period of time, so the effectiveness of these two measures have never been estimated quantitatively at a city level. The COVID-19 occurred in 2019 caused a large scale and long-term lockdown in Wuhan, and the restrictions on traffic and production in lockdown can be regarded as a natural experimental condition. Fig. 2 presented the implementation periods of detailed restrictions on traffic and production, after implementation of these restriction policies, the traffic and production in Wuhan have been extensively limited. Compared to 2019, the monthly bus passenger volume and taxi passenger volume in 2020 decreased by 99.26% and 98.68% in February, 98.52% and 98.10% in March, respectively (see Fig. 7 (a)-(b)). According to the data released by Wuhan Bureau of Statistics, in the first quarter of 2020 the Wuhan's GDP sharply declined by 40.5% and the secondary industry dropped by 45.4% in comparison with the same period in 2019 (Fig. 7 (c)).

Fig. 7. Monthly variation of (a) Bus Passenger Volume (BPV), (b) Taxi Passenger Volume (TPV), and (c) annual variation of output value in the first quarter

Based on the above consideration, the lockdown can be regarded as a natural experiment condition for analyzing the effects of traffic and production restriction on the air pollution. Moreover, as a typical industrial and resource-based city, Wuhan has suffered from heavy air

pollution containing aerosol particles ($PM_{2.5}$, PM_{10}) and gaseous pollutants (NO_x , SO_2 , O_3 , CO) for many years. Therefore, it is feasible to conduct this study based on the data collected during the lockdown period in Wuhan.

4.2 The reliability and validity of the results

(1) Similarities with previous studies

Collivignarelli et al. (2021) found the NO_2 concentrations in London, Milan and Paris under the travel restrictions decreased by 80.8%, 42.4% and 79.8%, respectively. Ju et al. (2021) obtained the conclusion that $PM_{2.5}$ and PM_{10} concentrations in Korea decreased significantly during the COVID-19 period under the traffic and production restrictions. All the above studies show that there are strong correlations between the restriction on traffic and production and the concentrations of $PM_{2.5}$, PM_{10} and NO_2 , which is consistent with the findings obtained in this study. Lian et al. (2020) found that the SO_2 concentration in Wuhan, China was not affected apparently by the lockdown, which is similar to the result found in this study.

(2) Differences with previous studies

Because the study area and period in this research were different from that in previous studies, this study also obtained some new findings which mainly includes the following two aspects.

(a) Tobias et al. (2020) found the O_3 concentration has an increasing trend during the lockdown period and deduced that the increasing trend of O_3 concentration was caused by the sharply decline of NO_2 concentration. Inconsistent to findings in Tobias et al. (2020), although this study also obtained the increasing trend of O_3 concentration during lockdown period, after comparing with changing trend of O_3 concentration in the past four years from 2017 to 2020, this study found that its increase was not limited to the lockdown period, i.e., the O_3 concentration presented the steady increase trend in the same periods for the past four years. Therefore, it can be concluded that the O_3 increase in the current study is unlikely to be attributable to the reduced production and traffic during the lockdown in Wuhan.

(b) Liu et al. (2021) found the CO concentration has a notably decreasing trend under the traffic and production restriction during the lockdown period, which indicates that the traffic and production restriction can affect the level of CO concentration. This study also found the decreasing trend of CO concentration in the lockdown, however, with comparison of the RDD estimated coefficient of $PM_{2.5}$ (-34.46), PM_{10} (-37.11), NO_2 (-19.15), the RDD estimated coefficient of CO (-0.32) indicates that the traffic and production restriction has less influence on CO concentration compared to that on $PM_{2.5}$, PM_{10} , NO_2 .

4.3 Effectiveness and limitation of traffic and production restriction

As the widely used measures for controlling the heavy air pollution, the traffic and production restriction have been verified in this study to be effective for reducing the $PM_{2.5}$, PM_{10} and NO_2 concentrations. However, the traffic and production restriction has nearly no effect on SO_2 and O_3 , in which O_3 has become the primary air pollutant in many places in China for several years (Wang et al., 2021a). Although the results of this study presented correlation between CO concentration and restriction on traffic and production, the traffic and production restriction has less influence on CO concentration compared to $PM_{2.5}$, PM_{10} and NO_2 . Therefore, in order to control the air pollution, the traffic and production restriction policy is not enough, more comprehensive measures should be adopted to control SO_2 , O_3 and CO concentrations.

4.4 Spring Festival effect on air pollution during lockdown

Wang et al. (2021b) found that the air pollution level can be affected apparently by the Spring Festival, this can be interpreted by the production reduction and traffic increase. However, through comparing the sharp changes in air pollutants in the year 2019 and 2020, it can be found that there are no any sharp changes in the air pollutants in 2019 during the Spring Festival. Therefore, it can be deduced that the sharp changes in the air pollutants in 2020 are unlikely to be caused by the Spring Festival.

5. Conclusions

Traffic and production restrictions are two widely used measures for controlling the heavy air pollution. However, these two measures are often applied in a small area for a short time in order to reduce the negative influences on human activities, therefore, the effectiveness of these two measures have not been scientifically verified through a city-level empirical study, which leads to the lack of implementation basis of these two measures. This study, adopted Wuhan as the study area, firstly verifies the existence of lockdown effect on air pollution and analyzes the change rule of six air pollutants ($PM_{2.5}$, PM_{10} , NO_2 , SO_2 , CO and O_3) in different lockdown periods using K-W, K-S and paired t-test methods. Then the structural break points in six air pollutants and the Spring Festival effect are investigated with RDD model.

The following six conclusions are obtained.

(1) Compared to the past three years from 2017 to 2019, the $PM_{2.5}$, PM_{10} and NO_2 concentrations declined sharply in lockdown period, indicating that the traffic and production restriction has apparently effects on these above three air pollutants' concentrations; (2) Compared to the past three years from 2017 to 2019, the CO concentration also has a decreasing trend in

lockdown, however, according to the RDD estimated coefficients of different air pollutants, it is found that the traffic and production restriction has less influence on CO concentration compared to that on PM_{2.5}, PM₁₀ and NO₂; (3) This study obtained the increasing trend of O₃ concentration during lockdown period, after comparing with the changing trend of O₃ concentration in the past four years from 2017 to 2020, this study found that its increase was not limited to the lockdown period, i.e., the O₃ concentrations have presented the steady increase trend in the same periods over the past four years. Therefore, it can be concluded that the increase in O₃ in the current study is unlikely to be attributed to the reduced production and traffic during the lockdown in Wuhan; (4) Compared to the past three years from 2017 to 2019, the SO₂ concentration has no apparent modification trend during the lockdown, indicating that the traffic and production restriction has no effect on SO₂ concentration; (5) The air pollution level can be affected apparently by the Spring Festival, but the sharp changes in the air pollutants in 2020 are unlikely to be caused by the Spring Festival; (6) The concentrations of PM_{2.5} and PM₁₀ started to decline in the Level-II period during lockdown, while the concentration of NO₂ has a rapid decreasing trend as soon as the traffic and production restriction is implemented in the Level-I period, indicating that there is an lagged effect on the influences of traffic and production restriction on the PM_{2.5} and PM₁₀; (7) Traffic and production restriction policy is effective for controlling the PM_{2.5}, PM₁₀ and NO₂, less effective for CO, and ineffective for SO₂ and O₃.

In summary, in order to control the air pollution, the traffic and production restriction policy is not enough, and more comprehensive measures should be adopted to control SO₂, O₃ and CO concentrations. Moreover, O₃ has become the primary air pollutant in many places in China for several years, therefore, O₃ controlling policy making may be an important issue in future.

Authors contribution Yiqing Chen collected the data and conducted the experiments. Deyun Wang designed the experiments and analyzed the results. Adnen Elamraoui and Haixiang Guo provided critical review and manuscript editing. Yiqing Chen and Deyun Wang wrote the paper. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are available from the corresponding author or the <http://www.aqistudy.cn> upon reasonable request.

Funding This research was funded by the Hubei Provincial Natural Science Foundation of China (Grant No. 2020CFB822); the National Natural Science Foundation of China (Grant Nos. 72074198, 71874165).

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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