Journal of Cleaner Production 279 (2021) 123622

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Have traffic restrictions improved air quality? A shock from COVID-19

Zhongfei Chen [a, b, c], Xinyue Hao [a], Xiaoyu Zhang [a, **], Fanglin Chen [a, *]

[a] School of Economics, Jinan University, Guangzhou, Guangdong, 510632, China
[b] Institute of Resource, Environment and Sustainable Development Research, Jinan University, Guangzhou, Guangdong, 510632, China
[c] School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China

ARTICLE INFO

Article history:
Received 14 April 2020
Received in revised form
20 July 2020
Accepted 3 August 2020
Available online 13 August 2020

Handling editor: Yutao Wang

Keywords:
Air pollution
COVID-19 epidemic
Traffic restriction

ABSTRACT

With the outbreak of COVID-19 (Corona Virus Disease, 2019), China adopted traffic restrictions to reduce the spread of COVID-19. Using daily data before and after the outbreak of COVID-19, an exogenous shock, this paper analyzes the effects of private vehicle restriction policies on air pollution. We find that the private vehicle restriction policies reduce the degree of air pollution to a certain extent. However, their effect varies with other policies implemented in the same period and the economic development of the city itself. Through the analysis of different categories of restrictions, we find that restriction policy for local fuel vehicles and the restriction policy based on the last digit of license plate numbers have the best effect in reducing air pollution. Under the background of COVID-19 epidemic and the implementation of private vehicle restriction policies and other traffic control policies during this period, we have also obtained other enlightenment on air pollution control.

1. Introduction

As air pollution has a significantly negative impact on economic development and health (Xu et al., 2013; Hao et al., 2018), scholars begin to pay attention to the ways to control air pollution. Traffic control has always been an important measure to control air pollution (Goddard, 1997; Shahbazi et al., 2014).

After the outbreak of COVID-19, as of February 11, 2020, 44,672 cases have been confirmed (diagnosis based on positive viral nucleic acid test results on throat swab samples) (Pneumonia Emergency Response Epidemiology Team, 2020). We have observed that the COVID-19 outbreak also affects the implementation and effect of normal traffic restriction policies in various regions. Not only have corresponding medical measures been taken in time and effectively, but many nonpharmaceutical interventions, such as travel restriction and public traffic suspension, have also been implemented by governments across different cities of China. The traffic restriction measures during special period create opportunities for studying the impact of traffic restrictions (Zhou et al., 2012; Wang et al., 2016). On the one hand, many studies have confirmed that large-scale city closures and traffic travel restrictions effectively reduce the transmission speed and scale of COVID-19 (Qiu et al., 2020; Chinazzi et al., 2020; Lau et al., 2020). On the other hand, the impact of various traffic control policies, adopted by many local governments after the outbreak of COVID-19, on air pollution has been observed (Wang et al., 2020).

To investigate the impact of the private vehicle restriction policy on air pollution and to find reasonable ways to implement this policy to improve air quality, we estimate the causal impact of private vehicle restriction on air pollution. We use daily data for the days between August 1, 2019 and February 7, 2020 in four provinces that have had the worst outbreaks of COVID-19. Given that these four provinces are the most affected by the COVID-19 epidemic, the subsequent policy changes are minimally affected by other endogenous factors. As the impact of the COVID-19 outbreak is an exogenous event, it gives us an excellent opportunity to study the impact of private vehicle restriction on air pollution. Taking account of six different meteorological factors, we comprehensively analyze the impact of private vehicle restriction policies on air pollution. Using a subsample from November 1 to February 7, we conduct a robustness check. Afterward, we make various heterogeneity analyses, including different restriction motivations, different restriction categories, restriction in different provinces, and restrictions in cities with different populations and economic situations. Based on these results, we speculate other key points of air pollution control that should be given great attention when the traffic control policy is implemented.

* Corresponding author.
** Corresponding author.
E-mail addresses: hongyeczf@163.com (Z. Chen), wjry78694@163.com (X. Hao), 18856026026@163.com (X. Zhang), achenfl@163.com (F. Chen).

https://doi.org/10.1016/j.jclepro.2020.123622
0959-6526/

This study makes three contributions to the existing literature. First, through the regression analysis of different types of private vehicle restrictions, we find the most effective kinds of restriction policies to reduce air pollution. Restrictions should focus on fuel vehicles and local vehicles, and the restriction policy based on the last digit of license plate numbers has a better effect. They significantly induce a 25.6%, 23.7%, and 22.2% reduction in the air quality index (AQI), respectively. Second, given the heterogeneous impact in different provinces, we find that the effects of private vehicle restriction policy are determined by the population size and economic development characteristics of the city. The policy on private vehicle restrictions induces a 32% reduction in the concentration of $PM_{2.5}$ in the cities with a GDP less than 3.6×10^6 million yuan, and a 31.6% reduction in the concentration of $PM_{2.5}$ in the cities with a GDP growth rate less than 7%. Finally, we find that during the epidemic, the effect of the policy varies with the suspension of public transport and the injunction of motor vehicles. This observation enlightens us to pay attention to the optimization of energy used by public transport while encouraging public transport travel and promoting new energy vehicles to replace traditional fuel vehicles.

The remainder of the paper is as follows. Section 2 describes the relevant studies. Section 3 describes the data and econometric methodology. Next section provides the baseline results and robustness check. Section 5 shows the heterogeneity analysis. Section 6 discusses the conclusion of this study.

2. Literature review

The significant impacts of traffic control policies on the decline of air pollution have always been a controversial topic. The effects of such policies may vary with implementation or the method of implementation across different countries or regions.

In China, many studies have confirmed the impact of private vehicle restriction policies on reducing air pollution (Cai et al., 2011; Viard et al., 2015; Ho et al., 2015). As for other countries, some studies have shown that policies on vehicle restriction have not succeeded in reducing air pollution (Davis, 2008; Chowdhury et al., 2017). As we can see, the effect of the restriction policies in China is different than that in other countries. Viard et al. (2015) put forward possible reasons for the success of these policies in China. The compliance of residents is important when the policy is implemented. At the same time, many studies have demonstrated that the timing of restrictions, the implemented way of policies, meteorological factors, and the characteristics of the city influence the effect of air quality improvement (Cheng et al., 2008; Lin et al., 2011). In previous studies, some scholars have also found that the choice of indexes used to determine traffic pollution also affects the result of the studies. In some studies, common air pollutant indexes, such as particulate pollutant concentration or carbon monoxide and nitrogen dioxide, are not a proxy for air pollution. Instead, these studies obtained black carbon measurements as an indicator of the impact of traffic restrictions (Wang et al., 2008; Westerdahl et al., 2009; Invernizzi et al., 2011). Invernizzi et al. (2011) found that compared with the zone without traffic restrictions, black carbon levels have a significant reduction in the zone with traffic restrictions. However, the concentrations of PM_{10}, $PM_{2.5}$, and PM_1 have not changed significantly.

The short-term policy changes caused by special events often enlighten us about the method of policy implementation. In the study of evaluating the impact of the 2008 Olympic Games on air quality, Chen et al. (2013) found that the effect of the restriction policy was also affected by the timing and location of plant closures and traffic control. Currently, some studies have been made on such policies during the COVID-19 epidemic. Comparing the air quality in 2019 and 2020, Cadotte (2020) found that governments have the capability to improve air quality through policy change. Fan et al. (2020) estimated the impact separately caused by the Spring Festival and the COVID-19 containment measures on the atmospheric composition using satellite data and ground-based observations. Some studies have also shown that air pollution is not reduced during this time. Huang et al. (2020) found that given the enhanced secondary pollution during the COVID-19 epidemic, the reduction of primary emissions caused by the policies of lockdown has been offset.

3. Data and methodology

To assess the effect of traffic restriction policies implemented by the government on air pollution during the COVID-19 epidemic in China, we have collected data for the days between August 1, 2019 and February 7, 2020. They include the timing of private vehicle restrictions and the timing of the suspensions of public transport, different air pollutant concentrations, and other types of traffic restriction policies and local meteorology characteristics. We will present the data and describe the econometric methods in this section.

We choose 49 cities from four provinces that have the worst outbreaks of COVID-19. Before the outbreak of COVID-19, some cities have already implemented policies on private vehicle restrictions to improve the traffic structure, and mitigate the traffic pressure during peak hours. Some of these cities have lifted restrictions during official holidays, such as Chinese New Year (January 24, 2020 to February 2, 2020). However, private vehicles are only restricted in some streets and bridges of cities, such as the restriction made by Zhuhai on the Hong Kong-Zhuhai-Macao Bridge, which started on October 24, 2018. Therefore, we have not considered the impact of these policies.

As the outbreak of COVID-19 and its impact, some cities have decided to cancel private vehicle restrictions to reduce public transportation (Some of these cities have extended the cancellation of such policies after the Chinese New Year). Other cities that have serious problems with the epidemic have decided to resume private vehicle restriction in advance to reduce the moving of people. Meanwhile, the remaining cities have never implemented such policies. Appendix Table 2 presents the dates of policy changing.

B. Suspensions of Public Transport

After the outbreak of COVID-19, the local governments of many cities have implemented policies to stop public transport. They have suspended the operations of buses and subways to prevent people from being infected with COVID-19, reduce the gathering of crowds. The buses and subways discussed in this study are in prefecture-level cities, excluding those that run from downtown to counties.

Excluding the special situation of public transport suspension caused by holidays in some areas during the Chinese New Year, we calculate that 19 out of 49 cities have decided to implement policies on public transport suspension because of the spread of the epidemic. In the four provinces with the most serious cases, public transport suspensions have mainly occurred in Hubei and Henan. Nine cities have taken measures to reduce bus and subway shifts by half and have not completely stopped public transportation. Appendix Table 1 presents the dates of suspensions of public transportation and the dates of reducing bus and subway shifts.

C. Air Pollution

Many studies showed that polluted air increases the risk of cardiovascular and respiratory diseases for residents (Matus et al., 2012; Chen et al., 2015; Ebenstein et al., 2017). The exhaust gas produced in the use of automobiles contains hundreds of different compounds, including solid suspension particles, carbon monoxide, carbon dioxide, nitrogen oxides, lead, and sulfur oxides. Thus, we measure the daily air pollution for each city from August 1, 2019 to February 7, 2020 in terms of AQI and six different air pollutant concentrations. The summary statistics on the air pollutant concentration are presented in Table 1. The AQI is an air quality indicator that has been published since March 2012 in China, which includes the monitoring of six pollutants: sulfur dioxide, nitrogen dioxide, PM_{10}, $PM_{2.5}$, carbon monoxide, and ozone. The data are updated every hour. We take the mean of 24-h observations to represents the concentration of each air pollutant every day.

D. Control Variables

As demonstrated by previous study (Li et al., 2019), precipitation and temperature play important roles in the distribution of particulate pollutants, such as $PM_{2.5}$, in Northeast China, and the effect of precipitation on the carbon monoxide (CO) concentration decreases from Southeast China to Northwest China. Cuhadaroglu et al. (1997) also showed that air pollution concentrations have a close relationship with meteorological factors. Thus, we use the relevant meteorological data recorded by the China Meteorological Administration to control the time-varying change of meteorological conditions in every city. They include five indicators: precipitation, atmospheric pressure, relative humidity, temperature, and average wind speed. The summary statistics on meteorology are provided by Table 1.

E. Methodology

Referring to Viard et al. (2015), we add meteorological factors as the control variables. Considering the inconsistency of occurrence time of the policy, we use a multiple-period difference-in-differences (DID) specification to assess the relation between private vehicle restriction and air pollution with the following regression set-up:

$$Y_{st} = \alpha + \beta D_{st} + \delta X_{st} + A_s + B_t + \varepsilon_{st}\ ,\ s = 1, \cdots, 49;\ t = Aug.1, 2019, \cdots, Feb.7, 2020. \quad (1)$$

In Equation (1), Y_{st} is a measure of air pollution in city s at day t. A_s and B_t are the vectors of city and date dummy variables that account for city and date fixed-effects, respectively. X_{st} is the set of time-varying, city-level variables, and ε_{st} is the error term. The variable of interest is D_{st}, a dummy variable that equals 1 in the days after the implementation of the private vehicle restriction policy and equals 0 otherwise. Note that if the policy is canceled because of other reasons after the policy is implemented, D_{st} takes a 0 value after the policy is canceled. The coefficient, β, therefore indicates the impact of private vehicle restrictions on air pollution. A positive and significant β suggests that private vehicle restrictions exert a positive effect on the degree of air pollution, whereas a negative and significant β indicates that private vehicle restrictions push the degree of air pollution lower. In total, we have data for 49 cities. Thus, there are 9307 city-day observations in our empirical analysis.

The DID estimation technique allows us to control for omitted variables. We include day-specific dummy variables to control for trends that shape the degree of air pollution over time, such as the changes in ultraviolet ray intensity, the formation and disappearance of the inversion layer, the working time of most residents, and the lifestyle preference of the local residents. We also include city-specific dummy variables to control for time-invariant, unobserved city characteristics that shape air pollution across cities, such as the geographical characteristics of cities.

4. Baseline results

Our identification depends on the condition that air pollution does not lead to restrictions on traffic. Some cities have been affected by COVID-19 and extended the policy of no restrictions during the Chinese New Year holiday. Other cities have implemented restrictions before the outbreak of COVID-19 in 2018 or even earlier. The timing of the implementation of these policies is difficult to observe statistically. Thus, we select the cities that have implemented policies on private vehicle restriction after the outbreak of the epidemic in this research. Appendix Fig. 1 shows that neither the level of the $PM_{2.5}$ concentration before private vehicle restrictions nor their rate of change prior to the restriction explains the timing of these restrictions.

A. Reduction of AQI and Air Pollution Concentrations Caused by Restriction

In Table 2, we estimate the impact of private vehicle restrictions on air pollution using AQI, the six different air pollutant

Table 1
Summary statistics on values of the air pollution and weather, August 1, 2019—february 7, 2020.

Air Quality Index	Observations	Mean	Min	Max	Std. Dev.
	9307	66.295	11.000	416.208	39.005
Air Pollution					
PM2.5 (μg/m3)	9307	41.897	1.000	385.000	32.374
PM_{10} (μg/m3)	9307	66.866	3.333	456.292	40.311
CO(μg/m3)	9307	0.824	0.159	3.509	0.292
NO_2 (μg/m3)	9307	30.693	2.435	114.083	16.517
SO2(μg/m3)	9307	8.910	2.042	36.000	4.334
O3 (μg/m3)	9307	116.864	4.500	365.696	53.007
Weather					
Average wind speed (0.1 m/s)	9307	20.624	0.000	123.000	10.473
Average temperature (0.1 °C)	9307	178.455	−46.000	338.000	88.257
Mean atmospheric pressure (0.1 hPa)	9307	10061.990	9352.000	10378.000	136.793
Average relative humidity (1%)	9307	73.597	15.000	100.000	14.215
Precipitation (0.1 mm)	9307	31.460	0.000	2891.000	121.256
Private vehicles restriction	9307	0.475	0	1	0.499
Public transport suspension	9307	0.024	0	1	0.155

Notes: Air pollutant concentrations are mean 24 h values for everyday and weather are statistics from the China meteorological administration. Means are across cities (i.e., not weighted). All data are for the period August 1, 2019—February 7, 2020.
A. Private Vehicle Restriction

Table 2
The impact caused by private vehicle restriction on air pollution.

	AQI	$PM_{2.5}$	PM_{10}	CO	NO2	SO2	O3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: No Controls							
Private vehicle restriction	−0.280***	−0.393***	−0.314***	−0.102**	−0.100	−0.103*	−0.132**
	(0.093)	(0.117)	(0.103)	(0.440)	(0.062)	(0.053)	(0.060)
R2	0.478	0.478	0.511	0.377	0.670	0.389	0.530
Observations	9307	9307	9307	9307	9307	9307	9307
Panel B: With Controls							
Private vehicle restriction	−0.266***	−0.369***	−0.289***	−0.101**	−0.094	−0.096*	−0.114*
	(0.091)	(0.113)	(0.098)	(0.044)	(0.062)	(0.053)	(0.060)
Average wind speed	−0.009	0.012	0.030	0.027	0.014	0.052**	0.074*
	(0.023)	(0.036)	(0.022)	(0.053)	(0.040)	(0.026)	(0.041)
Average temperature	−0.039	−0.300**	0.069	−0.077	0.057	0.176**	0.412
	(0.052)	(0.117)	(0.044)	(0.089)	(0.074)	(0.076)	(0.431)
Mean atmospheric pressure	0.077	−0.113*	−0.045	−0.027	0.043	−0.042	−0.123*
	(0.047)	(0.064)	(0.036)	(0.057)	(0.067)	(0.046)	(0.068)
Average relative humidity	0.088	0.451**	0.001	0.113	−0.071	−0.176*	−0.367
	(0.079)	(0.183)	(0.035)	(0.167)	(0.093)	(0.461)	(0.429)
Precipitation	−5.034***	−8.807***	−9.561***	−0.409	−2.189***	−2.795***	−7.197***
	(0.779)	(0.718)	(1.159)	(0.311)	(0.452)	(0.461)	(0.752)
R2	0.448	0.502	0.551	0.377	0.702	0.397	0.555
Observations	9307	9307	9307	9307	9307	9307	9307

Notes: The coefficient estimates and standard errors related to meteorological characteristics are multiplied by 10,000 for readability. All models control for city and day fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

concentrations with two different regression specifications. In Panel A, the regressions simply control for city and date fixed effects. Panel B further includes numerous time-varying, city-specific meteorological characteristics: precipitation, atmospheric pressure, relative humidity, temperature, and average wind speed.

The Panel A results indicate that private vehicle restrictions substantially reduce the degree of air pollution. The private vehicle restriction dummy is negatively and significantly at the 1% level in the regressions of AQI and concentrations of $PM_{2.5}$ and PM_{10}. In addition, it also enters negatively and significantly at the 5% level in the regressions of concentrations of carbon monoxide and ozone, and at the 10% level in the regressions of concentrations of sulfur dioxide. The restrictions also have a negative impact on the concentrations of nitrogen dioxide despite it is not significant. As shown by the results in Panel A, private vehicle restrictions induce a 28% reduction in the AQI, a 39.3% and 31.4% reduction in the concentrations of $PM_{2.5}$ and PM_{10} occur, respectively.

The Panel B results indicate that private vehicle restrictions reduce the level of air pollution even when conditioning on meteorological factors. After controlling for meteorological factors, the absolute value of the coefficient related to private vehicle restriction does not decrease drastically, and it maintains the same significance level as in Panel A. In previous studies, even though we can also observe that the AQI has a reduction after the implementation of the restriction policy, it is not as large as the value in this situation. In the study for the Odd-Even restrictions in Beijing, the aggregate AQI is 18% lower during the restriction (Viard et al., 2015), whereas in our study, the API has a 26.6% reduction. During the COVID-19 epidemic, various public health measures, such as encouraging social distancing in local communities, lockdown of cities, and travel restrictions, have been taken to avoid further infections and deaths (Qiu et al., 2020; Kraemer et al., 2020). Air quality also improves with the reduction of production activities and human mobility. At the same time, the restriction during COVID-19 is stricter, and the compliance of residents is better than usual. Therefore, the AQI decreases more after the private vehicles are restricted during this period.

As the identification in baseline regression results may be affected by sample selection, we symmetrically select samples from two months before and after the appearance of COVID-19 (the end of December 2019) to test the robustness of the results. We select samples from November 1 to February 7 for the robustness test, and the results are shown in Appendix Table 3. The results in Table 2 and Appendix Table 3 are similar, suggesting that our results are not driven by the sample in the normal period.

B. Dynamics of Restriction and Air Pollutant Concentration

We next investigate the dynamics of the relation between private vehicle restriction and air pollution. We include a series of dummy variables in the standard regression to trace out the day by-day effects of private vehicle restrictions on the logarithm of the concentrations of air pollutants:

$$\log(\text{air pollutant})_{st} = \alpha + \beta_1 D_{st}^{-5} + \beta_2 D_{st}^{-4} + \ldots\ldots + \beta_{15} D_{st}^{10} + A_s + B_t + \varepsilon_{st} \quad (2)$$

where the restriction dummy variables, the “D’s,” equal 0, except as follows: D^{-j} equals 1 for cities on the j^{th} day before restriction, while D^{+j} equals 1 for cities on the j^{th} day after restriction. We exclude the day of the private vehicle restriction, thus estimating the dynamic effect of the private vehicle restriction on air pollution relative to the date of the private vehicle restriction. A_s and B_t are the vectors of city and day dummy variables, respectively. At the end points, $D^{-5}{}_{st}$ equals 1 for five days before restriction, while $D^{+10}{}_{st}$ equals 1 for 10 days after the restriction. Thus, great variance exists for these end points, and the estimates may be measured with less precision. After detrending and centering the estimates on the date of restriction (day 0), Fig. 1 plots the results for six catergories of air pollutants with 95% confidence intervals, respectively.

Considering that the policy on private vehicle restrictions may change (temporary cancellation) because of legal holidays, large gatherings or various social activities, we set the research scope at five days before the restriction and 10 days after the restriction. To some extent, this approach reduces the impact of other policy changes and social activities on the dynamic effect caused by the policy on private vehicle restrictions over a long timeline.

Fig. 1 illustrates the results for $PM_{2.5}$ and PM_{10}, the decrease tendency in the air pollutant concentrations has preceded private vehicle restrictions. However, for other air pollutants, the impact of

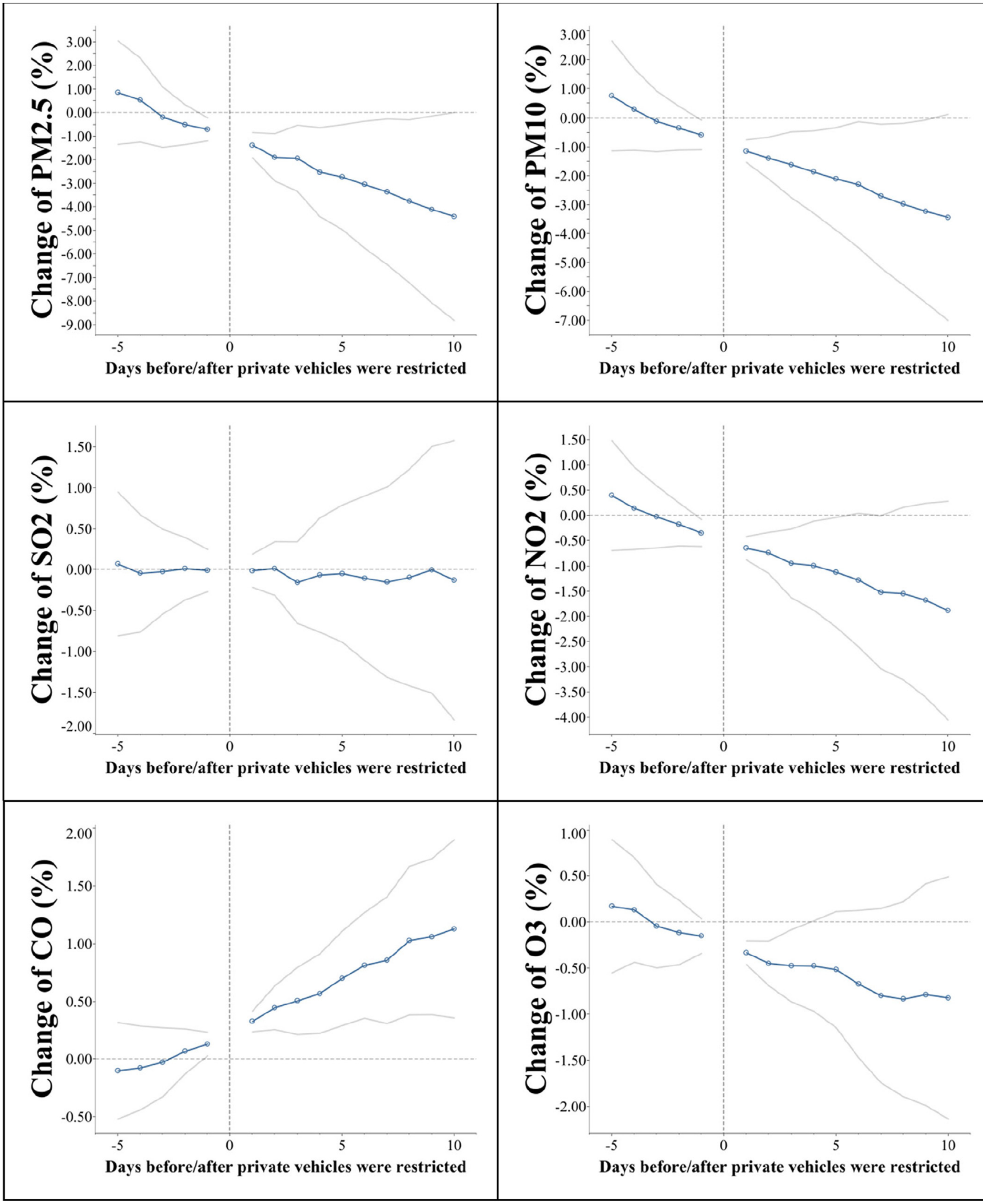


Fig. 1. The Dynamic Impact Caused by Private Vehicles Restriction. on the Natural Logarithm of Air Pollutant Concentration. Notes: We consider a 15-days window, spanning from 5 days before policy implementation until 10 days after policy implementation. The light gray lines represent 95% confidence intervals.

private vehicle restrictions on air pollution does not materialize very quickly. Next, we find that after the implementation of restriction policies, the change tendency of $PM_{2.5}$ concentrations is sharper than the concentrations of PM_{10}. The coefficients on the dummy variables for private vehicle restrictions are insignificant for all days before the implementation of policies. However, we have reason to speculate that the effect of this policy is influenced by other policies and other changes in the life of residents because of the trends in the change of concentration of pollutants prior to private vehicle restrictions.

5. Heterogeneity analysis

A. Regular Restriction and the One Caused by COVID-19.

According to whether the city has strictly restricted the movement and large-scale gathering of residents during the COVID-19 epidemic (this information comes from government documents and news reports), we divide the restriction into conventional restriction and the restriction caused by COVID-19. If the two conditions of prohibiting aggregation and private vehicle restriction are met at the same time, we consider that the policy is affected by COVID-19. Cities that have implemented policies because of COVID-19 include Xinyang, Zhumadian, Wuhan, Huangshi, Shiyan, Yichang, Xiangyang, Jingmen, Xiaogan, Jingzhou, Huanggang, and Wenzhou. We have made further regression analysis on their respective policy effects. The results are shown in Appendix Table 4.

From Appendix Table 4, we can find that the restriction policy during the COVID-19 epidemic has a significant effect on air pollution. The private vehicle restriction caused by COVID-19 induces a 22.4% reduction in the AQI and significantly at the 5% level. Compared with the regular restrictions, policies during the COVID-19 epidemic are affected by few endogenous factors and have stringent control mechanisms.

B. Impact Caused by Different Restriction Categories

The implementations of different kinds of private vehicle restriction policies are often accompanied by different kinds of original intention, such as reducing traffic pressure, controlling air pollution, and reducing travel during the epidemic. Therefore, we discuss the impact of the different kinds of private vehicle restriction policies on air pollution in three ways, with seven categories. Appendix Table 5 presents all the regression results and the differences among several different private vehicle restrictions.

Compared with other categories of restriction, the restrictions on local vehicles and fuel vehicles have a greater and more significant negative impact on air pollution. Both of them are significant in the impact on the concentration of $PM_{2.5}$, with a 34.7% and a 36% reduction, respectively. From Appendix Table 5, compared with other categories of restriction policy, the restriction for local vehicles based on the last digit of license plate numbers, the restriction for fuel vehicles, and the policy on the injunction of vehicles cause a negative impact on air pollution with great degree. These three categories of restriction policies all reduce the AQI, and we can see that compared with other air pollutants, the concentrations of $PM_{2.5}$ and PM_{10} and the particulate pollutants, have more significantly reduced. In Appendix Table 5, special attention should be paid to the fact that the implementation of the injunction of vehicles during the COVID-19 epidemic has a large negative impact on the concentration of five pollutants except on the ozone. Considering the sample size, we think that given the short implementation time and the data are only available in a few cities mainly in Hubei Province, the results do not reach the significance level of 5%.

Next, we compare the different categories of restriction policies in different classification methods. First, for the restrictions based on the ownership area of private vehicles, we can clearly observe that the impact caused by the restrictions of local vehicles on air pollution is evidently more significant and greater than that of the restrictions of nonlocal vehicles. However, the restrictions of nonlocal vehicles do not have a significant negative impact on air pollution. This kind of restriction policies even has a significant positive impact on the concentration of some pollutants. At the same time, through the observation of policy documents, we find that the policies to control environmental pollution, energy conservation, and emission reduction usually focus on the restriction of local vehicles. As for the policies to alleviate traffic pressure and reduce urban road congestion, nonlocal vehicles are usually added to the restriction scope in some cities. In some cases, only nonlocal vehicles are restricted.

In the restriction policies based on the tail number of license plates, the restricted license plates include temporary license plates, and vehicles with tail number of letters are treated as 0. For the restrictions based on specific license plate numbers, we can find that the restrictions based on the last digit of license plate numbers have the best result. The policies of private vehicle restriction based on even- and odd-numbered license plates do not have a significant impact on air pollution. The rules on private vehicle restrictions based on even- and odd-numbered license plates are as follows. On even-numbered days, only private vehicles with even numbers at the end of their license plates can be driven on the road. On odd-numbered days, only private vehicles with odd numbers at the end of their license plates can go on the road. However, another kind of private vehicle restriction policy usually only allows private vehicles with a tail number of two especially designated figures to drive on the road on the same day. Evidently, the private vehicle restriction based on the last digit of license plate numbers restricts more vehicles, and our results from the regression also confirm their enhanced effects.

Finally, for the policies of restriction based on the kind of energy used by vehicles, we can observe that the regression results related to the restrictions of fuel vehicles and the restrictions of plug-in hybrid electric and electric vehicles show a very evident polarization. The private vehicle restrictions of fuel vehicles have a significant negative impact on the degree of air pollution. In contrast, the restrictions of plug-in hybrid electric and electric vehicles have a significant positive impact on the degree of air pollution. The results of Appendix Table 5 suggest that the restrictions of plug-in hybrid electric and electric vehicles induce a 28.7%, 43.2%, and 36.8% increment in the concentrations of PM_{10}, nitrogen dioxide, and ozone, respectively, at the 1% significant level.

C. Heterogeneous Impact in Different Provinces

On the basis of the regression results of meteorological control factors on the impact of air pollution in Table 2, we can conclude that due to the geographical environment and meteorological factors, the degree of air pollution in coastal cities with high precipitation, such as Zhejiang and Guangdong, is lower than that in inland cities, such as Hubei and Henan. Combined with the main measures taken by Guangzhou and Shenzhen in the policies of private vehicle restriction, we can speculate a large flow of nonlocal vehicles and heavy traffic pressure in Guangzhou and Shenzhen.

We have made a regression analysis on the effect of the private vehicle restriction policies of four provinces on air pollution. The regressions are conditioned on city and date fixed effects, and they include numerous time-varying, city-specific meteorological characteristics. The regression results can be seen in Appendix Table 6. We find that, in addition to Hubei Province, the private vehicle restriction policies in three provinces have a certain degree of positive impact on air pollution. This phenomenon is more significant in two provinces, Guangdong and Zhejiang, with higher economic levels than other cities discussed in this study. The private vehicle restriction policy on air pollution in Guangdong Province has the most positive impact. The implementation of the vehicle restriction policies induces a 9.6%, 11.1%, 16.9%, 31.1%, and 5.1% increment in the concentrations of $PM_{2.5}$, PM_{10}, carbon monoxide, nitrogen dioxide, and sulfur dioxide, respectively, at the 1% significant level in Guangdong. In contrast, the implementation of the private vehicle restriction policy in Hubei has a significant negative impact on air pollution. The implementation of the private vehicle restriction policies induce a 23%, 17.1%, and 17% reduction in the concentrations of $PM_{2.5}$, PM_{10}, and sulfur dioxide, respectively, in Hubei, and all of these coefficients are significant at the 5% level. At the same time, the AQI also has a significant reduction.

In the three provinces, the positive impact of private vehicle restriction policies on air pollution is inconsistent with the regression result in Table 2. These policies can reduce the concentration of air pollutants significantly. Therefore, we further analyze another traffic control policy implemented during the COVID-19 epidemic: the suspension of public transport. In Appendix Table 6, we also assess the impact of the suspension of public transport on air pollution using AQI and the six different indicators for air pollutant concentrations.

In addition to Guangdong Province, which does not implement the policy on public transport suspension during the COVID-19 epidemic, the policy on public transport suspension adopted due to the outbreak of COVID-19 has a certain degree of negative impact on air pollution regardless of which province, and this impact is most significant in Hubei Province. Among them, the most evident effect can be observed on the change of the concentration of $PM_{2.5}$. The implementation of public transport suspension policies induces a 41.4% reduction in the concentrations of $PM_{2.5}$ in Hubei, which is significant at the 1% level. In Fig. 2, we examine the dynamics of the relation between public transport suspension and air pollution by the same measure as we assess dynamics of private vehicle restriction policies. Similar to Fig. 1, we can find that the impact caused by the policies on $PM_{2.5}$ and PM_{10} are more significant than that on other air pollutants. Private vehicle restriction and public transport suspension do not have much effect on the ozone. We speculate that this result is due to the complex formation of the ozone and its various precursor pollutants. Most coefficients on the dummy variables of public transport suspension are insignificant for all days before the implementation of the policy with no evident trends in the change of the pollutant concentration prior to public transport suspension. The impact of public transport suspension on air pollution grows for approximately 5–6 days after the implementation of the policy, and then the effect levels off. At the same time, we can find that the degree of the reduction of pollutant concentration in Fig. 1 is higher than that in Fig. 2. The policy on public transport suspension has impacts air pollution, but the results of the impact caused by private vehicle restriction on air pollution are not driven by it.

D. Heterogeneity Analysis for Population Size and Economic Development

To delve into the impact of private vehicle restriction policies on air pollution in different cities with different population sizes and economic developments, we conduct different regression for 49 cities on the basis of the total population at the end of year, GDP, and GDP growth rate. The results are shown in Appendix Table 7.

The results in Appendix Table 7 indicate there is no significant difference in the effect of private vehicle restriction policies in cities with different population sizes. In contrast, in cities with different levels of economic growth, significant differences are observed in the effect of the restriction policies, which are reflected in the two indicators of gross regional product and gross regional product growth rate. We find that the restriction policies of private vehicles have a significant impact on air pollution in the cities with low economic development levels. In the cities whose gross regional product is less than 3.6×10^6 million yuan, the implementation of the vehicle restriction policies induces a 23.6%, 32%, and 26% reduction in the concentrations of AQI, $PM_{2.5}$, and PM_{10}, respectively, at the 5% significant level. However, the results for the cities whose gross regional product are more than 3.6×10^6 million yuan show that the policies on private vehicle restrictions have no significant negative impact on the concentration of various pollutants. From the previous research, we can also see that GDP and private vehicles are significant positive factors for $PM_{2.5}$ (Zhao et al., 2018). Many other studies have also indicated that production activities are the main reason for the pollution problems in China (Liang et al., 2017; Zhao et al., 2019).

In combination with the specific implementation of the policies in Appendix Table 1, we find that in Guangdong Province, not only has the public transport suspension policy been implemented during the COVID-19 epidemic, but very few cities have also adopted the private vehicle restriction policy because of the epidemic after the outbreak of COVID-19. This feature is evidently different from the other three provinces. In such case, Guangdong Province, which shows the abnormal impact of the private vehicle restriction policy on the regression results, is mainly affected by the private vehicle restriction policies from the cities that have implemented them before the outbreak of the epidemic: Guangzhou and Shenzhen. From what has been discussed above, in combination with the regression result in Appendix Table 7, the restriction policy has little effect on cities with high economic level. The reasons why the policy on private vehicle restrictions does not reduce the air pollution in this area are clear. Moreover, its implementation is associated with serious air pollution. Compared with other cities in the same province, Guangdong and Shenzhen have significantly higher GRP, and we can speculate that they also have more people flow, vehicle flow, and traffic pressure, which also cause more vehicle exhaust emissions in the area. Even with the implementation of private vehicle restriction policies, they have not been able to result in lower levels of air pollution than other cities. Even its degree of air pollution is far higher than that in other cities in the same province, such as Shanwei and Shantou.

6. Conclusions

On the basis of daily data for the days between August 1, 2019 and February 7, 2020, we analyze the changes in private vehicle restriction policies and their impact on air pollution before and after the outbreak of COVID-19. We find that private vehicle restriction is a feasible policy for the improvement of air quality. However, its effect is determined by the economic development characteristics of the city. Different categories of the restriction may have various effects. The regression results show that the private vehicle restriction policies have a significant negative effect on air pollution during this period. However, the impact is also affected by the public transportation suspension policy and the reduction of human mobility and production activities in this period. Thus, we cannot blindly believe that the improvement of air quality in this period is entirely due to the restriction policy. Although these changes and policies are only temporary, and they may not continue to affect air pollution in the future, this study still enlightens us on the ways to implement private vehicle restriction policies in the future.

First, in areas with slow economic growth, private vehicle restrictions offer opportunities to produce good effects. If private vehicle restrictions are implemented in cities with rapid economic development, they do not significantly reduce the degree of air pollution due to the large traffic flow and severe traffic pressure in these cities. Instead, given that these policies are often designed to

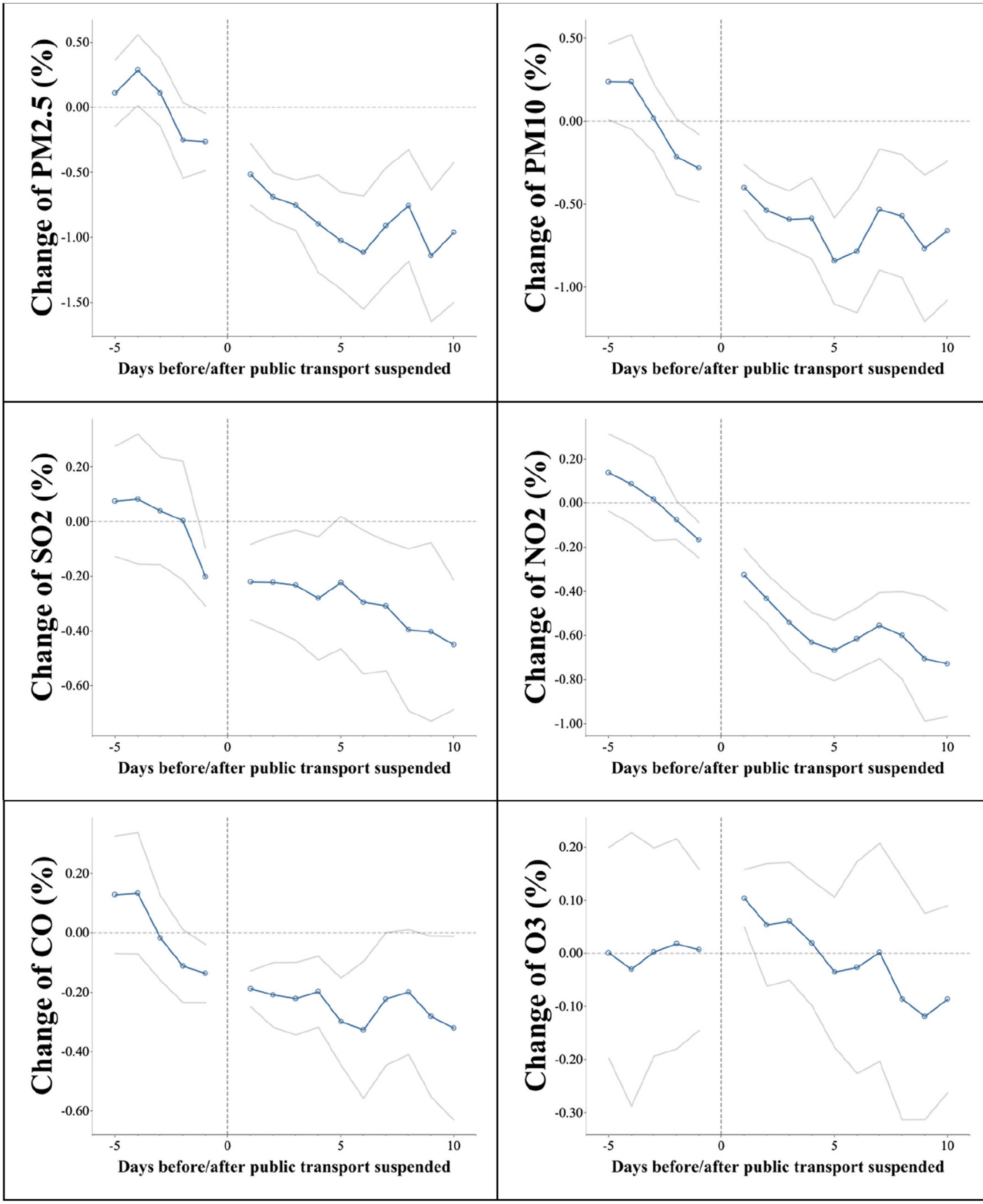


Fig. 2. The Dynamic Impact Caused by Suspension of Public Transport on the Natural Logarithm of Air Pollutant Concentration. *Notes:* We consider a 15-days window, spanning from 5 days before policy implementation until 10 days after policy implementation. The light gray lines represent 95% confidence intervals. And we report estimated coefficients by the same regression algorithm as in Fig. 1.

ease traffic congestion, their implementation is often a sign that the region has more traffic flow and air pollution than other regions. Second, we should focus on the restrictions on local vehicles and fuel vehicles and adopt private vehicle restriction policies based on the last digit of license plate numbers. If the implementation of private vehicle restriction policies is mainly to ease the traffic pressure of cities, their impact on air pollution is often not as significant as those that have been originally implemented to reduce air pollution and improve environmental quality. Finally, to control air pollution effectively, the use of fuel-powered vehicles should be reduced, and vehicles that use new energy should be promoted to replace traditional fuel-powered vehicles. While encouraging residents to use public transport to travel, we should also pay attention to the improvement of the energy used by vehicles for public transport.

This study also enlightens us that whether the use of new energy vehicles can effectively reduce air pollution, the different impacts of different travel modes such as public transport, subway and private vehicles on air pollution, and the impact of residents' compliance degree on the traffic restriction effect will attract more attention in the future.

CRediT authorship contribution statement

Zhongfei Chen: Conceptualization, Supervision, Project administration, Funding acquisition. **Xinyue Hao:** Writing - review & editing, Software, Writing - original draft, Visualization, Formal analysis. **Xiaoyu Zhang:** Methodology, Data curation. **Fanglin Chen:** Methodology, Software, Validation.

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.

Acknowledgements

We thank the support provided by the National Natural Science Foundation of China (NSFC) [Grant No. 71704065], the Natural Science Foundation of Guangdong Province of China [Grant No.2020A151501226] and the Fundamental Research Funds for the Central Universities-Ningjingzhiyuan Project of Jinan University [19JNQM21].

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.123622.

Appendix Table 1
Timing of Private Vehicle Restriction and Suspension of Public Transport

City	Province	Private vehicle restriction		Suspension of Public Transport
		Before the outbreaks of COVID-19	After the outbreaks of COVID-19	
Zhengzhou	Henan	Restricted	February 3, 2020 Cancel	January 27, 2020 (reduce)
Kaifeng	Henan	Restricted	February 3, 2020 Cancel	January 27, 2020
Luoyang	Henan	Restricted	February 3, 2020 Cancel	
Anyang	Henan	Restricted	February 3, 2020 Restricted	January 27, 2020
Xinxiang	Henan	Restricted	February 5, 2020 Cancel	January 28, 2020 (reduce)
Xuchang	Henan	Restricted	February 3, 2020 Cancel	January 26, 2020
Sanmenxia	Henan	Partial restricted	not Restricted	January 28, 2020
Nanyang	Henan	Partial restricted	February 1, 2020 Restricted	January 24, 2020
Shangqiu	Henan			January 28, 2020
Xinyang	Henan	Partial restricted	February 3, 2020 Restricted	January 26, 2020
Zhumadian	Henan	Restricted	February 3, 2020 Restricted	
Wuhan	Hubei	Restricted	January 26, 2020 Restricted	January 24, 2020
Huangshi	Hubei		January 27, 2020 Restricted	January 24, 2020
Shiyan	Hubei		January 27, 2020 Restricted	January 24, 2020
Yichang	Hubei		January 25, 2020 Restricted	January 24, 2020
Xiangyang	Hubei		January 31, 2020 Restricted	January 25, 2020 (reduce)
Jingmen	Hubei		February 2, 2020 Restricted	January 24, 2020
Xiaogan	Hubei		January 30, 2020 Restricted	January 24, 2020
Jingzhou	Hubei		February 3, 2020 Restricted	January 24, 2020
Huanggang	Hubei		January 31, 2020 Restricted	January 24, 2020
Suizhou	Hubei		February 4, 2020 Restricted	January 24, 2020
Guangzhou	Guangdong	Restricted	February 3, 2020 Cancel	
Shaoguan	Guangdong			
Shenzhen	Guangdong	Restricted	February 3, 2020 Cancel	
Zhuhai	Guangdong	Partial restricted		
Shantou	Guangdong			
Jiangmen	Guangdong	Partial restricted		
Zhanjiang	Guangdong			
Maoming	Guangdong			
Zhaoqing	Guangdong		February 7, 2020 Restricted	
Huizhou	Guangdong	Partial restricted		
Meizhou	Guangdong			
Shanwei	Guangdong			
Heyuan	Guangdong			
Yangjiang	Guangdong			
Qingyuan	Guangdong			
Dongguan	Guangdong	Partial restricted		
Zhongshan	Guangdong			
Yunfu	Guangdong			
Hangzhou	Zhejiang	Restricted	January 23, 2020 Cancel	February 3, 2020

(continued on next page)

Appendix Table 1 (*continued*)

City	Province	Private vehicle restriction		Suspension of Public Transport
		Before the outbreaks of COVID-19	After the outbreaks of COVID-19	
Ningbo	Zhejiang	Restricted	January 17, 2020 Cancel	January 28, 2020 (reduce)
Wenzhou	Zhejiang		February 5, 2020 Restricted	January 29, 2020 (reduce)
Jiaxing	Zhejiang			January 25, 2020 (reduce)
Huzhou	Zhejiang			February 6, 2020 (reduce)
Shaoxing	Zhejiang			
Jinhua	Zhejiang		February 3, 2020 Restricted	February 3, 2020 (reduce)
Zhoushan	Zhejiang			January 30, 2020 (reduce)
Taizhou	Zhejiang		February 5, 2020 Restricted	January 23, 2020
Lishui	Zhejiang			February 5, 2020

Notes: The table shows the restriction on private vehicles and suspension of public transport in 49 cities from 4 provinces which have the worst outbreaks of COVID-19. Cities will lift restrictions during the Chines New Year holiday (January 24, 2020 to February 2, 2020). Due to the impact of the COVID-19, some cities decided to cancel private vehicle restriction to reduce the number of people who will choice public transport, and some cities with more severe epidemics decided to resume private vehicle restriction in advance, in order to reduce the number of people going out. As for suspension of public transport, some cities just reduce partial public transport. A blank indicates that the relevant policy has not been implemented.

Appendix Table 2
Types of Private Vehicle Restriction in Different Cities

City	Province	Specific Region		Specific License Plate Number			Energy Using by Vehicle	
		Non-Local Vehicles	Local Vehicles	Even- and Odd- Number	The Last Digit of License Plates	Injunction of Vehicles	Fuel	Plug-in Hybrid Electric and Electric
Zhengzhou	Henan	Y	Y		Y		Y	Y
Kaifeng	Henan	Y	Y		Y		Y	
Luoyang	Henan	Y	Y		Y		Y	
Anyang	Henan	Y	Y		Y		Y	
Xinxiang	Henan	Y	Y		Y		Y	
Xuchang	Henan	Y			Y	Y	Y	
Sanmenxia	Henan	Y	Y	Y			Y	
Nanyang	Henan	Y	Y		Y		Y	Y
Shangqiu	Henan							
Xinyang	Henan	Y	Y	Y		Y	Y	
Zhumadian	Henan	Y	Y		Y		Y	
Wuhan	Hubei	Y	Y	Y		Y	Y	Y
Huangshi	Hubei	Y	Y	Y			Y	
Shiyan	Hubei	Y	Y			Y	Y	
Yichang	Hubei	Y	Y			Y	Y	
Xiangyang	Hubei	Y	Y			Y	Y	
Jingmen	Hubei	Y	Y			Y	Y	
Xiaogan	Hubei	Y	Y	Y			Y	Y
Jingzhou	Hubei	Y	Y			Y	Y	Y
Huanggang	Hubei	Y	Y	Y			Y	
Suizhou	Hubei	Y	Y	Y			Y	
Guangzhou	Guangdong	Y					Y	
Shaoguan	Guangdong							
Shenzhen	Guangdong	Y					Y	Y
Zhuhai	Guangdong							
Shantou	Guangdong							
Jiangmen	Guangdong							
Zhanjiang	Guangdong							
Maoming	Guangdong							
Zhaoqing	Guangdong	Y	Y	Y			Y	
Huizhou	Guangdong	Y		Y			Y	
Meizhou	Guangdong							
Shanwei	Guangdong							
Heyuan	Guangdong							
Yangjiang	Guangdong							
Qingyuan	Guangdong							
Dongguan	Guangdong							
Zhongshan	Guangdong							
Yunfu	Guangdong							
Hangzhou	Zhejiang	Y	Y		Y		Y	Y
Ningbo	Zhejiang	Y	Y	Y			Y	
Wenzhou	Zhejiang							
Jiaxing	Zhejiang							
Huzhou	Zhejiang							
Shaoxing	Zhejiang							
Jinhua	Zhejiang	Y	Y			Y	Y	
Zhoushan	Zhejiang							
Taizhou	Zhejiang	Y	Y			Y	Y	
Lishui	Zhejiang							

Notes: The table shows the different types of restriction on private vehicles in 49 cities from 4 provinces. Injunction of Vehicles was taken during the outbreak of COVID-19. A blank indicates that the relevant policy has not been implemented. Specially, Guangzhou's restriction policy of driving for up to 4 consecutive days and Shenzhen's traffic restriction for non local vehicles on specific road sections are not specifically reflected in the table. So it is explained here.

Appendix Table 3
Robustness Check

	AQI	$PM_{2.5}$	PM_{10}	CO	NO2	SO2	O3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Private vehicle restriction	−0.120*	−0.186**	−0.149**	−0.044	−0.100*	−0.078*	−0.136
	(0.063)	(0.077)	(0.073)	(0.034)	(0.055)	(0.044)	(0.086)
R2	0.352	0.372	0.512	0.315	0.759	0.439	0.506
Observations	4851	4851	4851	4851	4851	4851	4851
Weather Control	Y	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y	Y	Y

Notes: The table shows the impact caused by private vehicle restriction on the natural logarithm of the AQI (Air Quality Index) and the natural logarithm of the different air pollutant concentrations. The number of observations is 4851, from 49 cities, for the days between November 1, 2019 and February 7, 2020. All models control for city and day fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

Appendix Table 4
Conventional restriction and the one caused by the COVID-19

	AQI	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Conventional restriction	−0.044	−0.108	−0.089	−0.037	−0.038	−0.048	−0.046
	(0.086)	(0.110)	(0.092)	(0.041)	(0.067)	(0.062)	(0.068)
R^2	0.523	0.576	0.591	0.567	0.771	0.459	0.717
Observations	3228	3228	3228	3228	3228	3228	3228
Restriction caused by the COVID-19	−0.224**	−0.382*	−0.368**	−0.294**	−0.230*	−0.033	−0.021
	(0.091)	(0.178)	(0.152)	(0.130)	(0.121)	(0.063)	(0.065)
R^2	0.705	0.747	0.740	0.529	0.798	0.520	0.827
Observations	2090	2090	2090	2090	2090	2090	2090
Weather Control	Y	Y	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y	Y	Y

Notes: The observations do not contain control group. All models control for city and day fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

Appendix Table 5
The Impact Caused by Different Restriction Categories on Air Pollution

	AQI	PM2.5	PM10	CO	NO_2	SO_2	O_3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Specific Region							
Non-Local Vehicles	0.001	−0.043	0.026	−0.008	0.127*	−0.024	0.093
	(0.119)	(0.106)	(0.132)	(0.053)	(0.073)	(0.064)	(0.085)
R^2	0.523	0.539	0.605	0.426	0.689	0.479	0.515
Observations	4369	4369	4369	4369	4369	4369	4369
Local Vehicles	−0.256***	−0.347***	−0.281***	−0.063	−0.071	−0.135**	−0.010
	(0.081)	(0.101)	(0.097)	(0.044)	(0.067)	(0.052)	(0.066)
R^2	0.434	0.505	0.510	0.373	0.701	0.394	0.528
Observations	8737	8737	8737	8737	8737	8737	8737
Panel B: Specific License Plate Number							
Even and Odd Number License Plates	−0.117	−0.185	−0.102	0.038	0.064	−0.019	0.007
	(0.108)	(0.120)	(0.126)	(0.042)	(0.083)	(0.050)	(0.109)
R^2	0.468	0.496	0.557	0.367	0.689	0.412	0.489
Observations	5623	5623	5623	5623	5623	5623	5623
The Last Digit of License Plates Numbers	−0.222**	−0.318**	−0.238**	−0.076	−0.006	−0.176**	−0.237**
	(0.104)	(0.139)	(0.110)	(0.053)	(0.068)	(0.066)	(0.097)
R^2	0.451	0.490	0.537	0.389	0.685	0.429	0.492
Observations	5660	5660	5660	5660	5660	5660	5660
Injunction of Vehicles	−0.212	−0.418*	−0.347*	−0.090	−0.181	−0.097	0.042
	(0.128)	(0.201)	(0.178)	(0.078)	(0.140)	(0.109)	(0.046)
R^2	0.586	0.613	0.618	0.555	0.805	0.512	0.695
Observations	1633	1633	1633	1633	1633	1633	1633
Panel C: Energy Using by Vehicle							
Fuel Vehicle	−0.237**	−0.360***	−0.270**	−0.080*	−0.058	−0.092*	−0.077
	(0.096)	(0.119)	(0.106)	(0.045)	(0.065)	(0.050)	(0.062)
R^2	0.430	0.475	0.507	0.373	0.700	0.385	0.509
Observations	7978	7978	7978	7978	7978	7978	7978
Plug-in Hybrid Electric and Electric Vehicle	0.136	0.093	0.287***	0.117**	0.432***	0.083	0.368***
	(0.100)	(0.137)	(0.082)	(0.049)	(0.077)	(0.137)	(0.034)
R^2	0.523	0.535	0.600	0.421	0.689	0.479	0.515
Observations	3609	3609	3609	3609	3609	3609	3609

Notes: Robust standard errors are reported in parentheses. All specifications control for city and day fixed effects and do not include other control variables. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

Appendix Table 6
The Impact Caused by Private Vehicles Restriction and Suspension of Public Transport on Air Pollution in Different Provinces

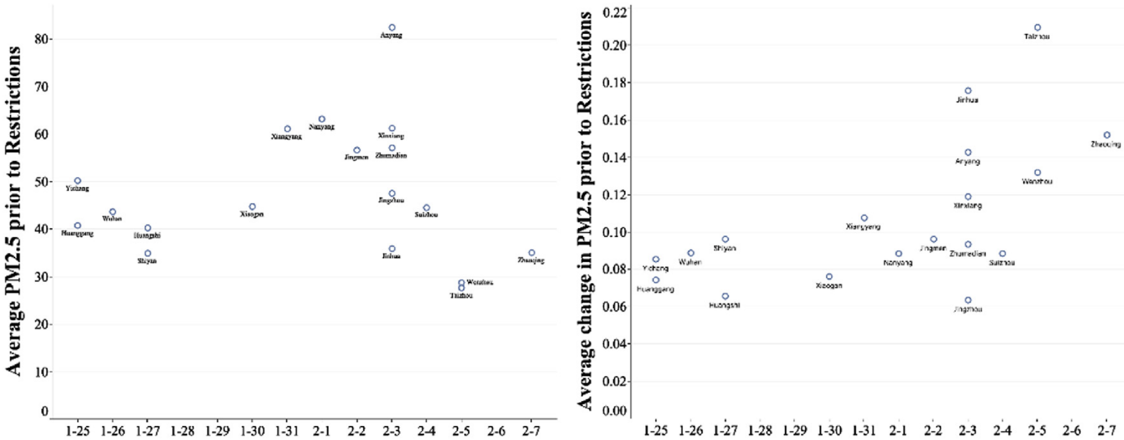
	AQI	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Hubei							
Private vehicle restriction	−0.135**	−0.230***	−0.171***	0.042	0.005	−0.170*	−0.030
	(0.063)	(0.077)	(0.059)	(0.048)	(0.079)	(0.091)	(0.057)
R^2	0.725	0.774	0.788	0.540	0.698	0.395	0.868
Observations	1710	1710	1710	1710	1710	1710	1710
Suspension of Public Transport	−0.359***	−0.414***	−0.270***	−0.141***	−0.240***	−0.411***	0.004
	(0.065)	(0.080)	(0.062)	(0.050)	(0.082)	(0.094)	(0.060)
R^2	0.729	0.776	0.781	0.542	0.700	0.401	0.868
Observations	1710	1710	1710	1710	1710	1710	1710
Panel B: Henan							
Private vehicle restriction	−0.006	0.021	0.065***	0.051***	0.071***	−0.004	0.036***
	(0.015)	(0.019)	(0.018)	(0.017)	(0.016)	(0.024)	(0.012)
R^2	0.792	0.821	0.789	0.549	0.710	0.324	0.869
Observations	2278	2278	2278	2278	2278	2278	2278
Suspension of Public Transport	−0.044	−0.053	−0.057	−0.183***	−0.136***	−0.180***	−0.001
	(0.040)	(0.050)	(0.043)	(0.045)	(0.042)	(0.064)	(0.033)
R^2	0.792	0.821	0.781	0.583	0.709	0.327	0.869
Observations	2278	2278	2278	2278	2278	2278	2278
Panel C: Guangdong							
Private vehicle restriction	0.047***	0.096***	0.111***	0.169***	0.311***	0.051**	−0.032**
	(0.014)	(0.018)	(0.016)	(0.010)	(0.024)	(0.020)	(0.014)
R^2	0.716	0.723	0.769	0.509	0.525	0.385	0.664
Observations	3420	3420	3420	3420	3420	3420	3420
Panel D: Zhejiang							
Private vehicle restriction	0.043***	0.074***	0.029	0.080***	0.290***	0.168***	0.013
	(0.015)	(0.023)	(0.018)	(0.012)	(0.020)	(0.016)	(0.015)
R^2	0.730	0.703	0.770	0.590	0.738	0.495	0.799
Observations	1899	1899	1899	1899	1899	1899	1899
Suspension of Public Transport	−0.015	−0.026	0.016	−0.005	−0.400***	−0.369***	0.001
	(0.058)	(0.088)	(0.070)	(0.047)	(0.081)	(0.063)	(0.058)
R^2	0.729	0.702	0.757	0.547	0.710	0.474	0.798
Observations	1899	1899	1899	1899	1899	1899	1899

Notes: Robust standard errors are reported in parentheses. All specifications control for city and day fixed effects and do not include other control variables.*, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

Appendix Table 7
Impact Caused by Restriction Policy on Air Pollution in Cities with Different Population size and Economic Development

	AQI	$PM_{2.5}$	PM_{10}	CO	NO_2	SO_2	O_3
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Total Population at the End of Year (10,000)							
Population≧520	−0.107	−0.175*	−0.147	−0.095	−0.015	−0.086	−0.120
	(0.071)	(0.096)	(0.097)	(0.060)	(0.075)	(0.051)	(0.080)
R^2	0.512	0.578	0.591	0.475	0.733	0.418	0.729
Observations	4368	4368	4368	4368	4368	4368	4368
Population<520	−0.013	−0.053	−0.034	0.020	−0.017	−0.033	−0.040
	(0.087)	(0.106)	(0.097)	(0.037)	(0.072)	(0.054)	(0.145)
R^2	0.450	0.499	0.561	0.387	0.718	0.415	0.533
Observations	4939	4939	4939	4939	4939	4939	4939
Panel B: GDP (100 million yuan)							
GDP≧3600	−0.001	−0.089	−0.049	−0.109	−0.047	−0.020	0.II8
	(0.081)	(0.112)	(0.105)	(0.070)	(0.092)	(0.067)	(0.084)
R^2	0.485	0.547	0.619	0.378	0.782	0.525	0.713
Observations	2848	2848	2848	2848	2848	2848	2848
GDP<3600	−0.236**	−0.320**	−0.260**	−0.040	−0.081*	−0.067	−0.146*
	(0.099)	(0.123)	(0.098)	(0.044)	(0.043)	(0.058)	(0.081)
R^2	0.457	0.512	0.540	0.496	0.689	0.374	0.547
Observations	6459	6459	6459	6459	6459	6459	6459
Panel C: GDP growth rate (%)							
GDP growth rate≧7%	−0.026	−0.072	−0.056	−0.005	−0.018	−0.020	−0.019
	(0.094)	(0.122)	(0.104)	(0.049)	(0.079)	(0.067)	(0.103)
R^2	0.454	0.509	0.564	0.359	0.706	0.525	0.577
Observations	5130	5130	5130	5130	5130	5130	5130
GDP growth rate < 7%	−0.215*	−0.316**	−0.265**	−0.112*	−0.068	−0.067	−0.145
	(0.105)	(0.132)	(0.124)	(0.064)	(0.063)	(0.058)	(0.096)
R^2	0.459	0.521	0.550	0.491	0.734	0.374	0.663
Observations	4177	4177	4177	4177	4177	4177	4177

Notes: Robust standard errors are reported in parentheses. Meteorological factors are the control variable. In Panels A–C the observations correspond to three different classifications: total population at the end of year, GDP, and GDP growth rate.The discontinuity point is selected by referring to the mean value of each index. All models control for city and day fixed effects. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.



Notes: These figures are for cities that have adopted policies after the outbreak outbreaks of COVID-19. Figure (A) shows a scatter plot of the average PM2.5 concentration of air pollution prior to private vehicles restriction and the date of private vehicles restriction. Figure (B) shows a scatter plot of the average change in the PM2.5 concentration of air pollution prior to private vehicles restriction and the date of private vehicles restriction.

Appendix Fig. 1. Timing of Private Vehicle Restriction and Previous pollution measured by $PM_{2.5}$ Concentration. *Notes:* These figures are for cities that have adopted policies after the outbreak outbreaks of COVID-19. Figure (A) shows a scatter plot of the average $PM_{2.5}$ concentration of air pollution prior to private vehicles restriction and the date of private vehicles restriction. Figure (B) shows a scatter plot of the average change in the $PM_{2.5}$ concentration of air pollution prior to private vehicles restriction and the date of private vehicles restriction.

References

Cadotte, M., 2020. Early evidence that COVID-19 government policies reduce urban air pollution. Down Earth.

Cai, H., Xie, S., 2011. Traffic-related air pollution modeling during the 2008 Beijing Olympic Games: the effects of an odd-even day traffic restriction scheme. Sci. Total Environ. 409 (10), 1935–1948.

Chen, G., Wan, X., Yang, G., Zou, X., 2015. Traffic-related air pollution and lung cancer: a meta-analysis. Thoracic cancer 6 (3), 307–318.

Chen, Y., Jin, G.Z., Kumar, N., Shi, G., 2013. The promise of Beijing: evaluating the impact of the 2008 Olympic Games on air quality. J. Environ. Econ. Manag. 66 (3), 424–443.

Cheng, Y.F., Heintzenberg, J., Wehner, B., Wu, Z.J., Su, H., Mao, J.T., 2008. Traffic Restrictions in Beijing during the Sino-African Summit 2006: Aerosol Size Distribution and Visibility Compared to Long-Term in Situ Observations.

Chinazzi, M., Davis, J.T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Piontti, A. P. y, Mu, K., Rossi, L., Sun, K., et al., 2020. The effect of travel restrictions on the spread of the 2019 novel coronavirus (covid-19) outbreak. Science. 368 (6489), 395–400.

Chowdhury, S., Dey, S., Tripathi, S.N., Beig, G., Mishra, A.K., Sharma, S., 2017. "Traffic intervention" policy fails to mitigate air pollution in megacity Delhi. Environ. Sci. Pol. 74, 8–13.

Cuhadaroglu, B., Demirci, E., 1997. Influence of some meteorological factors on air pollution in Trabzon city. Energy Build. 25 (3), 179–184.

Davis, L.W., 2008. The effect of driving restrictions on air quality in Mexico City. J. Polit. Econ. 116 (1), 38–81.

Ebenstein, A., Fan, M., Greenstone, M., He, G., Zhou, M., 2017. New evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River Policy. Proc. Natl. Acad. Sci. Unit. States Am. 114 (39), 10384–10389.

Fan, C., Li, Y., Guang, J., Li, Z., Leeuw, G.D., 2020. The impact of the control measures during the covid-19 outbreak on air pollution in China. Rem. Sens. 12 (10), 1613.

Goddard, H.C., 1997. Using tradeable permits to achieve sustainability in the world's large cities: policy design issues and efficiency conditions for controlling vehicle emissions, congestion and urban decentralization with an application to Mexico City. Environ. Resour. Econ. 10 (1), 63–99.

Hao, Y., Peng, H., Temulun, T., Liu, L.Q., Mao, J., Lu, Z.N., Chen, H., 2018. How harmful is air pollution to economic development? New evidence from PM2. 5 concentrations of Chinese cities. J. Clean. Prod. 172, 743–757.

Ho, K.F., Huang, R.J., Kawamura, K., Tachibana, E., Lee, S.C., Ho, S.S.H., et al., 2015. Dicarboxylic acids, ketocarboxylic acids, α-dicarbonyls, fatty acids and benzoic acid in PM2: 5 aerosol collected during CAREBeijing-2007: an effect of traffic restriction on air quality. Atmos. Chem. Phys. 15 (6).

Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., et al., 2020. Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. EarthArXiv.

Invernizzi, G., Ruprecht, A., Mazza, R., De Marco, C., Močnik, G., Sioutas, C., Westerdahl, D., 2011. Measurement of black carbon concentration as an indicator of air quality benefits of traffic restriction policies within the ecopass zone in Milan, Italy. Atmos. Environ. 45 (21), 3522–3527.

Kraemer, M.U., Yang, C.H., Gutierrez, B., Wu, C.H., Klein, B., Pigott, D.M., et al., 2020. The effect of human mobility and control measures on the COVID-19 epidemic in China. Science 368 (6490), 493–497.

Lau, H., Khosrawipour, V., Kocbach, P., Mikolajczyk, A., Schubert, J., Bania, J., Khosrawipour, T., 2020. The positive impact of lockdown in Wuhan on containing the COVID-19 outbreak in China. J. Trav. Med. 27 (3).

Li, R., Wang, Z., Cui, L., Fu, H., Zhang, L., Kong, L., et al., 2019. Air pollution characteristics in China during 2015–2016: spatiotemporal variations and key meteorological factors. Sci. Total Environ. 648, 902–915.

Liang, P., Zhu, T., Fang, Y., Li, Y., Han, Y., Wu, Y., Hu, M., Wang, J., 2017. The role of meteorological conditions and pollution control strategies in reducing air pollution in Beijing during APEC 2014 and Victory Parade 2015. Atmos. Chem. Phys. 17 (22), 13921.

Lin, C.Y.C., Zhang, W., Umanskaya, V.I., 2011. The Effects of Driving Restrictions on Air Quality. São Paulo, Bogotá, Beijing, and Tianjin. No. 321-2016-10830.

Matus, K., Nam, K.M., Selin, N.E., Lamsal, L.N., Reilly, J.M., Paltsev, S., 2012. Health damages from air pollution in China. Global Environ. Change 22 (1), 55–66.

Novel Coronavirus Pneumonia Emergency Response Epidemiology Team. Vital surveillances: the epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19)—China, 2020. China CDC Weekly. Accessed February 20, 2020.

Qiu, Y., Chen, X., Shi, W., 2020. Impacts of social and economic factors on the transmission of coronavirus disease 2019 (COVID-19) in China. J. Popul. Econ. 1.

Shahbazi, H., Hosseini, V., Hamedi, M., 2014. Investigating the Effect of Odd-Even Day Traffic Restriction Policy on Tehran Air Quality. No. 14-4257.

Viard, V.B., Fu, S., 2015. The effect of Beijing's driving restrictions on pollution and economic activity. J. Publ. Econ. 125, 98–115.

Wang, P., Chen, K., Zhu, S., Wang, P., Zhang, H., 2020. Severe air pollution events not avoided by reduced anthropogenic activities during COVID-19 outbreak. Resour. Conserv. Recycl. 158, 104814.

Wang, X., Westerdahl, D., Chen, L., et al., 2008. Evaluating the air quality impacts of the 2008 Beijing Olympic Games: on-road emission factors and black carbon profiles. Atmos. Environ. 43, 4535e4543.

Wang, Y., Zhang, Y., Schauer, J.J., de Foy, B., Guo, B., Zhang, Y., 2016. Relative impact of emissions controls and meteorology on air pollution mitigation associated with the Asia-Pacific Economic Cooperation (APEC) conference in Beijing, China. Sci. Total Environ. 571, 1467–1476.

Westerdahl, D., Wang, X., Pan, X., Zhang, K.M., 2009. Characterization of on-road vehicle emission factors and microenvironmental air quality in Beijing, China. Atmos. Environ. 43, 697e705.

Xu, P., Chen, Y., Ye, X., 2013. Haze, air pollution, and health in China. Lancet 382 (9910), 2067.

Zhao, C., Wang, Y., Shi, X., Zhang, D., Wang, C., Jiang, J.H., Zhang, Q., Fan, H., 2019. Estimating the contribution of local primary emissions to particulate pollution using high-density station observations. J. Geophys. Res.: Atmosphere 124 (3), 1648–1661.

Zhao, D., Chen, H., Li, X., Ma, X., 2018. Air pollution and its influential factors in China's hot spots. J. Clean. Prod. 185, 619–627.

Zhou, Y., Cheng, S.Y., Liu, L., Chen, D.S., 2012. A Coupled MM5-CMAQ modeling system for assessing effects of restriction measures on PM10 pollution in Olympic city of Beijing, China. Journal of Environmental Informatics 19 (2), 120–127.