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

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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.

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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.
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 PM2.5 in the cities with a GDP less than 3.6%.

In previous studies, some scholars have also found that the restriction policies in China is significantly induced a 25.6%, 23.7%, and 22.2% reduction in the air quality index (AQI), respectively. Second, given the heterogeneous impact across different countries or regions. As the outbreak of COVID-19, the local governments of many 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.

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.

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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., 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.

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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 represent 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:

\[
Y_{st} = \alpha + \beta D_{st} + \delta X_{st} + A_s + B_t + \epsilon_{st}, \quad s = 1, \ldots, 49; \quad t = \text{Aug. 1, 2019, ..., Feb. 7, 2020.}
\]

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 $\epsilon_{st}$ 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 $\beta$, therefore indicates the impact of private vehicle restrictions on air pollution. A positive and significant $\beta$ suggests that private vehicle restrictions exert a positive effect on the degree of air pollution, whereas a negative and significant $\beta$ 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

| Air Quality Index | Observations | Mean | Min | Max | Std. Dev. |
|-------------------|--------------|------|-----|-----|-----------|
| Air Pollution     |              |      |     |     |           |
| PM$_{2.5}$ (µg/m$^3$) | 9307 | 41.897 | 1.000 | 385.000 | 32.374 |
| PM$_{10}$ (µg/m$^3$) | 9307 | 66.866 | 3.333 | 456.292 | 40.311 |
| CO (µg/m$^3$)     | 9307 | 0.824 | 0.159 | 3.509 | 0.292 |
| NO$_2$ (µg/m$^3$) | 9307 | 30.693 | 2.435 | 114.083 | 16.517 |
| SO$_2$ (µg/m$^3$) | 9307 | 8.910  | 2.042 | 36.000  | 4.334  |
| O$_3$ (µg/m$^3$)  | 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 | 2.042 | 2891.000 | 121.256 |
| Private vehicles restriction | 9307 | 0.047  | 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
concentrations with two different regression specifications. In Panel A, the regressions simply control for city and date fixed effects. Robust standard errors are reported in parentheses. *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively.

|            | AQI     | PM$_{2.5}$ | PM$_{10}$ | CO     | NO$_2$ | SO$_2$ | O$_3$ |
|------------|---------|------------|-----------|--------|--------|--------|-------|
| 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.
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, Shiyang, 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 number plates, the restricted 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 where gross regional product is less than 3.6 × 10$^9$ 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$^9$ 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.

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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 Before the outbreaks of COVID-19 | After the outbreaks of COVID-19 | Suspension of Public Transport |
|------------|----------|-------------------------------------------------------------|--------------------------------|--------------------------------|
| 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       | January 27, 2020              |
| Anyang     | Henan    | Restricted                                                  | February 3, 2020 Restricted   | January 27, 2020              |
| Xinxian    | Henan    | Restricted                                                  | February 5, 2020 Cancel       | January 28, 2020 (reduce)     |
| Xuchang    | Henan    | Restricted                                                  | February 3, 2020 Cancel       | January 26, 2020              |
| Sannmenxi  | Henan    | Partial restricted                                          | not Restricted                | January 28, 2020              |
| Nanyang    | Henan    | Partial restricted                                          | February 1, 2020 Restricted   | January 24, 2020              |
| Shangqiu   | Henan    | Partial restricted                                          | February 3, 2020 Restricted   | January 28, 2020              |
| Xinyang    | Henan    | Partial restricted                                          | February 3, 2020 Restricted   | January 26, 2020              |
| Zhumadian  | Henan    | Restricted                                                  | February 3, 2020 Restricted   | January 24, 2020              |
| Wuhan      | Hubei    | Restricted                                                  | January 27, 2020 Restricted   | January 24, 2020              |
| Huangshi   | Hubei    | Restricted                                                  | January 27, 2020 Restricted   | January 24, 2020              |
| Shiyian    | Hubei    | Restricted                                                  | January 25, 2020 Restricted   | January 24, 2020              |
| Yichang    | Hubei    | Restricted                                                  | January 31, 2020 Restricted   | January 25, 2020 (reduce)     |
| Jiangmen   | Hubei    | Restricted                                                  | February 2, 2020 Restricted   | January 24, 2020              |
| Xiaogan    | Hubei    | Restricted                                                  | January 30, 2020 Restricted   | January 24, 2020              |
| Jingzhou   | Hubei    | Restricted                                                  | February 3, 2020 Restricted   | January 24, 2020              |
| Huanggang  | Hubei    | Restricted                                                  | January 31, 2020 Restricted   | January 24, 2020              |
| Suzhou     | Hubei    | Restricted                                                  | February 4, 2020 Restricted   | January 24, 2020              |
| Guangzhou  | Guangdong| Restricted                                                  | February 3, 2020 Cancel       | January 24, 2020              |
| Shaoguan   | Guangdong| Restricted                                                  | February 3, 2020 Cancel       | January 24, 2020              |
| Shenzhen   | Guangdong| Partial restricted                                          | February 3, 2020 Cancel       | January 24, 2020              |
| Zhuhai     | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Jiangmen   | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Zhanjiang  | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Maoming    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Zhaqing    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Meizhou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Shantou    | Guangdong| Partial restricted                                          | February 7, 2020 Restricted   | January 24, 2020              |
| Huizhou    | Guangd...
### 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       |
| Wenzhou       | Zhejiang | February 5, 2020 Restricted  | January 29, 2020 (reduce)    |
| Jiaxing       | Zhejiang | Zhejiang                     | January 25, 2020 (reduce)    |
| Huzhou        | Zhejiang | February 6, 2020 (reduce)    |                               |
| Shaoxing      | Zhejiang | February 3, 2020 Restricted  | February 3, 2020 (reduce)    |
| Jinhu         | Zhejiang |                             | January 30, 2020 (reduce)    |
| Zhoushan      | Zhejiang |                             |                               |
| 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 Chinese 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 choose 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 | Fuel Plug-in Hybrid Electric and Electric |
|---------------|----------|----------------|-------------------------------|-------------------------|------------------------------------------|
|               |          | Non-Local Vehicles | Even- and Odd-Number | The Last Digit of License Plates | Injunction of Vehicles |                                       |
| Zhengzhou     | Henan    | 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                                        |
| Xiamen        | Henan    | Y               | Y                             | Y                       | Y                                        |
| Nanyang       | Henan    | Y               | Y                             | Y                       | Y                                        |
| Xiangyang     | Henan    | Y               | Y                             | Y                       | Y                                        |
| Zhuhai        | Henan    | Y               | Y                             | Y                       | Y                                        |
| Wuhan         | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Huangshi      | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Shiyan        | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Xiangyang     | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Jingmen       | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Xiaogan       | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Jingzhou      | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Huairang      | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Suizhou       | Hubei    | Y               | Y                             | Y                       | Y                                        |
| Guangzhou     | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Shaoguan      | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Shenzhen      | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Zhuhai        | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Shantou       | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Jiangmen      | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Zhongshan     | Guangdong| Y               | Y                             | Y                       | Y                                        |
| Yunfu         | Guangdong| Y               | Y                             | Y                       | Y                                        |

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    | NO$_2$ | SO$_2$ | O$_3$ |
|---------------------|-----------|------------|-----------|-------|--------|--------|-------|
|                     | (1)       | (2)        | (3)       | (4)   | (5)    | (6)    | (7)   |
| Private vehicle restriction | -0.120*   | -0.185**   | -0.149**  | -0.044 | -0.100* | -0.078* | -0.136 |
| R$^2$               | 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)   |
| 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 |
| 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       | PM$_{2.5}$ | PM$_{10}$ | 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 |
| 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 |
| 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  | -0.117    | -0.185     | -0.102    | 0.038 | 0.064  | -0.019 | 0.007 |
| License Plates      | 0.018     | 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** |
| 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  |
| 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 |
| 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*** |
| R$^2$               | 0.523     | 0.535      | 0.600     | 0.421 | 0.689  | 0.479  | 0.515 |
| Observations        | 3695      | 3695       | 3695      | 3695  | 3695   | 3695   | 3695  |

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

| Panel | Variable | Hubei | Guangdong | Zhejiang |
|-------|----------|-------|-----------|----------|
|       |          | R²    |          |          |
|       |          |       | Observations |          |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
| Panel |          |       |          |          |
|       |          |       | Observations |          |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |
|       |          |       | 2278      | 2278      |

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

| Panel | Variable | AQI | PM<sub>2.5</sub> | PM<sub>10</sub> | CO | NO<sub>2</sub> | SO<sub>2</sub> | O<sub>3</sub> |
|-------|----------|-----|------------------|--------------|----|-------------|-------------|-----------|
|       |          | (1) | (2)             | (3)          | (4) | (5)         | (6)         | (7)       |
| Panel |          |     |                  |              |    |             |             |           |
|       | A: Total Population at the End of Year (10,000) | -0.107 | -0.175 | -0.147 | -0.095 | -0.015 | -0.086 | -0.120 |
|       |          |    | (0.071)         | (0.097)     | (0.060) | (0.075) | (0.051) | (0.080) |
|       |          |    | 0.512         | 0.578       | 0.591 | 0.475 | 0.733 | 0.418 | 0.729 |
|       |          |    | Observations | 4368      | 4368 | 4368 | 4368 | 4368 | 4368 |
|       |          |    | -0.013 | -0.053 | -0.034 | -0.029 | -0.017 | -0.033 | -0.040 |
|       |          |    | (0.087) | (0.106) | (0.097) | (0.098) | (0.072) | (0.054) | (0.145) |
|       |          |    | 0.450 | 0.499 | 0.561 | 0.387 | 0.718 | 0.415 | 0.533 |
|       |          |    | Observations | 4939      | 4939 | 4939 | 4939 | 4939 | 4939 |
|       | A: GDP (100 million yuan) | -0.001 | -0.089 | -0.109 | -0.019 | -0.005 | -0.005 | -0.019 |
|       |          |    | (0.081) | (0.112) | (0.105) | (0.070) | (0.092) | (0.067) | (0.084) |
|       |          |    | 0.485 | 0.547 | 0.619 | 0.378 | 0.782 | 0.525 | 0.713 |
|       |          |    | Observations | 2848      | 2848 | 2848 | 2848 | 2848 | 2848 |
|       |          |    | -0.236* | -0.320* | -0.360** | -0.040 | -0.081* | -0.067 | -0.146* |
|       |          |    | (0.099) | (0.123) | (0.098) | (0.044) | (0.043) | (0.058) | (0.081) |
|       |          |    | 0.457 | 0.512 | 0.540 | 0.496 | 0.689 | 0.374 | 0.547 |
|       |          |    | Observations | 6459      | 6459 | 6459 | 6459 | 6459 | 6459 |
| Panel | B: GDP growth rate (%) | -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) |
|       |          |    | 0.454 | 0.509 | 0.564 | 0.359 | 0.706 | 0.525 | 0.577 |
|       |          |    | Observations | 5130      | 5130 | 5130 | 5130 | 5130 | 5130 |
|       |          |    | -0.219* | -0.316** | -0.285** | -0.112* | -0.068 | -0.067 | -0.145 |
|       |          |    | (0.105) | (0.132) | (0.124) | (0.064) | (0.063) | (0.058) | (0.096) |
|       |          |    | 0.459 | 0.521 | 0.550 | 0.491 | 0.734 | 0.374 | 0.663 |
| Panel | C: 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) |
|       |          |    | 0.454 | 0.509 | 0.564 | 0.359 | 0.706 | 0.525 | 0.577 |
|       |          |    | Observations | 5130      | 5130 | 5130 | 5130 | 5130 | 5130 |
|       |          |    | -0.219* | -0.316** | -0.285** | -0.112* | -0.068 | -0.067 | -0.145 |
|       |          |    | (0.105) | (0.132) | (0.124) | (0.064) | (0.063) | (0.058) | (0.096) |
|       |          |    | 0.459 | 0.521 | 0.550 | 0.491 | 0.734 | 0.374 | 0.663 |

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 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.

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.

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