Research Article

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New Evidence of the Effect of Beijing's Driving Restriction and Other Olympic-Year Policies on Air Pollution

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Abstract: Seven Chinese cities have enacted One-Weekday Limit (OWL) driving restrictions following Beijing's implementation shortly after the Olympics in 2008. Existing literature examines the short-run effect of the OWL or the long-run effect of the Olympic-year policy package on air pollution in Beijing. Using two difference-in-differences (DD) approaches, this study compares the long-run effect of the Olympic-year policy package with the effect of the OWL. Using the city of Tianjin as a control, this study finds a significant drop in pollution due to the Olympic-year policy package. Using weekends as a control, this study finds a much smaller and less significant drop due to the OWL. These new findings suggest that compared to the OWL, other policies enforced in the Olympic year account for a greater portion of the drop.

Keywords: air pollution, driving restriction, difference-in-differences, Beijing

1 Introduction

Seven Chinese city governments have instituted the One-Weekday Limit (OWL) driving restrictions similar to the one the Beijing government imposed 11 years ago following the 2008 Olympics. These cities include Tianjin, Nanchang, Hangzhou, Lanzhou, Guiyang, Chengdu, and Changchun which are all municipality or provincial capitals located in the middle, west, and northeast parts of China. Given that these cities span one-fourth of provinces in China and affect roughly 1/20 of

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Chinese population,¹ it is expected that more provinces will adopt driving restrictions to fix worsened traffic congestion and air pollution issues.

Existing literature evaluates the short-run effects of driving restrictions or the long-run effects of the Olympic-related interventions, such as plant closures, subway extensions, and introduction of new emission standards, on air pollution in Beijing. Using a cohort of Chinese cities as a control group, Chen et al. (2013) found that the Olympic-related policies reduced Beijing's air pollution by 19 percent for one year and by 6 percent for the period from 7 to 13 months after implementation. Applying a regression discontinuity (RD) design, Viard and Fu (2015) claimed that the short-run effect of the post-Olympic driving restriction was a 21 percent decrease in pollution. Previous literature neither analyzes the long-run effect of driving restrictions nor compares the effect of driving restrictions with that of the Olympic-related environmental programs in Beijing.

This study fills the research gap by assessing and comparing the long-run effects² on pollution of both driving restrictions and the Olympic-year policy package implemented in Beijing. Using two difference-in-differences (DD) approaches, this study identifies both effects several years after the Olympics. The DD based on Tianjin identifies the effect of all Olympic polices while the DD based on weekends identifies the OWL effect. Using the city of Tianjin as a control group, the first DD approach finds a significant long-run effect of 13–19 percent reduction in pollution. Using weekends in both Beijing and Jing-Jin Bay (i.e.: the cities of Beijing and Tianjin) as a control group, the second DD approach finds a much smaller and less significant impact of a 3–5 percent reduction in pollution.

The paper uses the daily air pollution index (API) of PM₁₀ as a measure of pollution in addition to six weather variables as weather controls. The study period covers four years before and four years after the Olympic year. In both strategies, the estimation equations consider six specifications, including a standard DD specification, adding weather controls, time fixed effects, and a linear, quadratic, or cubic time trend. All DD analyses perform falsification tests by generating placebos before and after the Olympics to ensure the real effects obtained from the main analysis are causal.

Similar to Chen et al. (2013), this study finds that the one-year impact of the Olympic-year policy package is a 19 percent reduction of pollution in Beijing. By

¹ Populations of the seven cities and Beijing are extracted from World Population (2020) estimated by Population Stat. <https://populationstat.com/china/> (last accessed October 22, 2020).

² The long-run effect in this paper, if defined more concisely, should be denoted as a medium-term effect. Compared to the long run effects over decades, focusing on a few years after an intervention avoids any time-varying confounding factors that would make a policy no longer have an effect over decades.

extending the study period of Chen et al. (2013) up to four years, it further finds that the two-year, three-year, and four-year impacts of the policy package are 11–13 percent, not fading away. In contrast to Viard and Fu (2015), who claim a short-run impact of 21 percent, this study finds only a 3–5 percent less significant reduction in pollution of the OWL policy's two-year, three-year, and four-year impacts. Based on these new findings, this paper concludes that rather than the OWL, other Olympic-year policies contributed to a larger portion of the significant pollution drop in Beijing.

This paper distinguishes from previous papers of Beijing's driving restrictions in three essential aspects. First, it uses a different identification strategy to estimate the long-run effect than that used by Viard and Fu (2015), who applied an RD method to estimate the short-run effect. Second, similar to Chen et al. (2013), this study estimates long-run effects, but differs in that it tries to isolate the effects of the OWL from the Olympic-related environmental policies. Third, it provides an initial comparison of the effect of the OWL with that of other policies instituted during the Olympic year in Beijing, while previous studies only evaluate either effect individually.

2 Policy Background

Among cities in China, Beijing is highly developed in both economy and technology but had the poorest air quality. Blue sky days rarely appeared in Beijing, and people usually wore masks while outdoors. Schools were forced to cancel outdoor activities, and health experts recommended that children, the elderly, and people with respiratory ailments stay indoors. Inhalable Particulate Matters (IPMs or PM_{10}) has ranked first as the primary air pollutant since 2000, which was the only pollutant that exceeded the national standard.³ Among all the sources that contributed to PM_{10} , car emissions were the most critical, with other sources coming from burning coal, construction dust, and industrial emissions.

Major concerns for human health from exposure to PM_{10} include the effects on breathing and respiratory systems, the damage to lung tissue, and the risk of cancers and premature death. The elderly, children, and people with chronic lung disease, influenza, or asthma are especially sensitive to the effects of particulate matters. The social cost of PM_{10} in Asia is researched by Kan and Chen (2004) and

³ Beijing's health-based national air quality standard for PM_{10} is $100 \mu\text{g}/\text{m}^3$, which is two times higher than the World Health Organization's 2005 standard ($50 \mu\text{g}/\text{m}^3$). In 2007, 89 percent of the days had PM_{10} as its primary air pollutant, and the average concentrations of PM_{10} exceeded health-based national air quality standards by 22 percent. Source: Beijing's Municipal Environmental Protection Bureau (EPB).

Quah and Boon (2003). Kan and Chen (2004) claim that the total economic cost of health impacts caused by particulate air pollution was around 625.40 million US dollars in Shanghai in 2001, which was 1.03 percent of Shanghai's GDP. Quah and Boon (2003) found that the total economic cost of PM_{10} in Singapore was 3.362 billion US dollars, which was 4.31 percent of Singapore's GDP in 1999. From an economic cost perspective, therefore, it is important to reduce PM_{10} pollution.

As the host city for the Olympic Games (running from August 8 to 24, 2008), the Beijing government introduced a driving restriction to reduce severe air pollution and traffic congestion. The Odd–Even number Limit (OEL) was implemented before and during the Olympics (i.e., from July 1 to September 20). Based on the tail numbers on license plates, the OEL banned cars with odd tail numbers from running on odd days and cars with even tail numbers from running on even days. Statistics from Beijing's EPB show that air quality improved by 42.47 percent during the Olympics compared to the air quality three months before the OEL.

The reported success of the OEL led the Beijing government to announce a continued driving restriction known as the One-Weekday Limit. The OWL is a modified version of the OEL that bans most drivers from using their vehicles one weekday per week. It was initially enforced for a half-year from October 11, 2008 to April 10, 2009. Instead of banning five digits per day, as with the OEL, the OWL bans two digits per weekday based on the last digit of license plates.⁴ The OWL was in effect on every road within the Fifth Ring Road from 6:00 am to 9:00 pm every weekday, excluding holidays.⁵ It applied to most motor vehicles, excluding police cars, fire trucks, ambulances, project rescue vehicles, buses, taxis, and postal vehicles. Violators were fined 100 RMB (roughly 15 US dollars and 1/40 of Beijing citizens' average monthly salary) and were forced off the road. Since April 11, 2009, the OWL was extended four times with small modifications.⁶

Despite the OWL, the number of motor vehicles increased significantly after the Olympics in Beijing. Figure 1 demonstrates the annual growth of motor vehicles

⁴ Ten digits from 0–9 are divided into five groups (i.e., {1, 6}, {2, 7}, {3, 8}, {4, 9}, {5, 0}), and each group is bundled with a weekday (i.e., {1, 6} is bundled with Monday, {2, 7} with Tuesday, and so on). If the last digit of the tail number of a motor vehicle falls into a group, that car cannot be driven on the day bundled with that group. For example, if the license plate ends with 6, which falls into group {1, 6}, that car cannot be driven on Monday, the day bundled with {1, 6}.

⁵ The region within the Fifth Ring Road is the central metropolitan area of Beijing. It consists of four nested rings from the highest radius to the smallest radius, named as the Fifth Ring, the Forth Ring, the Third Ring, and the Second Ring, respectively. The area of the region is 652.2 km², which is around 4 percent of the administrative area of Beijing.

⁶ These modifications include shortening the restricted time to 7:00 am to 8:00 pm and excluding the Fifth Ring from the enforced region.

Figure 1: Motor vehicle growth in Beijing (2000–2013).

in Beijing since 2000.⁷ The gray bar denotes the annual motor vehicle stock, and the black line connects the annual growth rates. Growth was roughly stable from 2001 to 2007, hovering around 10 percent. After 2008, the growth exhibits a consistent upward trend until 2010, when the Car Purchasing Lottery (CPL)⁸ was announced. Though the high growth during 2010 could be partially explained by drivers' anticipation of the CPL, the absolute stock increase is still overwhelming for each year. For instance, the growth of 12 percent in 2008 shows that 376,000 cars were added to stock during 2008; the growth of 15 percent in 2009 means that 515,000 cars were added during 2009; and the growth of 20 percent in 2010 means 790,000 cars were added during 2010, which is double the added car stock of 2008.

Two reasons could account for this consistent increasing in car stock after the Olympic year. One reason could be an internal cause induced by the OWL: people reacted by purchasing additional cars to circumvent the policy. Another reason could be an income effect triggered by the Olympics⁹; more people gained

⁷ Data source: Beijing Traffic Management Bureau (BTMB). <http://jtgl.beijing.gov.cn> (last accessed October 22, 2020).

⁸ The CPL is another vehicle control policy that began on Dec. 23, 2010. This policy assigns quotas for purchasing cars, which may have contributed to the sharp reduction in the growth of motor vehicles after 2010. However, it may also contribute to the significant car growth in 2010, as people rushed to purchase cars before the policy was announced.

⁹ See Hotchkiss, Moore, and Zobay (2003), Madden and Crowe (1998), and Kasimati and Dawson (2009). These three papers discuss the economic impacts of the 1996 Atlanta Olympics, the 2000 Sydney Olympics, and the 2004 Athens Olympics using a macroeconomic model.

Table 1A: A timeline of all environmental programs in Beijing.

Time	Events	Type
Pre-Olympics		
2003–2004	Beijing reduced its industrial use of coal by 10 million tons, desulfurized air pollutants from the YanShan Petrochemical Company, shut down coal-red generators at the Capital Steel Company and Beijing Coking Plant.	PL
2004.7.1	China applied European II emission standard.	ES
2005	The largest plant Capital Steel Company was relocated.	PL
2005	The Capital Steel's largest production unit was permanently closed.	PL
2005.12.30	Beijing applied European III emission standard. Vehicles passed III standard before can install OBD after one year.	ES
2005–2006	China constructed desulfurization, dust removal, and denitrification facilities at the Beijing Thermal Power Plant and the power plant of Capital Steel.	PL
2006.7.23	Beijing Coking Plant was closed.	PL
2006.10.31	Beijing renovated 100% of the furnaces for clean fuel in five districts, and 50% in the three other districts.	PL
2006.12.1	New cars without OBD were prohibited to sell in Beijing.	ES
2007	Subway fare was changed from 3 yuan (US\$0.5) per ticket to 2 yuan (US\$ 0.3).	SF
2007.10.7	Line 5 was opened.	SE
2007.12.31	The Second Beijing Chemical Plant completed its production closure.	PR
2008.3.1	Beijing began to apply European IV emission standard applied to new vehicles.	ES
2008.6.30	Beijing required that all coal-red power plants install and operate denitrification equipment after installing desulphurization and high-efficient dust elimination equipment.	ES
Olympics		
2008.7.1–9.20	Odd Even Limit	VC
2008.7.19	Line 8, Line 10 and Airport Express were opened.	SE
2008.8.8–9.17	Non-essential businesses and factories were temporarily closed.	PL
Post-Olympics		
2008.10.11	One-weekday Limit	VC
2008.12.30	Beijing required that 40 high polluting and high energy-consuming enterprises shut down.	PL
2009.9.28	Line 4 was opened.	SE
2010.1.1	The book <i>Beijing Travel Geography</i> was published.	TR
2010.12.23	Car Purchasing Lottery (CPL) was put into place.	VC
2010.12.30	Five suburban lines (Line 15, Changping Line, Daxing Line, Fangshan Line, Yizhuang Line) were opened.	SE

Table 1A: (continued)

Time	Events	Type
2010.12.31	The Capital Steel completely stopped all its production.	PL
2011.7.1	Beijing to Shanghai High-speed Railway was opened.	HR
2011.12.31	Line 8 Phase II North, Line 9 South, Line 15 Phase I East were opened.	SE

PL standards for Plant related policies, ES standards for Emission Standard, SE standards for Subway Expansion, SF standards for Subway Fare change, HR standards for High-speed Railway, VC standards for Vehicle Control and TR for Travel related events.
Source: Author’s summary according to Chen et al. (2013), Viard and Fu (2015) and other online resources.

Table 1B: A Timeline of all environmental programs in Tianjin.

Time	Events	Type
Pre-Olympics		
2004.3.28	Line 9 Phase I was opened.	SE
2004.7.1	China applied European II emission standard.	ES
2006.6.12	Line 1 was opened.	SE
2007.5.10	Light trail 1 was opened.	SE
2007.7.1	European III emission standard was applied.	ES
Olympics		
2008.8.6–8.15	Odd Even Limit	VC
Post-Olympics		
2010.7.1	European IV emission standard was applied.	ES
2011.5.1	Line 9 Phase II East Part was opened.	SE
2011.7.1	Beijing to Shanghai High-speed Railway was opened.	HR
2012.7.1	Line 2 East and West Parts were opened.	SE
2012.10.1	Line 3 Phase I was opened.	SE
2012.10.15	Line 9 Phase II West Part was opened.	SE

Source: Author’s summary according to online resources.

resources due to the economic boom of the Olympics, and they began to buy their initial cars. In order to accurately assess the effects of the OWL, it is essential to rule out the possibility of the income effect caused by the Olympics.

Besides the Olympic shock that could confound the effects of the OWL, Beijing also instituted a series of other environmental programs before and after the Olympics.¹⁰ These programs include plant closures/relocations, introduction of new emission standards, subway extensions and fare changes, and vehicle controls. Table 1A summarizes these programs since 2003 in chronological order. It

10 Chen et al. (2013) examined the impact of Beijing’s Olympics on air pollution and documented all the environmental programs implemented in Beijing to prepare for the Games.

Table 2: A policy list of the treatment and control groups.

A policy list for treatment and control groups after the Olympic year:		
	Weekdays	Weekends
Beijing	Olympics + Other Olympics + OWL	Olympics + Other Olympics
Tianjin	Olympics	Olympics

Olympic-Year Policy Package:

European IV emission standard (2008.3.1)	} Other Olympic-Year Policies
De-nitrification equipment (2008.6.30)	
Line 8, Line 10 and Airport Express (2008.7.19)	
40 plants shut down (2008.12.30)	
The OWL (2008.11.10)	

can be seen that Beijing adopted an extensive plant relocation/closure plan to curb air pollution beginning in 2003. Beijing also applied a European emission standard and has updated it annually. Starting in 2007, the Beijing government opened a series of new subway lines annually to prepare for the Olympics and fill needs for an increased population living in the suburbs. During 2008, the Olympic year, vehicle controls including the OEL and the OWL were put into place.

The Olympic year witnessed the institution of the OWL policy as well as many other environmental policies, which included the introduction of the European IV emission standard (2008.3.1), the installation of de-nitrification equipment among all coal-red power plants (2008.6.30), the opening of three subway lines (2008.7.19), and the shutting down of 40 high polluting plants (2008.12.30). The OEL and the temporary plant closures are not considered as confounding policies, because they did not have a permanent effect on pollution. The bottom of Table 2 lists out the full components of the Olympic-year policy package that includes the OWL and other Olympic-year policies. These other Olympic-year policies could directly or indirectly affect PM_{10} pollution in Beijing and therefore confound the impact of the OWL.

3 Prior Literature

License plate-based driving restrictions originated from Athens, Greece in 1982 and were expanded to many large international cities. Similar restrictions were enacted in Mexico City, Mexico in 1989, São Paulo, Brazil in 1995, Manila, Philippines in 2003, Beijing, China in 2008, Quito, Ecuador in 2010, and New Delhi,

India in 2016 (see Davis 2017 for a detailed summary). These international cities are usually urban areas with populations greater than 20 million. Some cities have adopted driving restrictions as a permanent vehicle control policy, hence their presence and effects remain today, such as in Mexico City and Beijing.

Existing literature evaluating the effects of driving restrictions on air pollution is limited to the cases of Mexico City, Beijing, and Quito (Carrillo, Malik, and Yoo 2016; Chen et al. 2013; Davis 2008; Gallego, Montero, and Salas, 2013; Viard and Fu 2015). In contrast to studies of Mexico City's driving restrictions that were found to have no effect, studies on Beijing and Quito's similar restrictions were found to have a significant impact on air pollution.

Davis (2008) provides the first quasi-experimental study of the effect of driving restrictions on air pollution. Applying an RD method on time-series air pollution data, Davis finds that the short-run discontinuous effect of Mexico City's driving restriction was not effective. At the same time, Davis found counter-evidence of increased gasoline sales, new car purchases and registrations, and decreased subway ridership. Based on these findings, Davis concluded that Mexico City's driving restrictions were not effective in reducing air pollution, because drivers behaviorally adapted to the policy by purchasing second cars.

Employing a modified RD method, Gallego, Juan-Pablo, and Salas (2013) estimated the long-run effect of Mexico City's driving restrictions on air pollution. By adding monthly dummies to gauge the monthly effect of the policy in an RD model, Gallego et al. found that Mexico City's restrictions only had a significant impact in the first two months, and the effect faded in less than a year. They also found that the policy's short-run effect mainly existed in middle-income households, which are most likely to purchase a second vehicle to circumvent the restrictions.

Contrary to the findings of Mexico City's driving restrictions are studies of Quito and Beijing's driving restrictions. Using two DD and a difference-in-differences-in-differences (DDD) strategy generated by controls of non-restricted hours and/or non-restricted air monitoring stations, Carrillo, Malik, and Yoo (2016) found that the long-run effect of Quito's driving restriction was effective. Specifically, they found a 9–11 percent reduction in carbon monoxide concentrations for peak traffic hours and a 6 percent reduction for an extended daytime period. They did not find spillover of the effects of driving to other times of the day or the week, or to other locations.

Exploiting a fixed effect (FE) model with a cohort of non-Olympic cities as a control, Chen et al. (2013) evaluated the long-run effect of the full set of Beijing's Olympic policies on air pollution. They found that the policy package imposed during the Olympics (temporary plant closures, the OEL, and subway extensions) had significantly reduced PM_{10} pollution by 34 percent during this Games period,

while the policy mix instituted after the Olympics (the OWL and 40 plant closures) had reduced pollution by 19 percent in one year. By breaking the post-Olympic period into five short phases, Chen et al. (2013) further found that the effect of the post-Olympic policies (mainly the OWL policy) had faded to 6 percent reduction in pollution from 7 to 13 months after initiation.

Using an RD method in short time windows, Viard and Fu (2015) evaluated the short-run effects of Beijing's driving restrictions on air pollution. Based on both aggregate and station-level air pollution data, they found that PM_{10} pollution was significantly reduced by 18 percent due to the OEL and by 21 percent due to the OWL. In addition, they found no substitution of driving from weekday to weekend. To rule out the effect of any time-varying confounding factors, they also applied a DD method as a robustness that allowed for differential effects on monitoring stations near and far from major roads. This returned similar results of a 17 percent reduction due to the OEL and a 19 percent reduction due to the OWL.

Though both studies of Beijing's driving restrictions found a significant impact on reducing pollution, these studies have the following limitations. As an evaluation of the Olympic-year policy package, Chen et al. (2013) did not isolate the effects of the OWL from the effects of the policy package. Using RD to estimate the short-run effects, Viard and Fu (2015) failed to provide a long-run estimation of the effects of driving restrictions. Similarly, both studies were unable to provide a comparison of the effect of the OWL with that of the Olympic-year policy package, especially in the long run. This study solves the above limitations by designing two new quasi-experiments to estimate the long-run effects of both the OWL and the Olympic-year policy package, as well as providing a comparison of both effects.

4 Data

4.1 Air Quality and Meteorological Data

Since Oct. 1, 1996, air quality in China has been managed based on the ambient air quality standard (namely GB3095-1996). This standard stipulates categories, averaging times,¹¹ and concentration limits of different air pollutants in different areas. For example, Beijing, a metropolitan area, applied the Grade II standard for PM_{10} concentrations, which sets the limits of a yearly average of $100 \mu g/m^3$ and a daily average of $150 \mu g/m^3$. The PM_{10} concentrations in Beijing should not exceed those limits on account of health concerns. Concentrations of different pollutants

¹¹ The length of time in atmospheric dispersion testing over which concentration data are averaged to produce the concentration-time series.

Table 3: Summary statistics of API of PM₁₀ in Beijing: 2004–2012.

API (PM10)	Before				After				Diff	
	Obs.	Mean	Min	Max	Obs.	Mean	Min	Max	Mean	Pr (T < t)
Monday	213	112.009 [62.531]	51	500	180	89.906 [37.549]	52	333	22.104 (5.324)	1.000
Tuesday	206	113.466 [61.086]	52	500	176	94.739 [38.959]	51	307	18.727 (5.346)	0.999
Wednesday	216	109.269 [65.015]	51	500	177	93.746 [35.736]	51	268	15.523 (5.459)	0.998
Thursday	215	109.223 [60.712]	51	451	184	91.815 [35.979]	51	269	17.408 (5.105)	0.999
Friday	211	108.976 [61.101]	52	500	175	94.857 [46.377]	51	500	14.119 (5.615)	0.994
Saturday	213	105.873 [48.012]	51	472	178	93.242 [44.522]	51	500	12.632 (4.718)	0.996
Sunday	209	105.919 [52.076]	51	500	177	96.932 [54.546]	51	500	8.986 (5.437)	0.950

Note: Data are obtained from the website of the Ministry of Environmental Protection of the People's Republic of China. Standard deviations are reported in brackets. Standard errors are reported in parenthesis.

are monitored by multiple air monitoring stations distributed throughout a city. Depending on the nature of the pollutant, readings are averaged over a day or an hour. By simply averaging the concentrations of the same pollutant at different air monitoring stations in the city, daily or hourly concentrations of each pollutant are computed. Through a transformation function, these averaged concentrations are transformed into an Air Pollution Index (API).¹² The pollutant with the highest daily API is denoted as the major pollutant on that day.

Since 2000, the Ministry of Environmental Protection (MEP) of the People's Republic of China has reported daily API in major cities online.¹³ The API data used in this paper are manually copied from the MEP website. Focusing on Beijing, the pollutant PM₁₀ was the primary pollutant for most days of the year during the study period (see Table 3). Therefore, this study uses the API of PM₁₀ as the measure of pollution, similar to existing studies.

Since PM₁₀ is a pollutant affected by weather, this study also uses meteorological data to control for the weather. The China Meteorological Administration

12 The specific transformation procedure is shown on EPB's website. <http://sthjj.beijing.gov.cn/> (last accessed October 22, 2020).

13 The detailed air quality daily report data is available on MEP's website. <https://www.mee.gov.cn/> (last accessed October 22, 2020).

(CMA) collects daily meteorological data in major Chinese cities and files it annually. Through an online application process, we obtained the meteorological data during the study period in both Beijing and Tianjin. The data file contains seven key meteorological variables, including average barometric pressure, average temperature, average water vapor pressure, average relative humidity, total rainfall, average wind speed, and sunshine hours. The empirical analysis uses all seven variables to control for the weather.

4.2 Study Period

This study focuses on a few years before and after the policy interventions to avoid any unobserved time-varying confounding factors in the very long run. Specifically, it examines a symmetric eight-year time window (2004–2012) with four years before and four years after the Olympic year. It is the largest available time window to perform this long-run analysis with consistent measures, because China applied a new air quality measure in 2013.¹⁴ The year of the Olympics, 2008, is dropped, because many policies occurred at different times during 2008, making it hard to assign a consistent event time. These 2008 policies are treated as the Olympic-year policy package as summarized in Table 2, which includes the OWL and other Olympic-year policies such as the introduction of new emission standards, subway expansions, plant closures, etc.

4.3 Descriptive Statistics

Figure 2 plots the daily averaged API of PM_{10} in Beijing from 2004 to 2012. The vertical line denotes the date when the OWL was implemented (i.e., Oct 11, 2008). The daily API plot is scattered, and the line of fitted values shows a slightly downward sloping trend. To have a better understanding of the API, the average residuals are plotted by weekday and weekend in Figure 3(a) and 3(b) respectively. Residuals are calculated from a regression controlling for weather and day of week fixed effects, then averaged across five weekdays in Figure 3(a) or across both weekend days in Figure 3(b). These weekly averaged graphs look similar to the daily graph in terms of scattering and the downward trend.

Summary statistics of the day of week API of PM_{10} in Beijing is described in Table 3. Focusing on the Before and After panels, there are more observations before

¹⁴ In 2013, China introduced worldwide air quality measures denoted as air quality index (AQI) instead of API.

Figure 2: Average daily API of pm 10 in Beijing (2004–2012).

the Olympics than after the Olympics. This is probably due to the Olympic-year policy package that reduced PM_{10} pollution so that it became less likely to be the major pollutant of a specific day. The fact that PM_{10} is less often the primary pollutant post-Olympics could introduce bias in the estimates. The maximum values within each panel reveal similar information. Monday to Thursday highest values were reduced from around 500 to roughly 300 after the Olympics—a 40 percent decrease—while Friday and weekend highest values maintained roughly the same level at 500. This is probably because of the OWL that restricts motor vehicles running on weekdays. Moving to the mean values column, they are in the range of 106–113 before the Olympics and reduced to the range of 90–97 after the Olympics. Statistical tests show that these differences in means are all highly significant, suggesting that there were significant reductions in pollution after the Olympic year.

Focusing on the rows in the Before panel, Monday and Tuesday have the highest averaged APIs (112–113), Wednesday to Friday have medium averaged APIs (109), and Saturday and Sunday have the lowest averaged APIs (106). Those readings make sense, because the beginning two days of the week are usually commuting summits; companies with less workload may not require everyone to physically report to work on the other workdays, and most people do not work during weekends. Moving to the After panel, weekday averaged APIs are reduced to similar levels as weekend ones. This suggests that the Olympic-year policy package may have had a strong effect in reducing weekday pollution, which is very likely to be caused by the OWL.

Figure 3: Average residuals of API by week (2004–2012).

5 The Effect of the Olympic-Year Policy Package on Air Pollution

Because the OWL is enacted with a combination of other policies such as plant closures, emission standards, and subway extensions in the Olympic year in

Beijing, it is much easier to evaluate the impact of the Olympic-year policy package first. This information is also relevant to compare its effect with the effect of the OWL that will be examined in the next section. By introducing a twin city for Beijing and applying a DD method, the objective of this section is to assess the effects of the Olympic-year policy package on air pollution in Beijing.

5.1 A Twin City for Beijing

As the world's most populated economy, China has several cities similar to Beijing in terms of the economic, population, and social scope. Due to their fast-developed economies, the central government selects four super-large cities as its direct-controlled municipalities. They are Beijing, Tianjin, Shanghai, and Chongqing, the administrative rank of which is similar to provinces. Figure 4 graphs the annual GDP of these four municipalities from 2003 to 2013.¹⁵ Since 2003, the GDP growth has shared a similar trend for these municipalities. Focusing on each municipality, Beijing's GDP ranks No. 2, with Shanghai's GDP roughly one third above and Tianjin's and Chongqing's GDPs roughly one third below. Based on the economic scope, each of the other three municipalities could serve as a control candidate for Beijing.

To be similar to Beijing, the control city also needs to be an Olympic city to exclude the possible economic effect generated by the Olympics. Figure 5 maps the

Figure 4: GDP growth in China's municipalities (2003–2013).

¹⁵ Data source: National Bureau of Statistics of China. <http://data.stats.gov.cn/> (last accessed October 22, 2020).

Figure 5: Location of China's olympic cohosting cities.

locations of the 2008 Olympic co-hosting cities in China. Seven cities were selected to co-host the Olympic Games, including three municipalities, three cities in the north and northeast, and a special administrative district. Since the three north and northeast cities are not comparable with Beijing in the economic scope and Hong Kong has a different institution than Beijing, they are removed as control candidates. The three remaining municipalities are Beijing (the headquarters), Tianjin, and Shanghai, the latter two of which cohosted football matches.¹⁶ Chongqing is the only municipality that did not co-host the Olympics; it is therefore removed from our control candidates.

Air pollution, especially for PM_{10} pollution, is highly affected by weather. The control group therefore needs to have similar weather conditions to Beijing. Tianjin is similar in latitude to Beijing and is located in the interior, while Shanghai is at a different latitude and is near the coast, so Tianjin is expected to have more similar weather conditions to Beijing. Monthly weather conditions of Beijing, Tianjin, and Shanghai are graphed in the Appendix. These graphs include three key weather variables: mean maximum temperature, mean minimum temperature, and rainfall amount. The solid line, dashed line, and dotted line represent corresponding weather variables in Beijing, Tianjin, and Shanghai, respectively. The lines for Beijing and Tianjin roughly overlap, while the line for Shanghai has either a different shape or a different shift. These graphs verify our intuitive reasoning that Tianjin provides a better control candidate for Beijing relative to Shanghai.

In terms of other non-Olympic year environmental policies, both Beijing and Tianjin worked to reduce air pollution before and after 2008. To be comparable

¹⁶ See the 2008 Beijing Olympics' official website. <http://en.beijing2008.cn/> (last accessed October 22, 2020).

with policies enforced in Beijing, Table 1B lists the timeline of all the environmental programs introduced in Tianjin from 2004 to 2012. It can be seen that both Beijing and Tianjin extended subway lines, updated emission standards, and constructed high-speed railways before and after 2008. Though other policies specific to Beijing are most related to plant relocations before 2008 as well as the CPL and a plant relocation after 2008, the effect of these confounders can be measured through a placebo test. Otherwise, the non-Olympic year policies introduced in both Beijing and Tianjin could be treated as a similar policy package. Therefore, the only difference between Beijing and Tianjin is the Olympic-year policy package implemented in Beijing only. This includes the OWL (2008.11.10) and other Olympic-year policies containing the European IV emission standard (2008.3.1), the installation of the de-nitrification equipment (2008.6.30), the opening of three subway lines (2008.7.19), and 40 plants shutting down (2008.12.30).

Based on the economic scope, Olympic effect, weather conditions, and other non-Olympic year policies, Tianjin was selected as the control city for Beijing. Figure 6 graphs the air pollution trend of PM_{10} in Beijing and Tianjin before and after the Olympic year. The cut vertical line denotes the Olympic year. The solid marker line denotes the air pollution trend in Beijing, and the hollow marker line denotes the trend in Tianjin. Tianjin seems to share similar trends in air pollution with Beijing before 2007, but no policy enacted after 2007 in Tianjin has had a big effect. Its pollution bounces back starting from 2009. In contrast, Beijing’s pollution experiences a consistent drop after 2006 and becomes very stable after 2009.

Figure 6: API trends of PM_{10} over time in Beijing and Tianjin.

As for the changes in pollution levels, Beijing's pollution is significantly reduced from the range of (107, 117) to the range of (90, 95) after 2008, a drop of more than 10 indices. In contrast, Tianjin's pollution does not exhibit an obvious change and maintains the range of (80, 90). This graph reveals two major points of information: (1) Tianjin seems to be a good twin city for Beijing, because it shared a parallel pollution trend with Beijing before the intervention; and (2) the Olympic-year policy package had a visible impact on the pollution drop in Beijing.

5.2 A Difference-in-Differences Method

As shown on top of Table 2, a comparison of the rows in Column 1 identifies the total effect of all Olympic policies (i.e.: the OWL plus other Olympic-year policies). It is suitable to perform a difference-in-differences analysis. Treating Tianjin as the city control for Beijing and the pre-Olympic period as the time control for the post-Olympic period, a DD method is applied to estimate the impact of the Olympic-year policy package on air pollution. The estimation equation is:

$$API_{it} = \gamma_0 + \gamma_1 \text{After}_t + \gamma_2 \text{Beijing}_i + \gamma_3 \text{After}_t * \text{Beijing}_i + \varepsilon_{it}, \quad (1)$$

where API_{it} is the API of PM_{10} in the city i on day t , After_t denotes the time dummy with value 1 if t is a day after 2008 and value 0 if t is a day before 2008,¹⁷ Beijing_i denotes the city dummy with value 1 if city i is in Beijing and value 0 if city i is in Tianjin, $\text{After}_t * \text{Beijing}_i$ is an interacted dummy which equals 1 if both the day t is after the Olympic year and the city i is in Beijing and equals 0 otherwise, and ε_{it} is an error term. γ_3 is the DD estimator of interest, which measures the impact of the Olympic-year policy package on air pollution in Beijing. To be comparable with previous studies, a log format of the API is also estimated. Since weather characteristics, seasonality, and time trends are also determinants of PM_{10} pollution, Equation (1) is also estimated by gradually adding weather controls, the time FE (including the week of year FE, the day of week FE, and the month FE), and a linear, quadratic, or cubic time trend. These specifications are denoted as specification (2), (3), (4), (5), and (6) respectively.

The effects estimated in the real event analysis include four time intervals: 2007–09^a, 2006–10^a, 2005–11^a, and 2004–12^a, which compare the effect of the Olympic-year policy package one year before and one year after, two years before and two years after, three years before and three years after, and four years before and four years after the Olympic year. The average treatment effect (ATE) is

¹⁷ Observations in the Olympic year, 2008, are excluded from the sample to facilitate the evaluation of the policy package enacted at different times in 2008.

estimated by running separate regressions for each time window. The estimated effects are denoted as the one-year, two-year, three-year, and four-year impacts of the policy package on air pollution in Beijing.

In order to show that the effects obtained from the real event analysis are causal, the falsification test is performed by generating placebo events for both the pre-Olympic period and the post-Olympic period. There are a total of six placebo events, three for each period. The pre-Olympic period contains placebo events generated one year before, two years before, and three years before the Olympic year. Similarly, the post-Olympic period contains placebo events generated one year after, two years after, and three years after the Olympic year. For each fake event, there exists a maximum two-year radius time window. For instance, the pre-Olympic period contains three placebo events in 2005, 2006, and 2007. These placebo events generate four available time windows from which to perform the falsification test: three one-year radius time windows (04vs05, 05vs06, 06vs07), and a two-year radius time window (04–05vs06–07). A similar arrangement is used for the post-Olympic period placebo events and time windows. A separate regression is run for each of these eight time windows. The results from these placebos suggest any significant change in pollution in Beijing relative to Tianjin in the absence of the policy (i.e., for either the pre-Olympic period or the post-Olympic period).

5.3 Empirical Results

Table 4 presents the results of the effect of the Olympic-year policy package on air pollution in Beijing in each time window. Only the results for logged APIs are reported except for otherwise using leveled APIs have very different estimates and hence are added in the reporting. Across time windows and specifications, all the DD estimates are negative and highly significant. This suggests that on average, the Olympic-year policy package significantly reduced Beijing's air pollution relative to Tianjin from a one-year up to a four-year period after the Olympics. Specifically, the results from the 2007–09 time window indicate that the one-year impact of the Olympic-year policy package was on average an 18 to 20 percent reduction of air pollution in Beijing. Similarly, the results from the 2006–10 time window suggest that the two-year impact of the policy package was on average a 13 to 15 percent reduction of pollution. The results from the 2005–11 and 2004–12 time windows illustrate the three-year and four-year impacts demonstrated, respectively, an 11 to 13 percent and a 13 percent reduction of pollution. The effect of the policy package does not seem to fade away after the second year.

Table 4: The effect of the Olympic-year policy package on air pollution in Beijing.

	(1)	(2)	(3)	(4)	(5)	(6)
2007–09 ^a	–0.180*** (0.0379) [0.090]	–0.197*** (0.0357) [0.210]	–0.180*** (0.0310) [0.438]	–0.180*** (0.0310) [0.438]	–0.175*** (0.0310) [0.443]	–0.175*** (0.0311) [0.439]
2006–10 ^a	–0.141*** (0.0278) [0.080]	–0.153*** (0.0261) [0.206]	–0.131*** (0.0235) [0.382]	–0.132*** (0.0235) [0.385]	–0.130*** (0.0234) [0.391]	–0.129*** (0.0232) [0.393]
2005–11 ^a	–0.125*** (0.0228) [0.081]	–0.128*** (0.0215) [0.211]	–0.114*** (0.0194) [0.382]	–0.114*** (0.0193) [0.386]	–0.114*** (0.0194) [0.383]	–0.114*** (0.0193) [0.386]
2004–12 ^a	–0.133*** (0.0200) [0.077]	–0.133*** (0.0187) [0.206]	–0.127*** (0.0168) [0.386]	–0.129*** (0.0167) [0.389]	–0.127*** (0.0168) [0.387]	–0.129*** (0.0167) [0.388]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimator for the logged API in four enlarged time windows. Robust standard errors are in parenthesis. R-squared are in brackets. (1)–(6) denotes specification (1) to (6) as discussed in the empirical strategy section. The number of observations for each time window is 1148, 2341, 3439, and 4571 respectively.

^aThe period excludes the year of 2008.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

However, those Beijing-specific policies instituted in non-Olympic years may be a threat to the results obtained in the real event analysis. For instance, the plant-related policies and a subway fare change before the Olympic year, as well as the CPL and the closure of the Capital Steel after the Olympic year together may have caused the significant drop in pollution. To test whether these Beijing-specific non-Olympic-year policies are possible confounders, a falsification test is performed to rule out this possibility. If a policy implemented before or after the Olympic year had a significant impact on pollution, the results of the falsification test would show the impact.

Table 5 presents the results of the falsification test on the effects of the placebo events on air pollution in Beijing. The upper half of the table presents the results for the pre-Olympic period, and the lower half of the table presents the results for the post-Olympic period. Focusing on the pre-Olympic period, the DD estimates of all placebo events are not significantly different from zero. This suggests that weekend air pollution was not significantly different from weekday air pollution in Beijing relative to Tianjin before the intervention, which also verifies the parallel trend

assumption for the weekend to be a good control group. Moving to the post-Olympic period, the DD estimates of most placebo events are not significantly different from zero, except for the 11vs12 placebo. The 11vs12 placebo exhibits negative and significant signs, suggesting that events happened in 2012 in Beijing that significantly

Table 5: Falsification test: first diff-in-diff.

	(1)	(2)	(3)	(4)	(5)	(6)
Pre-Olympics						
04vs05	0.00536 (0.0418) [0.087]	−0.0230 (0.0381) [0.256]	−0.0312 (0.0310) [0.547]	−0.0311 (0.0310) [0.547]	−0.0317 (0.0310) [0.547]	−0.0317 (0.0310) [0.547]
05vs06	−0.00900 (0.0418) [0.085]	−0.00372 (0.0378) [0.255]	0.00672 (0.0333) [0.471]	0.00661 (0.0333) [0.471]	0.00873 (0.0329) [0.483]	0.00761 (0.0329) [0.483]
06vs07	0.0539 (0.0406) [0.106]	0.0575 (0.0371) [0.260]	0.0485 (0.0345) [0.413]	0.0483 (0.0344) [0.414]	0.0499 (0.0343) [0.418]	0.0509 (0.0343) [0.418]
04–05 vs	0.0178 (0.0293) [0.092]	0.0178 (0.0293) [0.092]	0.0134 (0.0269) [0.250]	0.0146 (0.0268) [0.253]	0.0138 (0.0269) [0.251]	0.0135 (0.0269) [0.250]
Post-Olympics						
09vs10	0.0173 (0.0376) [0.022]	0.0279 (0.0363) [0.144]	0.0505 (0.0310) [0.421]	0.0500 (0.0310) [0.421]	0.0414 (0.0308) [0.431]	0.0432 (0.0307) [0.433]
10vs11	0.0246 (0.0385) [0.033]	0.0215 (0.0361) [0.162]	−0.0224 (0.0305) [0.467]	−0.0222 (0.0305) [0.468]	−0.0245 (0.0305) [0.467]	−0.0241 (0.0305) [0.467]
11vs12	−0.0702* (0.0392) [0.024]	−0.0723** (0.0368) [0.160]	−0.0592* (0.0328) [0.390]	−0.0599* (0.0329) [0.391]	−0.0564* (0.0327) [0.391]	−0.0563* (0.0327) [0.391]
09–10 vs	−0.00280 (0.0272) [0.022]	−0.00280 (0.0272) [0.022]	−0.000135 (0.0257) [0.162]	−4.26e-05 (0.0257) [0.162]	−0.000159 (0.0256) [0.162]	−0.000337 (0.0256) [0.162]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimators of the placebo events for the logged API. Robust standard errors are in parenthesis. R-squared are in brackets. All specifications are the same as reported in Table 4. The number of observations for each time window is 1120, 1164, 1196, 2316, 1145, 1127, 1110, and 2255 respectively.
***Significant at the 1 percent level.
**Significant at the 5 percent level.
*Significant at the 10 percent level.

reduced its pollution relative to Tianjin. This is probably due to the opening of three subway lines at the end of 2011 (2011.12.31). Other than that, these insignificant DD estimates of the placebo events imply that the pollution trend between Beijing and Tianjin do not have a significant change in the absence of the Olympic-year policy package. The results from both pre-Olympic and post-Olympic placebos verify that the main results from our real event analysis are causal.

5.4 Relationship with Chen et al. (2013)

Similar to Chen et al. (2013), this section estimates the long-run effect of the Olympic-related environmental policies on air pollution in Beijing. Using a different strategy with an Olympic co-hosting city, Tianjin, as a control, this section finds a 17–20 percent significant reduction of air pollution one year after the Olympic year in Beijing. This is similar to the estimate found by Chen et al. (2013) of a 19 percent reduction of pollution using a cohort of Chinese cities as a control. In one respect, this section confirms the findings of Chen et al. (2013).

Additionally, this section expands the long-run analysis of Chen et al. (2013) from a one-year up to a four-year post-period. Applying the same methodology on these extended time windows, we further find that the two-year impact of the Olympic-year policy package is a 13–15 percent reduction in pollution; the three-year impact is 11–13 percent; and the four-year average impact is 13 percent. In contrast to Chen et al. (2013) that claim the effect faded to 6 percent starting from 7–13 months, this study finds that the effect is roughly stable after the second year.

6 The Effect of the OWL on Air Pollution

By comparing air pollution in Beijing with its twin city Tianjin before and after the Olympic year, the previous section evaluates the long-run effects of the Olympic-year policy package on air pollution in Beijing. By introducing a twin day for the restricted day and applying a similar DD method, this section seeks to isolate the long-run impact of the OWL from the Olympic-year policy package, which has not been conducted in previous literature.

6.1 A Twin Day for Restricted Day

In order to estimate the effect of the OWL, a control group needs to have all aspects similar to Beijing weekdays (when the OWL was enforced) except for the presence

of the OWL policy. The uniqueness of the OWL that only restricts weekdays instead of weekends allows the choice of weekends in Beijing as a control group. The upper part of Table 2 lists out the policies that affect both weekdays and weekends in Beijing. It can be seen that both the Olympics and other Olympic-year policies are common to weekdays and weekends in Beijing after the intervention. Therefore, pollution coming from the Olympic shock and other Olympic-year policies could be treated as background pollutions. The only policy difference between weekdays and weekends in Beijing after the Olympic year is the OWL policy. Thus, using weekends in Beijing as a control identifies the sole impact of the OWL policy.

To further ensure that weekends serve as a good control group, one assumption needs to be satisfied: the parallel pre-treatment trends. Under that assumption, the pollution trends of weekdays and weekends need to be parallel before the OWL, i.e., had the OWL not occurred. In other words, weekends should serve as a valid counterfactual for weekdays before the OWL. This will be seen from the following graphs of pre-treatment pollution trends of weekdays and weekends.

A condition ancillary to the parallel trend assumption is the absence of substitution after the OWL policy. In theory, there could exist two types of substitution driven by the OWL: substitute to other weekdays or substitute to weekends, in which only the former behavior is covered by this weekday–weekend comparison. If in any event there exists substitution to weekends, the weekday–weekend comparison would be contaminated by mistakenly treating the amount of substitution as a pollution increase for weekends. Since we do not know how large the later substitution is, the results from this weekday–weekend comparison may overestimate the real impact of the OWL.

Now it comes to the number of observations in the weekday–weekend comparison. Since there are fewer observations for weekends compared to weekdays, focusing on Beijing only may yield insignificant results due to the small sample size. A bigger sample of the Jing-Jin Bay area is also analyzed to overcome the small sample size problem. Beijing and Tianjin are often treated as an economic bay due to their tight economic connection, which is very similar to the connection between New York City and Jersey City in the United States. A significant amount of Beijing drivers living in Tianjin are subject to the OWL driving restriction.¹⁸ Therefore, using both samples has disadvantages in that the real impact of the OWL may be underestimated due to the spillover of Beijing drivers to Tianjin and the shrunken effect in the absence of the OWL policy in Tianjin.

18 The southeast part of Beijing is connected with the northwest part of Tianjin. People who live in the northwest part of Tianjin could drive to the Fifth Ring of Beijing within less than an hour. The OWL driving restriction applies to any car entering into the restricted region, even if the license plate is coming from outside of Beijing, i.e., Tianjin.

Figure 7(a) and 7(b) demonstrate the weekday and weekend air pollution trends over time before and after the OWL year in both the Beijing and the Jing-Jin Bay samples. Both graphs exhibit similar pollution trends for weekdays and weekends before the OWL year. As for a visual pre-trend assessment, the trends

Figure 7: API trends of PM10 over time in weekdays and weekends.

from 2006 to 2008 are fairly parallel. Therefore, putting the most emphasis on the estimates of the 2006–10 time window may reveal relevant information about the OWL's real impact.

6.2 A Difference-in-Differences Strategy

As shown on top of Table 2, a comparison of the columns in Row 1 identifies the effect of the OWL. Treating weekends as a spatial control for weekdays and years before the OWL as a temporal control for years after the OWL, a DD strategy similar to that of the previous section is applied to estimate the impact of the OWL in Beijing. The Beijing sample and the Jing-Jin Bay sample are estimated respectively to compare the possible difference. The standard DD estimation equation is shown as follows:

$$API_{it} = \beta_0 + \beta_1 \text{After}_t + \beta_2 \text{Weekday}_t + \beta_3 \text{After}_t * \text{Weekday}_t + \varepsilon_{it}, \quad (2)$$

where API_{it} denotes the API of PM_{10} in the city i on day t , After_t indicates if t is after the OWL, Weekday_t indicates if t is a weekday, $\text{After}_t * \text{Weekday}_t$ indicates if day t is both a weekday and after the OWL, and ε_{it} is a random noise term. β_3 is the DD estimator of interest, which measures the effect of the OWL on air pollution in Beijing based on changes in variations of pollution between weekdays and weekends before and after the OWL. The log format of the API is also estimated. Besides the standard specification, five alternative specifications are used to estimate Equation (2), similar to the previous section. This includes adding weather controls, adding time FE, and adding a linear, quadratic, or cubic time trend. For the estimation of the Jing-Jin Bay sample, standard errors are clustered at the city level.

Similar to the previous section, the OWL's real effect is examined on four symmetric enlarged time windows, 2007–09, 2006–10, 2005–11, and 2004–12, which compare the weekday–weekend pollution gap one year before and one year after, two years before and two years after, three years before and three years after, and four years before and four years after the OWL year. By running separate regressions on these time windows, the ATEs are obtained standing for the one-year, two-year, three-year, and four-year average impact of the OWL policy.

To ensure the causality from the real event analysis, similar placebo events are generated in both the pre-OWL period and the post-OWL period. The pre-OWL period includes three placebo events: 2005, 2006, and 2007. These placebo events generate three one-year radius comparison (04vs05, 05vs06, and 06vs07) and a two-year radius comparison (04–05vs06–07), similar to the post-OWL events and comparisons. Separate regressions are run for these eight placebo time intervals.

The estimated fake effects measure how weekday–weekend pollution would change had the OWL not occurred (i.e., the pre-OWL placebos) or in the absence of the OWL (i.e., the post-OWL placebos).

6.3 Empirical Findings of the Two Samples

The results of the OWL’s effect on air pollution in the Beijing sample and the Jing-Jin Bay sample are presented in Tables 6A and 6B respectively. Only the logged format is reported, except for those with different significance signs for levels estimates. Though the estimates are all negative for the Beijing sample, no significant signs appear for these time windows. This is probably because the Beijing

Table 6A: The effect of the OWL on air pollution: second diff-in-diff (Beijing sample).

	(1)	(2)	(3)	(4)	(5)	(6)
2007–09 ^a	–0.0473 (0.0582) [0.042]	–0.0276 (0.0529) [0.190]	–0.0369 (0.0488) [0.456]	–0.00150 (0.0647) [0.457]	–0.0380 (0.0488) [0.459]	–0.0368 (0.0489) [0.456]
2006–10 ^a	–0.0579 (0.0449) [0.039]	–0.0414 (0.0414) [0.196]	–0.0519 (0.0376) [0.385]	–0.0525 (0.0376) [0.385]	–0.0526 (0.0372) [0.393]	–0.0538 (0.0373) [0.390]
2005–11 ^a	–0.0399 (0.0378) [0.037]	–0.0268 (0.0349) [0.197]	–0.0334 (0.0313) [0.384]	–0.0329 (0.0313) [0.384]	–0.0335 (0.0313) [0.384]	–0.0328 (0.0313) [0.385]
2004–12 ^a	–0.0370 (0.0331) [0.038]	–0.0286 (0.0306) [0.194]	–0.0260 (0.0274) [0.389]	–0.0259 (0.0274) [0.392]	–0.0263 (0.0274) [0.390]	–0.0261 (0.0273) [0.392]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimator for the logged API in four enlarged time windows. Robust standard errors are in parenthesis. R-squared are in brackets. (1)–(6) denotes specification (1) to (6) as discussed in the empirical strategy section. The number of observations for each time window are 634, 1271, 1852, and 2346 respectively.

^aThe period excludes the year of 2008.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

sample is too small to have enough observations to perform strong statistical tests. Moving to the Jing-Jin Bay sample, the two-year and three-year average estimates show negative and significant signs across most specifications. Given the effects are shrunk in the Jing-Jin Bay sample, the real impact of the OWL is expected to be larger than the two-year and three-year impacts estimated here of a 4–5 percent reduction in pollution. Though the four-year impact of the OWL is not significant using the logged format, it becomes more significant using the levels format, which was calculated to be roughly a 3 percent reduction of pollution.

Table 6B: The effect of the OWL on air pollution: second diff-in-diff (Jing-Jin Bay sample).

	(1)	(2)	(3)	(4)	(5)	(6)
2007–09 ^a	–0.0282 (0.0415) [0.081]	0.00275 (0.0389) [0.193]	–0.0344 (0.0353) [0.422]	–0.0329 (0.0449) [0.422]	–0.0359 (0.0352) [0.428]	–0.0329 (0.0354) [0.424]
2006–10 ^a	–0.0481 (0.0309) [0.072]	–0.0288 (0.0287) [0.196]	–0.0460* (0.0264) [0.374]	–0.0474* (0.0263) [0.378]	–0.0459* (0.0261) [0.383]	–0.0489* (0.0260) [0.386]
2005–11 ^a	–0.0451* (0.0259) [0.075]	–0.0280 (0.0240) [0.203]	–0.0399* (0.0218) [0.377]	–0.0393* (0.0217) [0.380]	–0.0402* (0.0217) [0.378]	–0.0392* (0.0217) [0.381]
2004–12 ^a	–0.0354 (0.0225) [0.069]	–0.0246 (0.0211) [0.198]	–0.0255 (0.0190) [0.379]	–0.0257 (0.0189) [0.381]	–0.0258 (0.0189) [0.379]	–0.0258 (0.0189) [0.380]
API	–6.403** (2.920) [0.056]	–5.074* (2.756) [0.165]	–5.244** (2.606) [0.287]	–5.269** (2.603) [0.289]	–5.268** (2.605) [0.288]	–5.278** (2.603) [0.288]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimator for the logged API in four enlarged time windows except for otherwise marked as API in the last window. Robust standard errors are clustered at the city level and presented in parenthesis. R-squared are in brackets. (1)–(6) denotes specification (1) to (6) as discussed in the empirical strategy section. The number of observations for each time window is 1148, 2341, 3439, and 4571 respectively.

^aThe period excludes the year of 2008.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

As for the placebos presented in Tables 7A and 7B, both samples do not have negative and significant estimates in the pre-OWL period. This suggests that the weekday–weekend air pollution gap does not significantly reduce in the absence

Table 7A: Falsification test: second diff-in-diff (Beijing sample).

	(1)	(2)	(3)	(4)	(5)	(6)
Pre-Olympics						
04vs05	−0.0384 (0.0699) [0.001]	−0.0486 (0.0641) [0.185]	−0.0255 (0.0525) [0.570]	−0.0425 (0.0564) [0.571]	−0.0229 (0.0527) [0.571]	−0.0237 (0.0527) [0.571]
05vs06	0.0460 (0.0694) [0.003]	0.0473 (0.0637) [0.204]	0.0690 (0.0552) [0.482]	0.0869 (0.0702) [0.482]	0.0740 (0.0553) [0.492]	0.0703 (0.0554) [0.492]
06vs07	0.0886 (0.0648) [0.009]	0.0648 (0.0599) [0.201]	0.0712 (0.0563) [0.396]	0.0413 (0.0702) [0.396]	0.0697 (0.0556) [0.401]	0.0711 (0.0555) [0.402]
04–05 vs 06–07	0.0695 (0.0479) [0.002]	0.0695 (0.0479) [0.002]	0.0685 (0.0463) [0.155]	0.0683 (0.0463) [0.156]	0.0685 (0.0463) [0.155]	0.0686 (0.0463) [0.155]
Post-Olympics						
09vs10	−0.110* (0.0612) [0.006]	−0.0986* (0.0572) [0.152]	−0.0922* (0.0512) [0.449]	−0.0977* (0.0527) [0.450]	−0.0867* (0.0501) [0.456]	−0.0868* (0.0501) [0.457]
10vs11	0.0238 (0.0683) [0.005]	0.0161 (0.0629) [0.180]	0.00532 (0.0528) [0.498]	0.0179 (0.0542) [0.499]	0.00653 (0.0528) [0.499]	0.00621 (0.0528) [0.499]
11vs12	0.00849 (0.0687) [0.002]	0.0106 (0.0643) [0.177]	0.0108 (0.0596) [0.436]	0.0701 (0.0759) [0.439]	0.0112 (0.0599) [0.436]	0.0109 (0.0597) [0.436]
09–10 vs 11–12	−0.0259 (0.0460) [0.001]	−0.0259 (0.0460) [0.001]	−0.0318 (0.0436) [0.130]	−0.0318 (0.0436) [0.130]	−0.0317 (0.0436) [0.131]	−0.0316 (0.0436) [0.131]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimators of the placebo events for the logged API. Robust standard errors are in parenthesis. R-squared are in brackets. All specifications are the same as reported in Table 6. The number of observations for each time window is 599, 624, 656, 1255, 615, 594, 566, and 1181 respectively.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

of the OWL policy. Though there appear to be some positive and significant signs for the 05vs06 and 04–05vs06–07 time windows on the Jing-Jin Bay sample, it suggests that the weekday–weekend pollution gap gets enlarged in the absence of the OWL policy. In this case, the real effects of the OWL may be underestimated,

Table 7B: Falsification test: second diff-in-diff (Jing-Jin Bay sample).

	(1)	(2)	(3)	(4)	(5)	(6)
Pre-Olympics						
04vs05	−0.0296 (0.0457) [0.088]	−0.0538 (0.0425) [0.256]	−0.0238 (0.0349) [0.547]	−0.0453 (0.0375) [0.548]	−0.0227 (0.0349) [0.547]	−0.0230 (0.0349) [0.547]
05vs06	0.0381 (0.0458) [0.085]	0.0484 (0.0424) [0.256]	0.0712* (0.0373) [0.473]	0.0936* (0.0478) [0.473]	0.0792** (0.0371) [0.485]	0.0749** (0.0371) [0.485]
06vs07	0.0638 (0.0433) [0.109]	0.0291 (0.0403) [0.260]	0.0381 (0.0376) [0.413]	0.0110 (0.0477) [0.413]	0.0350 (0.0372) [0.417]	0.0363 (0.0372) [0.417]
04–05 vs 06–07	0.0531* (0.0318) [0.094]	0.0531* (0.0318) [0.094]	0.0617** (0.0302) [0.251]	0.0616** (0.0302) [0.254]	0.0619** (0.0302) [0.252]	0.0618** (0.0302) [0.251]
Post-Olympics						
09vs10	−0.103** (0.0426) [0.027]	−0.0987** (0.0402) [0.148]	−0.0702* (0.0358) [0.422]	−0.0665* (0.0369) [0.422]	−0.0629* (0.0351) [0.432]	−0.0630* (0.0350) [0.433]
10vs11	−0.00577 (0.0463) [0.039]	−0.0106 (0.0429) [0.167]	−0.0280 (0.0358) [0.467]	−0.0154 (0.0363) [0.468]	−0.0271 (0.0356) [0.467]	−0.0273 (0.0356) [0.467]
11vs12	0.0604 (0.0473) [0.025]	0.0569 (0.0446) [0.160]	0.0583 (0.0411) [0.390]	0.125** (0.0509) [0.394]	0.0610 (0.0414) [0.391]	0.0598 (0.0412) [0.391]
09–10 vs 11–12	−0.0255 (0.0318) [0.022]	−0.0255 (0.0318) [0.022]	−0.0280 (0.0294) [0.162]	−0.0281 (0.0294) [0.162]	−0.0280 (0.0294) [0.162]	−0.0281 (0.0294) [0.162]
Weather		Yes	Yes	Yes	Yes	Yes
Time FE			Yes	Yes	Yes	Yes
Linear				Yes		
Quadratic					Yes	
Cubic						Yes

Notes: Column (1)–(6) reports the estimated coefficients of the DD estimators of the placebo events for the logged API. Robust standard errors are clustered at the city level and presented in parenthesis. R-squared are in brackets. All specifications are the same as reported in Table 6. The number of observations for each time window is 1,120, 1,164, 1,196, 2,316, 1,145, 1,127, 1,110, and 2,255 respectively.

***Significant at the 1 percent level.

**Significant at the 5 percent level.

*Significant at the 10 percent level.

given the enlarged pollution gap in the instances of placebo events. Focusing on the post-OWL period, all fake estimates are not significantly different from zero, except for 09vs10. The negative and significant estimates of 09vs10 are probably because the book *Beijing Travel Geography*, published in the beginning of 2010 (see Table 1A), attracted more travelers to Beijing during weekends. Travelers may cause more pollution during weekends in Beijing, which could account for increased pollution during weekends in Beijing, as shown in Figure 7(a). Otherwise, the insignificant estimates for the post-OWL period suggest that the results from the real DD analysis are causal.

6.4 Relationship with Previous Studies

Using the weekend as a twin day for weekdays, this section isolates the long-run impact of the OWL from the Olympic-year policy package and identifies an impact of 3–5 percent reductions in pollution. These estimates are close to the one-year estimate found by Chen et al. (2013) of 5.8 percent reduction mostly caused by the OWL, but are much smaller than the short-run estimate found by Viard and Fu (2015) of a 20 percent reduction due to the OWL. Compared with the estimates found in the previous section, these estimates suggest that other Olympic year policies rather than the OWL played a major role in the significant air pollution drop in Beijing.

These smaller estimates of the OWL's impact are reasonable. First, a rudimentary calculation yields an impact of a 10 percent reduction, given car emissions contribute to 50 percent of total emissions, and the OWL restricts 20 percent of cars. Second, the API data reported by MEP is highly aggregated into daily and city averages, which also covers the unrestricted hours and unrestricted stations. Third, using either the Beijing sample or the Jing-Jin Bay sample tends to underestimate the real impact, as explained in the first subsection. Therefore, the estimated impact of a 3–5 percent reduction is reasonable because both data aggregation and sample underestimation shrunk the number from the rudimentary calculation.

7 Conclusion

Air pollution is still a major environmental problem in the developing world, and an increasing number of cities have enforced or extended driving restrictions in recent years. Previous literature finds that the short-run effect of the OWL is 21 percent and the one-year impact of the Olympic-year policy package is 19 percent

in reducing Beijing's air pollution. The long-run effect of the OWL and how the effect is compared with that of the policy package were unknown. Using a twin city as a control, this study finds that the two-year, three-year, and four-year average impact of the Olympic-year policy package is 13–15 percent. Exploiting a twin day as a control, this study further identifies that the two-year, three-year, and four-year impact of the OWL policy is 3–5 percent, though only significant for the Jing-Jin Bay sample.

These new findings suggest that compared to the OWL, other policies enacted in the Olympic year played a major role in the significant air pollution drop in Beijing. This information is relevant for policymakers in other parts of China to make decisions about whether to reduce local pollution by enforcing driving restrictions or applying other policies similar to Beijing's in the Olympic year. To finally figure out which policy may have a largest impact, further analysis needs to be done concerning the impact from plant closures/relocations, the introduction of new emission standards, subway extensions, and so forth.

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