The Effects of Driving Restrictions on Air Quality: São Paulo, Bogotá, Beijing, and Tianjin

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Abstract

In a typical driving restriction, vehicle use is restricted based on the vehicle's license plate; one cannot drive vehicles with certain license plate numbers on certain days. Driving restrictions have been used as a method to reduce urban air pollution or traffic congestion because they are easy and inexpensive to implement. We investigate whether driving restrictions introduced in São Paulo, Bogotá, Beijing and Tianjin have improved air quality. Across different versions of the driving restrictions there is no evidence that the overall air quality at different places has been improved. However, several important results show up in this extensive analysis. Temporal shifting of driving is likely to appear when the restrictions are only effective during certain hours of weekdays. Driving restrictions could potentially reduce the extreme concentrations of air pollutants. Driving restrictions can only be expected to alleviate air pollution when implemented with an extended schedule or in an extended region. The effects of the driving restrictions are primarily on the concentrations of CO and PM_{10}.

Keywords: driving restriction, air quality

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Introduction

Motor vehicles are the primary source of carbon monoxide (CO) and are an important source of volatile organic compounds (VOC) and oxides of nitrogen (NO_x) that are responsible for the formation of photochemical smog and ground-level ozone. Vehicular emissions also contribute to the ambient air concentrations of sulfur dioxide (SO_2) and particulate matter (PM_{10}) (EPA, 1994). Due to low assimilative capacity, vehicular emissions have been a major concern in urban areas. Measures to improve urban air quality often target motor vehicles, such as increasing fuel economy and altering gasoline content. In this paper we focus on one such policy for reducing emissions from vehicles: driving restrictions.

In a typical driving restriction, vehicle use is restricted based on the vehicle's license plate; one cannot drive vehicles with certain license plate numbers on certain days. Driving restrictions have been used as a method to reduce urban air pollution or traffic congestion because they are easy and inexpensive to implement. The *Restricción Vehicular* (traffic restriction) policy in Santiago, Chile was implemented in 1986 and *Hoy No Circula* (One day without a car) was adopted in the Mexico City metropolitan area in 1989. Following these two, several more Latin American cities introduced driving restrictions, including São Paulo, Brazil and Bogotá, Columbia. Beijing and its neighboring city Tianjin also implemented driving restrictions during the 2008 Olympic Games and a modified version of the restriction continued in Beijing after the Olympics.

Although driving restrictions have been in place for a long time and discussions are ongoing about whether to adopt similar restrictions in places around the world, there are not many studies, empirical or theoretical, of the effect of driving restrictions on air quality, congestion, or energy saving. Eskeland and Feyzioglu (1997) examine the effect of *Hoy No Circula* on gasoline demand and car ownership in Mexico City during the period 1984-1993. Davis (2008) measures the effect of *Hoy No Circula* on air quality using hourly air pollution records from monitoring stations. With pollution levels before the implementation of *Hoy No Circula* as a comparison group to control for seasonality, pollution levels of five major pollutants before and after the restrictions are compared. Davis (2008) controls for possible confounding factors by restricting his analysis to a relatively small time window around the implementation of the restriction and by using a regression discontinuity (RD) design. These two studies found no evidence that *Hoy No Circula* improved air quality in Mexico City.

In our study we investigate whether driving restrictions in São Paulo, Bogotá, Beijing, and Tianjin have improved air quality. Compared to *Hoy No Circula*, the driving restrictions we study are different in terms of the number of restricting hours and the percentage of vehicles that are restricted on each day, and whether the restriction alternates its schedule. *Hoy No Circula* has a fixed schedule—the same last digits of the license plate number are banned on a fixed weekday—which makes it easier to be bypassed. The driving restrictions in Bogotá and Beijing periodically change the days on which vehicles with a certain last digit are banned from the road. We will examine whether these different versions of driving restrictions implemented at different places have improved air quality.

We use several strategies to control for possible confounding factors. Similar to Davis (2008), we restrict our samples to relatively narrow time windows around the implementation of the restrictions and we also use a regression discontinuity (RD) design. Another approach we use for addressing time-varying omitted variables is to compare where the driving restriction is implemented to adjacent regions. Across different versions of the driving restrictions there is no evidence that the overall air quality at different places has been improved. However, several important results show up in this extensive analysis. Temporal shifting of driving is likely to appear when the restrictions are only effective during certain hours of weekdays. Driving restrictions could potentially reduce the extreme concentrations of air pollutants. Driving restrictions can only be expected to alleviate air pollution when implemented with an extended schedule or in an extended region. The effects of the driving restrictions are primarily on the concentrations of CO and PM_{10}.

The rest of the paper proceeds as follows: In Part I we investigate the two driving restrictions adopted in the metropolitan region of São Paulo and São Paulo municipality respectively. Part II is devoted to the ongoing driving restriction in Bogotá, and in Part III we examine the restrictions introduced during the 2008 Olympic Games in Beijing and Tianjin and a revised restriction that is still in place in Beijing. We conclude in the last part.

Part I: São Paulo

A survey of 1000 São Paulo residents conducted in the early 1990s revealed that air pollution was considered the prime environmental problem at the neighborhood level by most respondents, with 89% of respondents agreeing that some government action was necessary to solve the problem (Jacobi et al., 1999). To respond to these public views, in winter 1995 the driving restriction *Operação Rodízio*, as a voluntary scheme, was introduced by the Technical Agency for Environmental Sanitation of the State government (*Companhia de Tecnologia de Saneamento Ambiental*—CETESB) in the São Paulo metropolitan region (SPMR). SPMR consists of São Paulo municipality and other 38 municipalities. *Operação Rodízio* restricted the use of 20% of the car fleet in the SPMR between 7:00 a.m. and 8:00 p.m. on each weekday, based on the last digit of the vehicle’s license plate number. For example, vehicles with license plate ending with 1 or 2 could not be used on Mondays. The success of the trial scheme encouraged the state to legalize *Operação Rodízio* in 1996. The compliance rate of the program was high. A total of 93% of cars adhered to the program (Hochstetler and Keck, 2007). The adoption of the driving restriction was primarily intended to control the high levels of air pollution in the SPMR during the winter months. The restriction lasted for only three years, during August of 1996, and June to August of 1997 and 1998 (Mahendra, 2008).

In 1997, however, a city *rodízio* was adopted by the São Paulo municipal authority to be effective only in a 152 km^2 area within the 'enlarged downtown' (*centro expandido*) of the city. The city *rodízio* program that is currently in operation for 11 months of the year (excluding January) became permanent in 1999 after the State government scheme was terminated. It limits the circulation of 20% of the vehicles in peak hours, between 7:00–10:00 a.m. and 5:00–8:00 p.m. on weekdays.

In recent years, the vehicle fleet in São Paulo has been increasing rapidly in spite of the driving restriction program. Because of the accelerated rate of motorization occurring since 2003, the fleet is growing at a rate of 7.5% per year, with almost 1,000 new cars bought in the city every day. Evidence indicates that 25% of restricted drivers have bought more cars with varying last digits on the license plates (Mahendra, 2008). The fixed schedule of the city *rodízio* makes it easy to be bypassed as also seen in Mexico City (Davis, 2008).

Air quality monitoring in the SPMR started in 1974 by the CETESB. In 1982 a network of automatic stations was introduced and modified in 1996. Currently there are 21 monitoring stations located throughout the SPMR and twelve of them are in the São Paulo Municipality. The network reports hourly measures of CO, PM_{10}, nitrogen monoxide (NO), nitrogen dioxide (NO_2), NO_x, ozone and SO_2. These measures have been used in scientific works and are reported to the public in the form of an Air Quality Index.

For *Operação Rodízio*, the best data we could gather are annual averages and maxima of the air pollutants monitored at each station from the historical reports prepared by the CETESB covering 1990-1997. About 30% of the historical annual statistics were marked as "unrepresentative" in the reports, which means that the criterion for representativeness of the data used by the CETESB was not met.[4] We form the base sample of the analysis by excluding these "unrepresentative" observations. For robustness we also estimate the model using all the data points we gathered. Meteorological data of this time period are collected from the Global Surface Network of the Global Climate Observing System[5]. Table 1 describes these pollutant and temperature statistics.

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[4] There are 23, 34, 21, 27 and 38 statistics of CO, PM_{10}, NO_2, O_3, and SO_2 respectively are marked as unrepresentative. The criterion for representativeness of the data used by CETESB is "for yearly average, 1/2 of the daily averages have to be valid for the four-month period from January to April, May to August and September to December" (CETESB, personal communication, January 2010).

[5] The Global Climate Observing System is an international institution co-sponsored by the World Meteorological Organization, the Intergovernmental Oceanographic Commission, the United Nations Environment Programme, and the International Council for Science. Its goal is to provide comprehensive information on the total climate system.

The empirical analysis of the city *rodizio* focuses on the period of 1998-2008 using hourly air pollution records from the CETESB monitoring stations in São Paulo municipality. Data from 15 stations were collected. Ten of them were in operation during the entire study period. For our analysis we only use observations from the stations that ran through the entire study period to prevent compositional changes from biasing the results. Weather parameters, temperature, relative humidity and wind speed, were collected from the same monitoring network. Table 2 describes pollution levels and weather parameters of the sample period.

In the base specification, air pollution in logs, y_t, is regressed on an indicator variable D_t for observations under the implementation of a driving restriction and on a vector of covariates x_t:

$$y_t = \gamma_0 + \gamma_1 D_t + \gamma_2 x_t + u_t. \tag{1}$$

The coefficient of interest $\gamma_1$captures the effect of the driving restriction on air pollution level.

For *Operação Rodízio*, x_t in (1) includes annual mean and maximum temperature. We estimate the effect of *Operação Rodízio* by ordinary least squares (OLS) using the base sample for the time period 1990-1997. We also run the same set of regressions for the time window 1990-1997 with all data we collected, i.e. including "unrepresentative" observations. For these two specifications, the indicator variable takes the value one after 1996 when the driving restriction was legalized. We also estimate the effect of *Operação Rodízio* with the indicator variable equal one after 1995 when the driving restriction was voluntary. Table 3 reports OLS estimates and standard errors of the coefficient of interest for each pollutant. Standard errors are clustered at monitoring station. Across different specifications, most of the coefficients for carbon monoxide and PM_{10} are negative and significant at different levels. The first maximum of PM_{10} is significantly reduced under all specifications. Taken literally, the coefficient of the first maximum of PM_{10} implies that *Operação Rodízio* is associated with at 10% percent reduction in the first maximum of PM_{10} during the sample period. Given the availability of data, we cannot further use a RD design to control for possible time-varying omitted variables.

For city *rodízio*, since we only have data after the implementation of the policy we cannot use pollution levels before the implementation as a comparison group to control for seasonality or use a RD design to control for possible time-varying confounding factors. Given that the policy is only effective in the "enlarged downtown" of São Paulo municipality, we use the outskirt of São Paulo municipality, where the driving restriction was not implemented, to control for seasonality and possible time-varying confounders. Note that in this way we only identify the relative effects of the driving restriction. Figure 1 plots weekly average pollution levels across hours of the day for both the downtown and the outskirts of São Paulo municipality.

Weekly average pollution levels are constructed by averaging across the same hours for each week and all monitoring stations. There is substantial variation in pollution levels over the course of the day. Compared to the outskirts, the downtown area has higher concentrations of CO, NO, NO_2 and NO_x during the day, and has higher concentration of SO_2 during both the day and night. The two areas have similar levels of $PM_{10,}$ and ozone during both the day and night. The vertical lines indicate the beginning and the end of the driving restriction on each day. There is no visible change in patterns for any of the pollutants that coincides with the hours of implementation of city *rodízio*.

In our analysis of city *rodízio*, the indicator dummy variable D_t equals 1 for the observations from the stations located in the downtown area and when the restriction is effective, i.e., 7:00–10:00 a.m. and 5:00–8:00 p.m. on weekdays. The vector of covariates, x_t, includes a dummy variable indicating the stations located in the downtown and another dummy variable indicating the hours when the restriction is effective; and indicator variables for month of the year, day of the week and hour of the day. In addition, x_t, includes quartics in temperature, relative humidity and wind speed.

We first estimate the effect of city *rodízio* on mean air pollution levels by OLS. Results are shown in the first row of Table 4a. The OLS results provide no evidence of an overall improvement in air quality. The only significant reduction is for ozone. A potential concern with the OLS estimates are possible changes in the way monitoring stations monitor and report air quality, because any changes in monitoring stations that are correlated with pollution levels will cause the estimates to be biased. To address this concern we report in the second row of Table 4a estimates from a station fixed effects specification. The estimates are very close to the first row of Table 4a. We should be cautious when interpreting the coefficients of ozone. Ozone is not usually emitted directly into the air, but at ground-level is created by a chemical reaction between NOx and VOC in the presence of sunlight. Even though vehicles contribute to both NOx and VOC, given that the chemical reactions through which NOx and VOC form ozone are complex and we do not observation VOC concentrations, we should not interpret too much of the coefficients of ozone.

Given that the *Operação Rodízio* reduced the maxima of several pollutants, we wonder whether city *rodízio* could also be associated with any reduction in extreme concentrations of pollutants. Moreover, there seems to be nonlinearities in the relationship between pollution and health (Davis, 2008), so it is important to assess the impact not only on mean pollution levels but also on maximum pollution levels. The third row of Table 4a provides estimates from an alternative specification of equation (1), with daily maximum air pollution as the dependent variable. The daily maximum pollution level is constructed by averaging across monitoring stations for each hour and then taking the maximum for each day. The reported coefficients correspond to the indictor of interest, which equals one for weekday observations from the stations located in the downtown area[6]. There is no evidence that daily maximum pollution levels were reduced by the implementation of city *rodízio*.

Even though the direct effect of the policy will be experienced during the hours when it is implemented, it could potentially affect pollution levels during all hours of a day. The last row of Table 4a reports OLS estimates of the effect of city *rodízio* on daily average pollution levels. The averages are constructed by averaging across all hours of each day and all monitoring stations. The regressors in this specification are the same as in the specification of daily maximum. For five out of the seven pollutants, we see negative effects even though the effect is only significant for NO_2.

To further investigate the effects of city *rodízio* during different hours of a day, Table 4b reports OLS estimates of the effects of the restriction on pollution levels in six intervals of hours: two intervals when the restriction is implemented (7:00-10:00 a.m. and 5:00-8:00 p.m.), three intervals when substitutive traveling of displaced trips are likely to happen (5:00-7:00 a.m., 10:00 a.m.-5:00 p.m. and 8:00 p.m.-12:00 a.m.) and one interval of night hours (12:00-5:00 a.m.). The results of this breakdown are interesting. The effects of city *rodízio* contradict during the two intervals when it is implemented, except for NO_2. During the morning interval (7:00-10:00 a.m.), city *rodízio* could be associated with reductions in CO, NO, NO_2, NO_x and SO_2 and increases in PM_{10} and ozone, even though the reductions are only statistically significant for NO and $NO_{2.}$ During the evening interval (5:00-8:00 p.m.), the restriction increases the concentrations of CO, NO, NO_x and $SO_{2,}$ and decreases the concentration of PM10 and ozone. During 5:00-7:00 a.m., the driving restriction has no significant effect on air quality; during 10:00 a.m.-5:00 p.m, city *rodízio* could be associated with significant increases in all air pollutant levels except ozone; and during 8:00 p.m.-12:00 a.m., city *rodízio* reduces most air pollutant levels. City *rodízio* could also be associated with significant decreases in all air pollutant levels except ozone during the night (12:00-5:00 a.m.).

In summary, city *rodízio* could only be associated with trivial alleviation of air pollution, which can be seen from the reductions in daily average pollution levels. The temporal shifting effect of the driving restriction deserves attention. However, when we interpret these results we should be aware that we only identify the relative effects of city *rodízio* since we use the outskirt of São Paulo to control for seasonality, and unobservable time-varying confounders. That is, when we see a negative coefficient, it should be interpreted as the net effect of the restriction on the pollution levels in the downtown area. We cannot separate whether the restriction reduces air pollution in the downtown area or increases pollution in the outskirt area. Results in Table 4b indicate that city *rodízio* could be associated with net reductions in some air pollutants during the hours when it is implemented and at night. However, during the daytime when the restriction is not effective, net increases in air pollutions in the

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[6] In this specification, the covariates include a dummy variable for weekday and a dummy variable for the downtown area, indicators for month of the year and day of the week, and weather quartics.

downtown area are large enough to overturn the reductions at night and during the hours when the restriction is effective in terms of the overall air quality.

Part II: Bogotá

Vehicular restrictions were first implemented in Bogotá in August 1998 as part of a program called *Pico y Placa*. 40% of private vehicles were restricted from operating in the city during weekdays between 7:00 and 9:00 a.m. and between 5:30 and 7:30 pm. Vehicles having any of four digits as the last digit of their number plate are restricted on each day. Thus, each vehicle is restricted from circulation during peak hours on 2 days per week. Since August 2001, public transportation in Bogota, including buses, minibuses and taxies, has also been restricted according to their license plates. 20% public vehicles are restricted from 5:00 a.m. to 9:00 p.m. from Monday to Saturday (*El Tiempo* 2001). TransMilenio buses, shuttles for work and school and tourism buses were exempted. In June 2004, the schedule of the restriction for private vehicles was expanded to from 6:00 to 9:00 a.m. and from 4:00 to 7:00 p.m. (Mahendra 2008). In February 2009, the ban was expanded again for private cars to be effective from 6 a.m. to 8 p.m. on each weekday. The schedule of the *Pico y Placa* is changed once a year to avoid the problem of buying another car.

The *Pico y Placa* scheme was implemented at the time the exemplary Bus Rapid Transit system of Bogotá, the TransMilenio, was being planned. So, one rationale for the program was to curb congestion while the TransMilenio was being constructed. The environmental argument for preventing air pollution was mentioned but not as the driving force behind the implementation of *Pico y Placa*. The schedule of the *Pico y Placa* scheme changes once a year in order to avoid the problem of households purchasing another car with a different last digit of the license plate number. Over the years the program has significantly reduced peak-hour congestion in Bogotá (Mahendra 2008). However, there has not been any study on the effect of *Pico y Placa* on air quality.

Since 1997, Bogotá has an air quality monitoring network administered by the District Administrative Department of the Environment (then Departamento Te´cnico Administrativo del Medio Ambiente (DAMA), Secretaría Distrital de Ambiente (SDA) since 2007). The network currently has 14 stations monitoring PM_{10}, $PM_{2.5}$, total suspended particulate (TSP), SO_2, NO, NO_2, NO_x, CO, O_3, and meteorological data (Zárate et al. 2007). Our empirical study uses hourly level pollution records from this monitoring network during the period 1997-2009. Our sample consists of observations from seven stations that were in use during the entire study period. Table 5 describes pollution levels from these stations. These stations do not monitor weather parameters, so we use weather averages from the same monitoring system for the study period. The descriptive statistics of weather parameters are also included in Table 5.

Figure 2 plots average daily pollution levels during the period of 1997-2009. Average daily pollution levels are constructed by averaging over all hours of the day and all monitoring stations. The vertical lines indicate the starting and changing points in the course of *Pico y Placa* on August 18, 1998, August 29, 2001, June 15, 2004 and February 6, 2009. CO levels decrease and then increase again in the early 2000s. PM_{10} levels remain stable with a small increase. All other pollutants vary widely across days but exhibit no discernable long-term patterns. Thus, there is no visible reduction in air pollution that coincides with the implementation or the expansions of *Pico y Placa*.

We first estimate the effect of *Pico y Placa* on air pollution during the hours when it is implemented. Given that the driving ban has gone through three expansions, we include four driving restriction indicator variables in equation (1). For the period 8/18/1998 to 8/28/2001, D_t equals one for the eighth, ninth, and 18th to 20th hours of weekdays. For the following periods 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009, D_t equals 1 from 5:00 a.m. to 9:00 p.m., from Monday to Saturday. The vector of covariates, x_t, includes indicator variables for month of the year, day of the week and hour of the day, and quartics in temperature, relative humidity and wind speed. Results estimated by OLS are shown in Table 6. Rows correspond to different driving restriction indicators. The coefficients are negative for CO, ozone and SO_2 after the first expansion of the restriction in 2001, but the coefficients are only statistically significant for ozone.

To address the potential bias caused by time-varying omitted variables, we estimate the effect of *Pico y Placa* using a RD design. Within a narrow time window, the unobserved factors influencing air quality are likely to be similar so that observations when *Pico y Placa* was not effective provide a comparison group for observations when *Pico y Placa* was effective. Thus, equation (1) is also estimated with a seventh-, eighth- or ninth-order polynomial time trend. Results are shown in Tables 7a-c. Across different specifications, estimates are very similar. Even though several negative coefficients show up, there is not enough evidence that *Pico y Placa* has significantly improved air quality. To control for time-invariant station heterogeneity, we also estimate a fixed-effect specification with a ninth-order time trend. Results are shown in Table 8, which are very similar to those in Table 7c.

Although *Pico y Placa* restrictions were only in place during certain hours, they could potentially affect pollution levels during all hours of the week. Thus, we also examine the effect of the policy by specifying the driving restriction dummies equal one for the entire period that the restrictions are implemented. For example, the first indicator variable equals one for every hour in the period 8/18/1998-8/28/2001. We first estimate this specification using OLS. Table 9 reports the estimates. As before, negative coefficients appear mostly for CO, ozone and SO_2. Results from a RD design with a seventh-, eighth- or ninth-order polynomial time trend are shown in Tables

10a-c. Still, we do not have enough evidence that *Pico y Placa* has significantly improved the overall air quality. Estimates from a fixed-effect model with a ninth-order time trend are also reported Table 11. These estimates are very similar to those in Table 10c.

Figure 3 plots residuals from a regression of log pollution levels on weather and seasonality covariates. These residuals are averaged across monitors within each week. The fitted lines are the predicted values of a regression of these residuals on driving restriction dummies specified as in Table 10c and a ninth-order polynomial time trend. Again, the vertical lines indicate the beginning and changing points in the course of *Pico y Placa*. CO decreases in 2004 and increases again later, PM_{10} decreases with the implementation of the policy but increases in 2001. The ninth-order polynomial seems to describe the underlying time trend adequately while maintaining some degree of smoothness. Thus, neither the OLS nor the RD specifications provide evidence of any improvement in the overall air quality in Bogotá.

To investigate the effects of *Pico y Placa* during the hours when it is not implemented, we report RD estimates of the effects of the restrictions on pollution levels for week nights (10:00 p.m.-5:00 a.m.) and weekends[7] in Table 12a-b. They both include a ninth-order polynomial time trend. Except for ozone, negative estimates show up for all air pollutants. For PM_{10} concentrations, especially, *Pico y Placa* can be associated with as high as 26% reductions during week nights after the last expansion. The restriction reduces about 6% of NO_2 and 10% of NO_x during weekends after the last expansion. Similar to the analysis of city *rodízio*, we also report RD estimates of the effects of the driving restrictions on maximum daily air pollution levels in Table 12c.[8] Negative coefficients show up for CO, PM_{10} and SO_2. Taken literally, after the last expansion of *Pico y Placa*, it can be associated with 51% and 48% reductions in daily maximum of CO and PM10 respectively.

In summary, even though *Pico y Placa* has not been effective in improving the overall air quality, it can be associated with some mild reductions in air pollution levels during week nights and weekends. One possible explanation is that even though public transportation has been under restriction all daytime, from 5 a.m. to 9 p.m. after it has been covered by the restriction, private vehicles are only restricted under peak hours in the morning and evening before the last expansion. Therefore, shifting displaced trips to other hours by private cars, as what we have seen under city *rodízio* in São Paulo, may have happened, but unfortunately we cannot separately identify this effect. That is, restraining the usage of public transportation in extensive may have lead to mild alleviation of air pollution levels, but the overall air quality has not been

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[7] For the time period 8/18/1998 to 8/28/2001, weekday nights include Monday to Friday nights and both Saturdays and Sundays are considered as weekends; and for 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009, weekday nights include Monday to Saturday nights and only Sundays are considered as weekends.

[8] The daily maximum pollution level is constructed by averaging across monitoring stations for each hour and then taking the maximum for each day. In this specification, the driving restriction dummies equal one for the entire period that the restrictions were implemented.

improved by the restriction. More importantly, *Pico y Placa* has significantly reduced the daily maximum of several air pollutants. Two factors could have lead to this result: one is that the restriction has spread out the driving of private vehicles and the other is that it has reduced the ridership of public vehicles.

Part III: Beijing and Tianjin

During the 2008 Beijing Olympics, similar driving restrictions were also adopted in Beijing and its neighboring municipality Tianjin. From 7/20 to 9/20/2008, a driving restriction was implemented in Beijing. 50% of the vehicle fleet—about 1.5 million cars—were taken off the road around the clock on alternate days. The same restriction was implemented in Tianjin during 8/6-8/15/2008, effective from 12 p.m. to 10 p.m. Police cars, fire trucks, ambulances, taxis, buses and a series of vehicles with special permits were exempt from the above traffic restrictions.

In addition to the above traffic control measures, before and during the Olympics Beijing Municipal Government implemented a series of air quality improvement measures in other sectors, including enhancing the utilization of natural gas to replace coal for electricity generation and heating, reducing local power generation by importing electricity from surrounding areas, suspending construction as well as imposing strict dust control on construction sites, and closing or relocating polluting industrial plants. Also, in the neighboring Tianjin municipality, Hebei, Shanxi, and Shandong provinces, and Inner Mongolia Autonomous Region, polluting factories were closed and high-emission cars were removed from roads (Clean Air Initiative, 2008). Given that these regulations came into effect gradually before the Olympics, we use a RD design to control for the potential confounding factors.

One major Post-Olympics traffic control measure in Beijing is “one day off the roads”. Under this regulation, 20% of cars are taken off roads on each weekday according to the last digit of license plates. The restriction was adopted on October 11, 2008. It was applicable within the 5th Ring Road, from 6 am to 9 pm for private cars and round the clock for government and business vehicles. On April 10, 2009 small changes were made to the restriction, with the effective hours changed to 7am to 8pm on weekdays for private cars. Every thirteen weeks cars alternate their restriction days according to the ending number of their plates.

Although there are multiple air quality monitoring stations in both Beijing and Tianjin monitoring PM_{10}, NO_2, SO_2, ozone and CO, real-time data from these stations are not available to the public. Instead, Daily Air Pollution Index (API) is reported by both the Ministry of Environmental Protection (MEP) of China, and Beijing and Tianjin Environmental Protection Bureau. The Chinese API is based on the air quality index used in the United States, and although the standards vary, the calculation methodology is the same. Each day the highest API value is reported, and the prominent pollutant is identified if API is greater than 50. We could retrieve average daily concentrations of the prominent pollutant from API. The conversion method is detailed in MEP technical notes in both Chinese and English, and has been used in several scientific studies (e.g., Andrews, 2008).

For our analysis of the driving restrictions in Beijing we use the API data from MEP for the time period 7/20/2007-10/31/2009. 19 days of this time window have SO_2 as the prominent pollutant, 109 days have API less than 50 and the rest have PM_{10} as the prominent pollutant. We focus our analysis on the concentrations of PM_{10}. For the days with SO_2 as the prominent pollutant, PM_{10} concentrations are treated as missing. For the days with API less than 50, the API levels are treated as the concentrations of PM_{10}. Figure 4 plots average daily PM_{10} concentrations for the study period. Vertical lines indicate the start and the end of the restriction during the Olympics and the start of the revised restriction. Weather parameters are collected from Weather Underground. Meteorological data from this website have been used in scientific studies, e.g., Wang, X. et al. (2009). Table 13 describes PM_{10} levels during this time period, as well as weather data. Wang, W. et al. (2009) collected PM_{10} samples at Peking University from 7/28 to 10/7/2008. For this time period, the correlation between their sample and our sample is 0.9383.

We set two indicator variables to estimate the effect of the driving restrictions on PM_{10} levels in Beijing. The first indicator variable equals one for the period 7/20-9/20/2008 and the second indicator variable equals one after October 11, 2008. The vector of covariates, x_t, includes indicator variables for month of the year, day of the week, and quartics in temperature, relative humidity and wind speed. We first estimate by using OLS, and then by using a RD design by adding a seventh-, eighth- or ninth-order polynomial time trend to the regression. Estimates are reported in Table 14a. The coefficients indicate that during the 2008 Olympics, the odd-even driving restriction was associated with at least 38% reduction in PM_{10} concentrations. But there is no evidence that the driving restriction after the Olympics has improved air quality. Figure 5 plots residuals from a regression of log PM_{10} levels on weather and seasonality covariates. The fitted lines are the predicted values of a regression of these residuals on driving restriction dummies and a ninth-order polynomial time trend. PM_{10} levels decrease substantially during the Olympics but go back to the levels before the Olympics. The discontinuities indicated in Figure 5 are consistent with the estimates reported in Table 14a. We also estimate the model using a sample excluding the days with APIs less than 50. Results are shown in Table 14b. These estimates could be interpreted as a lower bound of the effect of the driving restrictions.

We use the same method to construct the PM_{10} sample of Tianjin for the time period of 8/6/2007-10/31/2009. Summary statistics are shown in Table 15. 177 days of this time window have SO_2 as prominent pollutant, 99 days have API less than 50 and the rest have PM_{10} as prominent pollutant. Figure 6 plots average daily PM_{10} concentrations for the study period. Vertical lines indicate the start and the end of the restriction during the Olympics. We set the driving restriction indicator variable equal to one for 8/6-8/15-2008. Estimates using OLS and RD are put in Table 16a. The restriction could only be associated with mild reductions in PM_{10} given that the estimates are negative, but not statistically significant. Similar to Figure 5, Figure 7a plots residuals and a ninth-order polynomial time trend with a restriction intercept. Figure 7b is a zoom-in of Figure 7a between April and October in 2008. There is no discernable discontinuity. Estimates from a sample excluding the days with APIs less than 50 are reported in Table 16b.

Conclusion

This article examines the effectiveness of the driving restrictions in São Paulo, Bogotá, Beijing and Tianjin. Similar to what Davis (2008) found in his study of Mexcio City, there is no evidence that these restrictions have improved the overall air quality at different places. However, several important results show up in this extensive analysis. First, driving restrictions that are effective during peak hours of weekdays are likely to result in temporal shifting of driving. This type of restrictions is hardly to have any effect on overall air quality. Our analysis of city *rodízio* in São Paulo municipality clearly demonstrates the temporal variations in air pollutant levels with the effective hours of the restriction, and city *rodízio* can only be associated with trivial alleviation of air pollution. Second, driving restrictions could potentially reduce the extreme concentrations of air pollutants. *Operação Rodízio*, which was implemented in SPMR during winter months, successfully reduced the annual maximum of CO and PM10. The *Pico y Placa* in Bogotá has also reduced the daily maximum of CO and $PM_{10.}$ Third, only driving restrictions with extended implementation schedule and large implementation region are likely to be effective in improving air quality. This is not hard to understand. The more the extensive the restrictions are, the less room there is for temporal and spatial shifting of driving. *Operação Rodízio* was enforced for thirteen hours on each weekday. Even though our data for the time period when *Operação Rodízio* was implemented in SPMR are quite limited, we can still trace out its effects on the reduction of air pollution. Also, the odd-even restriction in Beijing, which put 50% of the vehicle fleet off the road during the Olympics, significantly reduced the concentration of PM_{10}. Fourth, the effects of the driving restrictions are primarily on the concentrations of CO and PM_{10}. Given the complexity of the chemical reactions between NOx and VOC that generate ozone and the lack of data of VOC, we tend not to interpret too much of the effects of the driving restrictions on ozone. Further research in this area is promising.

Future studies regarding the effects of different driving restrictions on the ridership of public transportation, vehicle registrations and composition, and gasoline sales are important to provide comprehensive evaluations of this urban policy. Moreover, welfare analysis of driving restrictions on different population groups, such as households with different income levels, also deserves more attention.

References

Andrews, S. Q. 2008. “Inconsistencies in Air Quality Metrics: ‘Blue Sky’ Days and PM10 Concentrations in Beijing.” *Environmental Research Letters* 3: 1-14.

Clean Air Initiative. 2008. “Temporary Air Quality Measures by Beijing for the Olympic Games.” URL: http://www.cleanairnet.org/caiasia/1412/article-72771.html, last accessed 2010-6-20.

Davis, L.W. 2008. “The Effect of Driving Restrictions on Air Quality in Mexico City.” *Journal of Political Economy* 116:38-81.

El Tiempo. 2001. “Pico Y Placa, Sign In, El Tiempo, 29 August.” URL: http://www.eltiempo.com/archivo/documento/MAM-464627, last accessed June 18, 2010.

Eskeland, G. S., and T. Feyzioglu. 1997. “Rationing Can Backfire: The ‘Day without a Car’ in Mexico City.” *World Bank Economic Review* 11 (3): 383–408.

Hochstetler, K. and Keck, M. 2007. *Greening Brazil: Environmental Activism in State and Society*, Durham, NC, and London: Duke University Press.

Jacobi, P., et al. 1999. “Governmental Responses to Air Pollution: Summary of a Study of the Implementation of *rodízio* in São Paulo.” *Environment and Urbanization* 11(1): 79-88.

Mahendra, A. 2008. “Vehicle Restrictions in Four Latin American Cities: Is Congestion Pricing Possible?” *Transport Reviews* 28(1): 105-133.

U.S. EPA. 1994. “Automobile Emissions: An Overview.” Fact Sheet OMS-5.

Wang, X., et al. 2009. “Evaluating the Air Quality Impacts of the 2008 Beijing Olympic Games: On-road Emission Factors and Black Carbon Profiles.” *Atmospheric Environment* 43: 4535-4543.

Wang, W., et al. 2009. “Atmospheric Particulate Matter Pollution during the 2008 Beijing Olympics.” *Environmental Science and Technology* 43: 5314-5320.

Zárate, E., et al. 2007. “Air Quality Modeling Over Bogota, Colombia: Combined Techniques to Estimate and Evaluate Emission Inventories.” *Atmospheric Environment* 41: 6302-6318.

Table 1
Air Quality in the SPMR, 1990-1997: Summary Statistics

	Observations	Mean	Standard Deviation	Minimum	Maximum
1st Maximum of CO	22	15.62	5.38	7.60	27.80
2nd Maximum of CO	22	13.37	3.65	7.30	20.70
Mean of PM_{10}	155	69.34	23.96	21.00	190.00
1st Maximum of PM_{10}	155	227.01	90.85	90.00	789.00
2nd Maximum of PM_{10}	155	196.65	59.24	82.00	460.00
Mean NO_2	13	0.06	0.02	0.03	0.09
1st Maximum of O_3	26	302.58	102.32	123.00	523.00
2nd Maximum of O_3	26	274.19	85.78	118.00	486.00
Mean SO_2	125	16.32	7.53	2.00	39.00
1st Maximum of SO_2	125	71.19	29.44	22.00	177.00
2nd Maximum of SO_2	125	61.46	24.96	21.00	154.00
Mean Temperature	165	20.00	0.30	19.67	20.54
Maximum Temperature	165	23.48	0.57	22.60	24.40

Note: CO and NO_2 are in parts per million. PM_{10} and O_3 and SO_2 are in micrograms per cubic meter. Temperature is in Celsius. The sample consists of the data are not marked as “unrepresentative” in the reports.

Table 2
Air Quality in São Paulo Municipality 1998-2008: Summary Statistics

	Observations	Mean	Standard Deviation	Minimum	Maximum
CO	517,696	1.41	1.17	0.00	21.70
PM_{10}	746,073	44.27	33.20	0.00	847.00
NO	311,588	82.23	109.46	0.00	1808.00
NO_2	298,173	60.48	36.24	0.00	399.00
NOx	298,289	0.10	0.10	0.00	1.63
O_3	408,093	32.62	33.74	0.00	390.00
SO_2	299,524	13.86	13.34	0.00	376.00
Temperature	143,232	19.90	4.61	1.30	36.90
Humidity	150,674	78.03	19.07	0.00	100.00
Wind speed	384,978	1.45	0.91	0.00	9.70

Note: CO and NO_x are in parts per million, and other pollutants are in micrograms per cubic meter.

Temperature is in Celsius and wind speed is in meters per second. Data are from stations that ran through the study period.

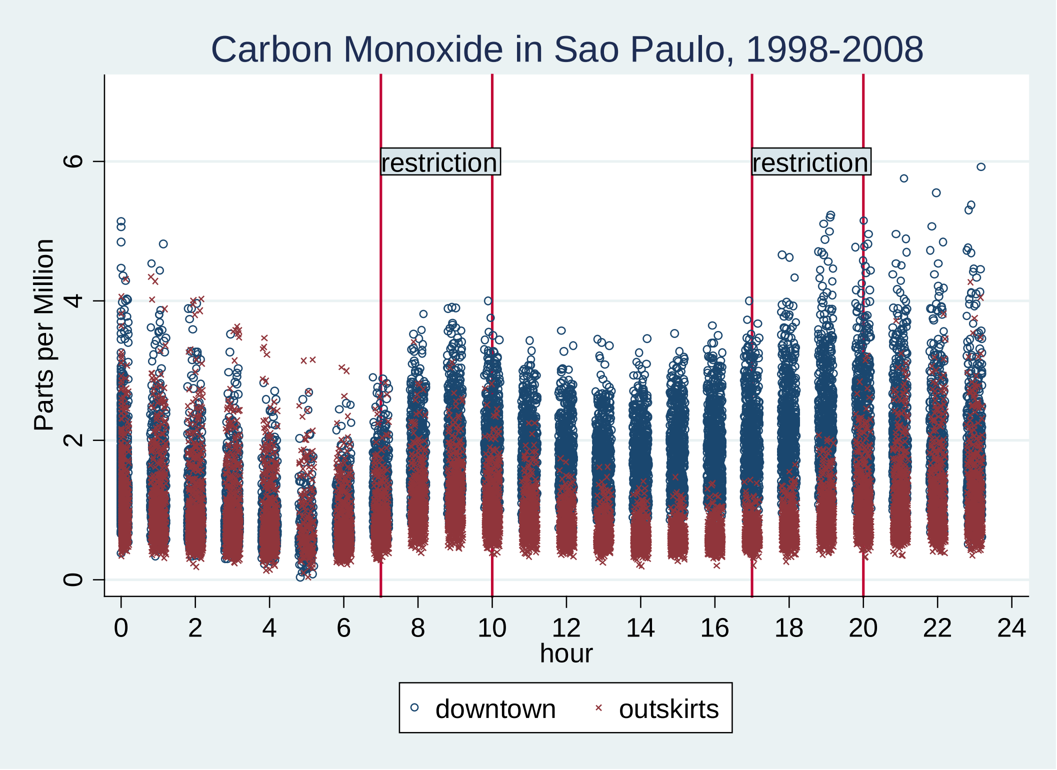
Table 3

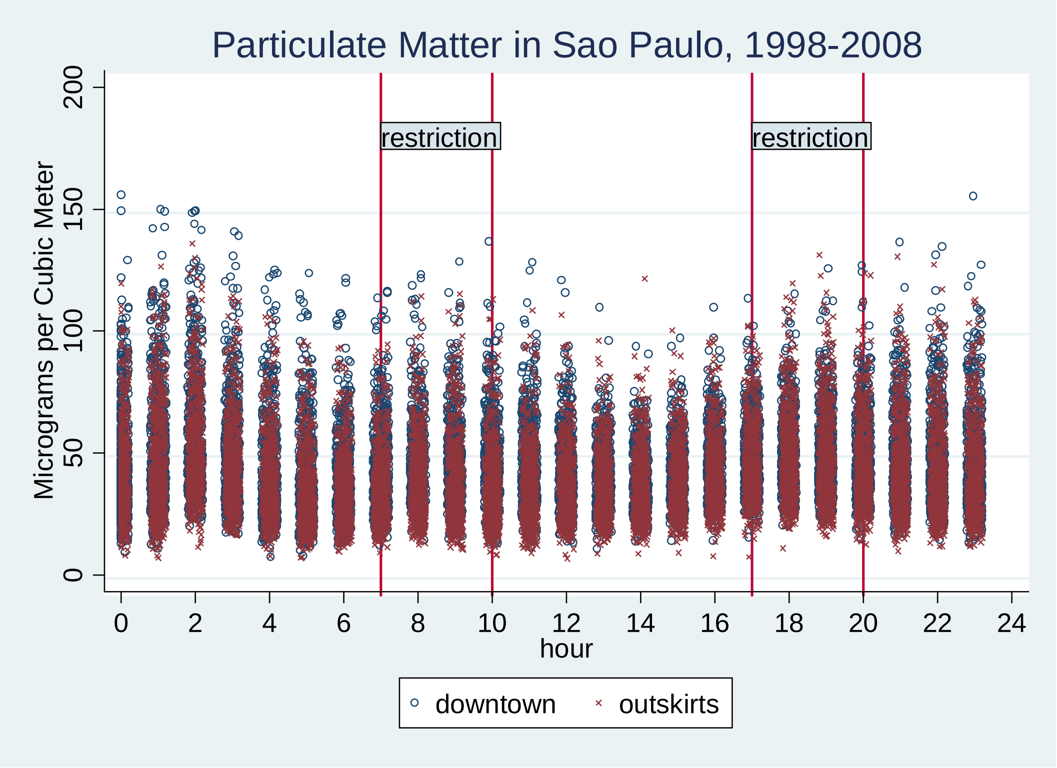
Effect of *Operação Rodízio* on Pollution Levels of SPMR: Least Squares

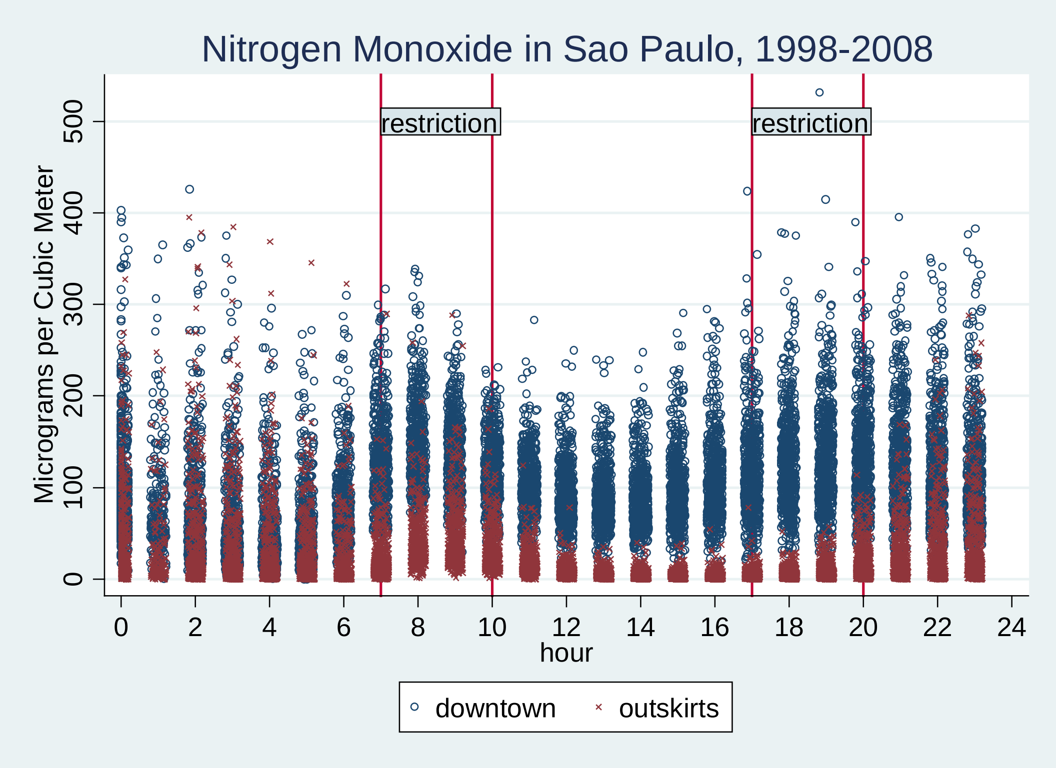
	CO 1st Max	CO 2nd Max	PM$_{10}$ Mean	PM$_{10}$ 1st Max	PM$_{10}$ 2nd Max	NO$_2$ Mean
1990-1997	-0.410**	-0.247*	-0.129*	-0.175***	-0.135**	0.246
	(0.096)	(0.091)	(0.059)	(0.040)	(0.041)	(0.160)
1990-1997 (All Data)	-0.222	-0.135	-0.056	-0.173***	-0.089**	0.268
	(0.164)	(0.133)	(0.056)	(0.034)	(0.031)	(0.148)
1990-1997 (Voluntary)	-0.406**	-0.252*	0.01	-0.100*	-0.054	0.246
	(0.091)	(0.083)	(0.044)	(0.044)	(0.037)	(0.160)

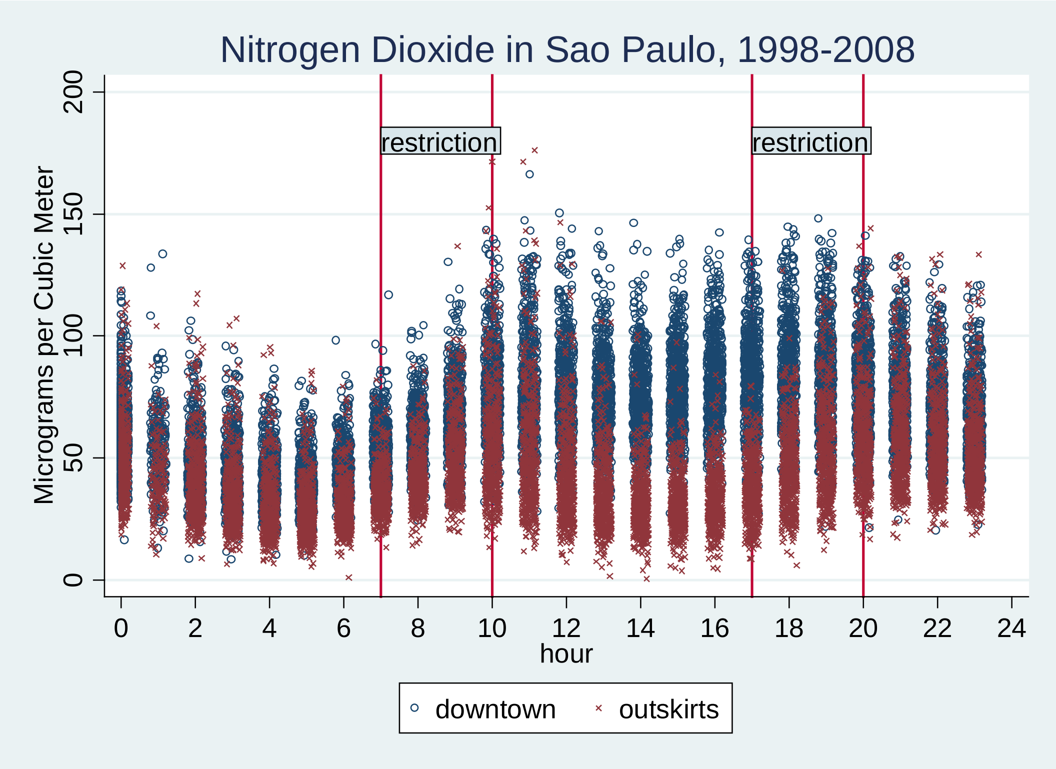
	O$_3$ 1st Max	O$_3$ 2nd Max	SO$_2$ Mean	SO$_2$ 1st Max	SO$_2$ 2nd Max
1990-1997	-0.177	-0.135	0.121	-0.136	-0.092
	(0.145)	(0.112)	(0.131)	(0.167)	(0.161)
1990-1997 (All Data)	0.119	0.127	0.366***	0.094	0.132
	(0.180)	(0.167)	(0.098)	(0.101)	(0.103)
1990-1997 (Voluntary)	-0.177	-0.135	0.188	-0.023	-0.02
	(0.145)	(0.112)	(0.105)	(0.119)	(0.107)

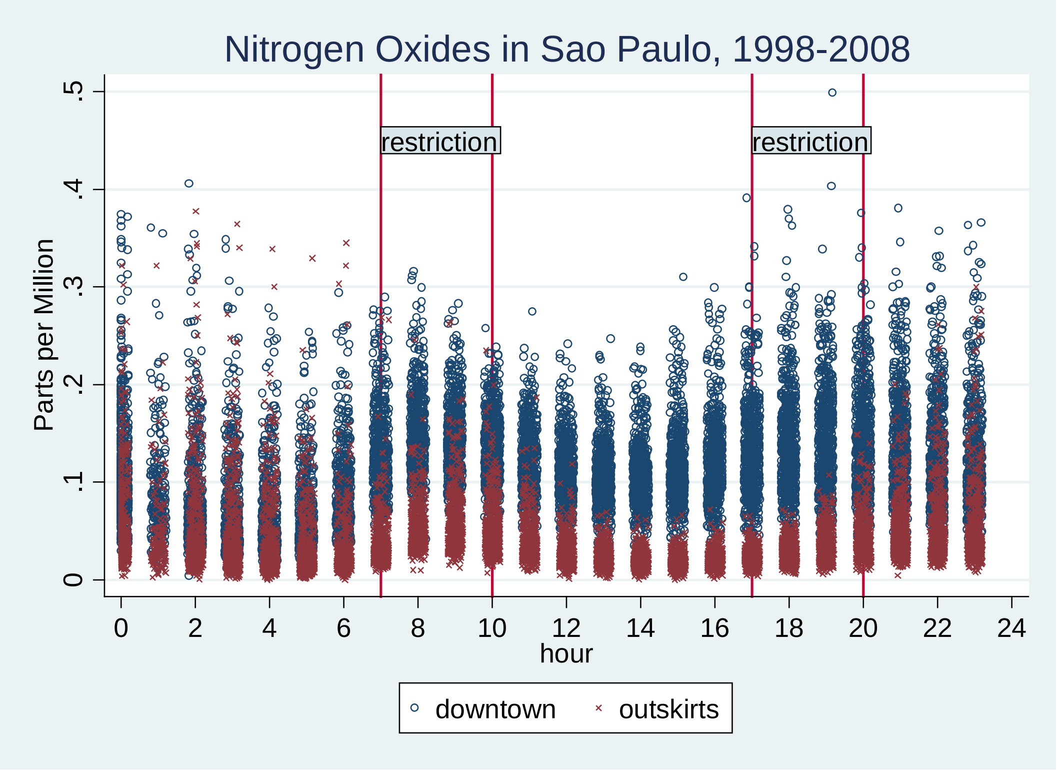
Note: This table reports estimates from 33 separate regressions. The dependent variable is pollution level in logs. The reported coefficients correspond to the indicator variable equal to one after the implementation of Operação Rodízio. For the first three rows the indicator variable is equal to one after 1996 and for the last row it is after 1995. Standard errors, in parentheses are cluster robust. * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

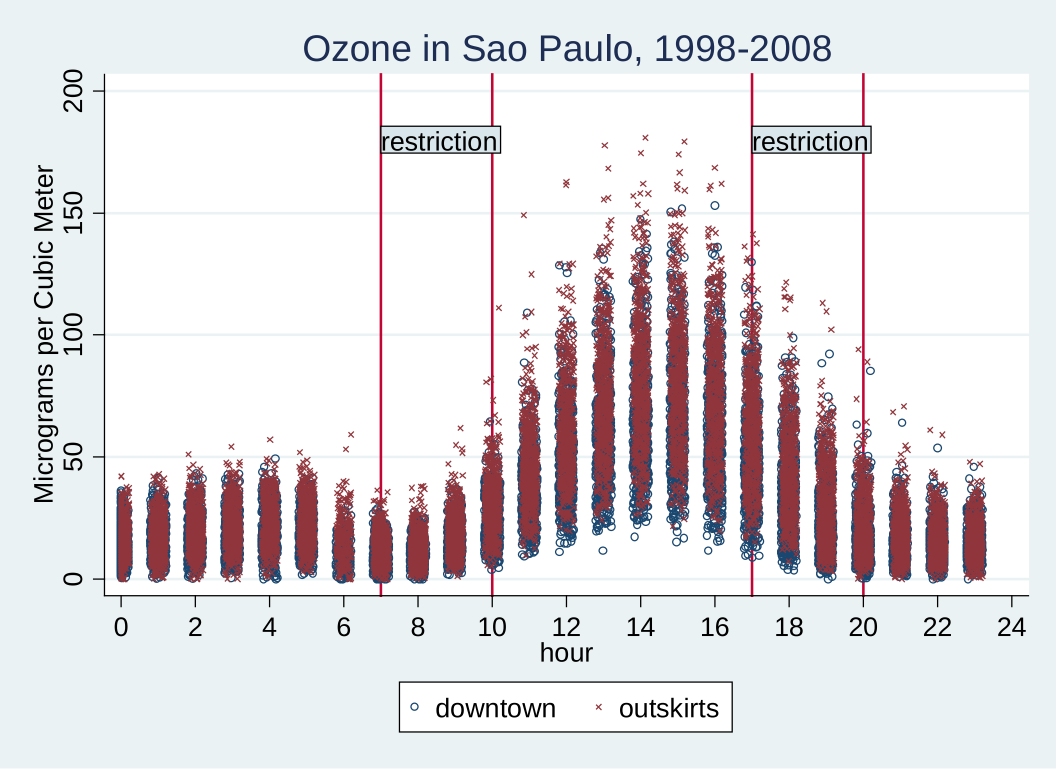

Carbon Monoxide in Sao Paulo, 1998-2008
Parts per Million
0
2
4
6
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
downtown
outskirts


Particulate Matter in Sao Paulo, 1998-2008
Micrograms per Cubic Meter
0
50
100
150
200
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
downtown
outskirts


Nitrogen Monoxide in Sao Paulo, 1998-2008
Micrograms per Cubic Meter
0
100
200
300
400
500
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
○ downtown
× outskirts


Nitrogen Dioxide in Sao Paulo, 1998-2008
Micrograms per Cubic Meter
0
50
100
150
200
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
○ downtown
× outskirts


Nitrogen Oxides in Sao Paulo, 1998-2008
Parts per Million
0
.1
.2
.3
.4
.5
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
○ downtown
× outskirts


Ozone in Sao Paulo, 1998-2008
Micrograms per Cubic Meter
0
50
100
150
200
restriction
restriction
0
2
4
6
8
10
12
14
16
18
20
22
24
hour
○ downtown
× outskirts

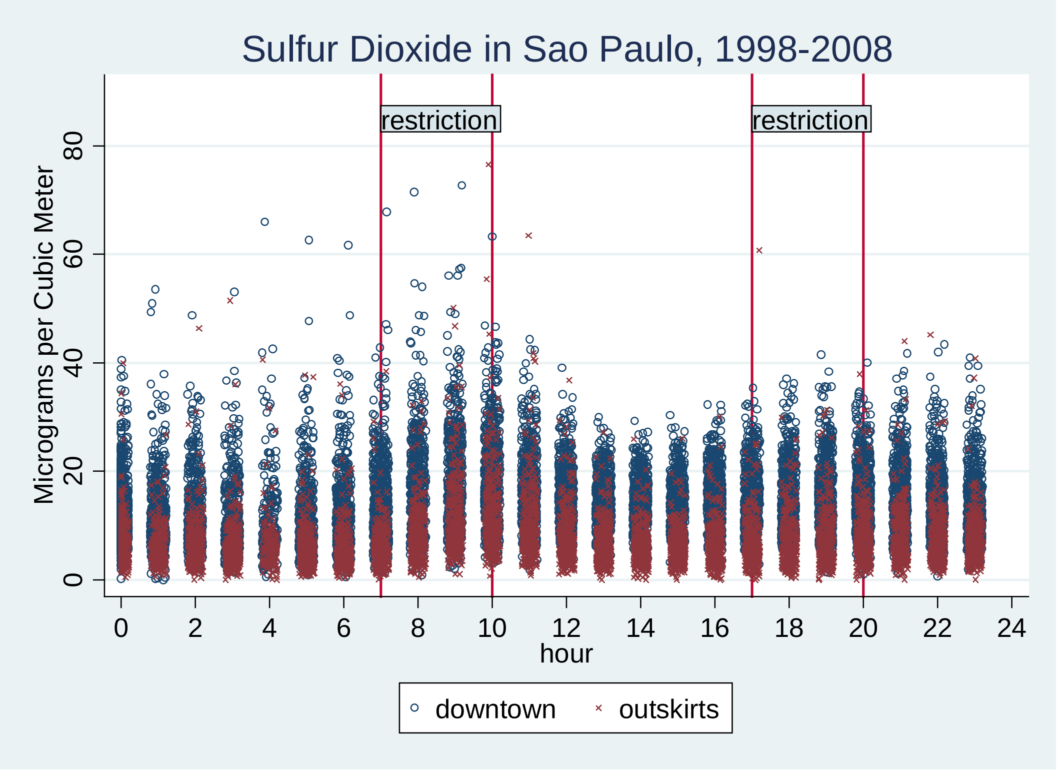


Figure 1: Air quality in São Paulo municipality, 1998-2008

Table 4a
Effect of City *rodízio* on Pollution Levels of São Paulo Municipality: Least Squares

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Weekdays 7:00-10:00 a.m., 5:00-8:00 p.m.	0.262***	0.118***	0.199	0.044	0.161*	-0.154**	0.125***
	(0.038)	(0.020)	(0.117)	(0.059)	(0.075)	(0.053)	(0.025)
Fixed Effects	0.263***	0.118***	0.201	0.044	0.162*	-0.154**	0.126***
	(0.037)	(0.020)	(0.116)	(0.059)	(0.075)	(0.054)	(0.025)
Daily Maximum	0.058*	0.007	0.038	0.018	0.032	-0.006	0.001
	(0.030)	(0.025)	(0.030)	(0.035)	(0.025)	(0.034)	(0.029)
Daily Mean	-0.01	0.006	0.029	-0.028**	-0.022	-0.027	-0.002
	(0.017)	(0.011)	(0.037)	(0.012)	(0.022)	(0.027)	(0.033)

Note: This table reports estimates from 28 separate regressions. All results are for 1998-2008. The dependent variable is pollution level in logs.

The reported coefficients correspond to the indicator variable equal to one for the observations from the stations located in the "enlarged downtown" area and when the driving restriction was effective.

Standard errors, in parentheses are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 4b

Effect of City *rodízio* on Pollution Levels of São Paulo Municipality by Hours: Least Squares

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
12:00-5:00 a.m.	-0.488***	-0.100**	-1.397***	-0.168***	-0.438***	0.096	-0.224***
	(0.074)	(0.031)	(0.071)	(0.022)	(0.054)	(0.073)	(0.048)
5:00-7:00 a.m.	-0.216	0.036	0.161	-0.055	0.143	-0.055	0.116
	(0.133)	(0.047)	(0.174)	(0.051)	(0.101)	(0.115)	(0.082)
7:00-10:00 a.m.	-0.048	0.150**	-0.673*	-0.127**	-0.165	0.05	-0.052
	(0.075)	(0.058)	(0.292)	(0.042)	(0.168)	(0.112)	(0.121)
10:00 a.m.-5:00 p.m.	0.476***	0.148***	0.854***	0.387***	0.504***	-0.145	0.265***
	(0.087)	(0.037)	(0.068)	(0.043)	(0.055)	(0.117)	(0.055)
5:00-8:00 p.m.	0.297**	-0.025	0.535*	-0.039	0.128	-0.136**	0.147
	(0.092)	(0.056)	(0.201)	(0.022)	(0.115)	(0.047)	(0.119)
8:00 p.m.-12:00 a.m.	-0.103**	-0.027	-0.210**	-0.266***	-0.239***	0.069	-0.038
	(0.034)	(0.032)	(0.054)	(0.023)	(0.028)	(0.097)	(0.030)

Note: This table reports estimates from 42 separate regressions. All results are for 1998-2008. The dependent variable is pollution level in logs.

The reported coefficients correspond to the indicator variable equal to one for the observations from the stations located in the "enlarged downtown" area and during each hour interval.

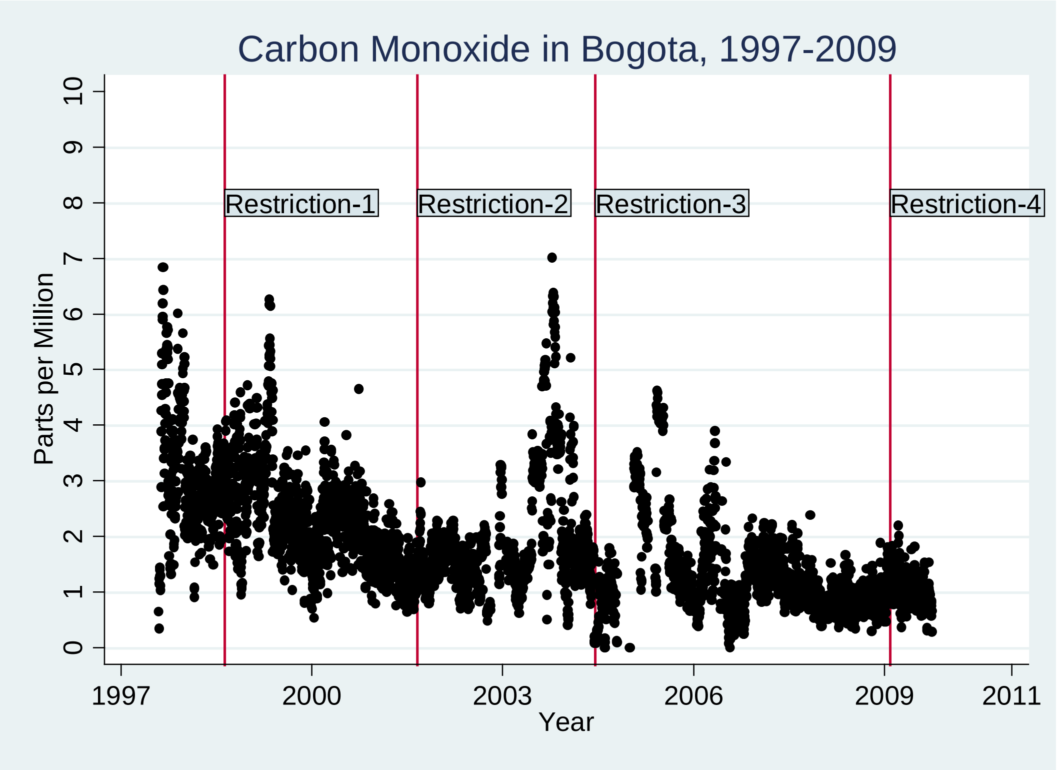
Standard errors, in parentheses are cluster robust.

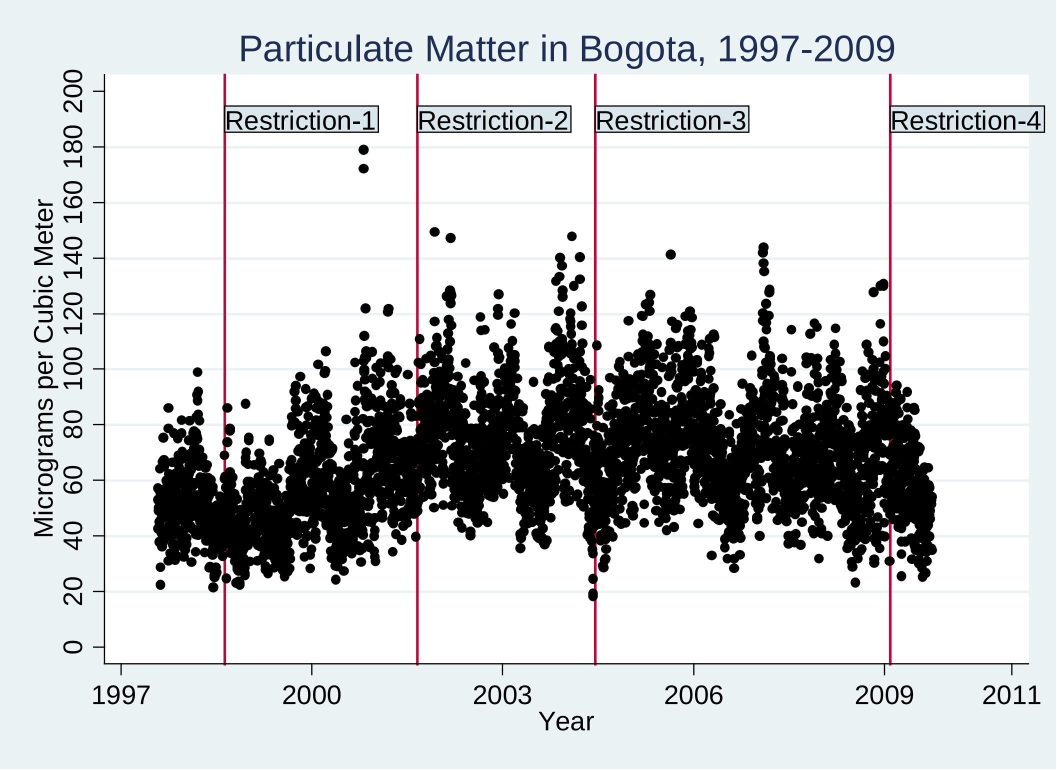
* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

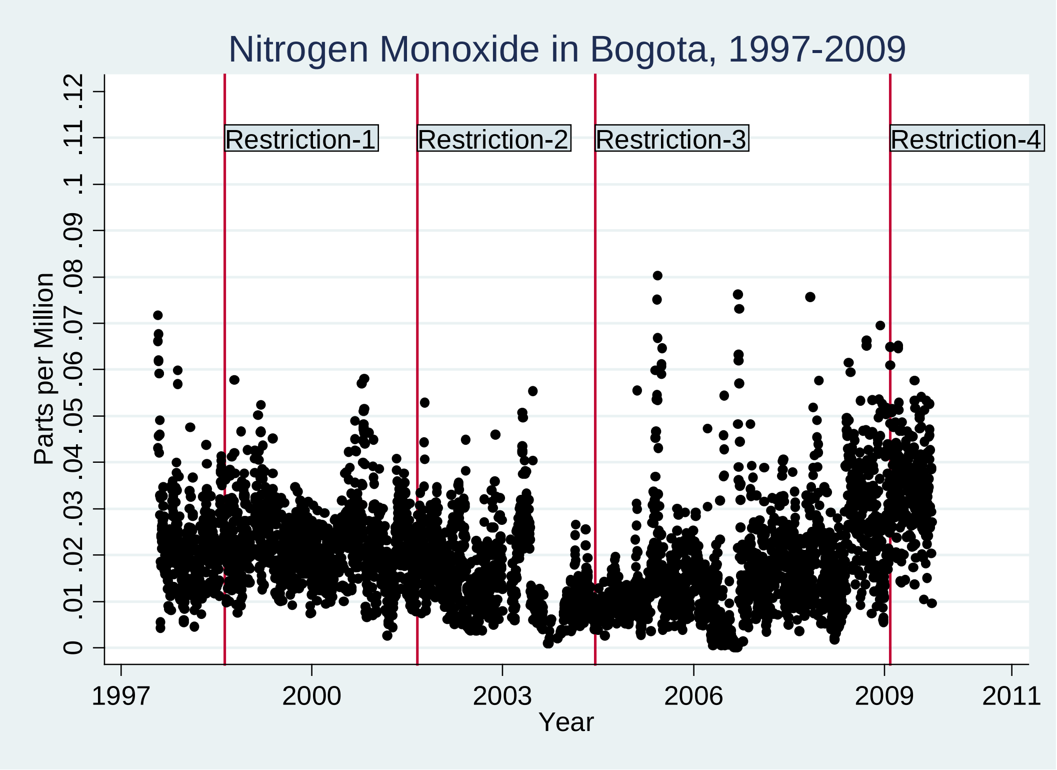
Table 5
Air Quality in Bogotá, 1997-2009: Summary Statistics

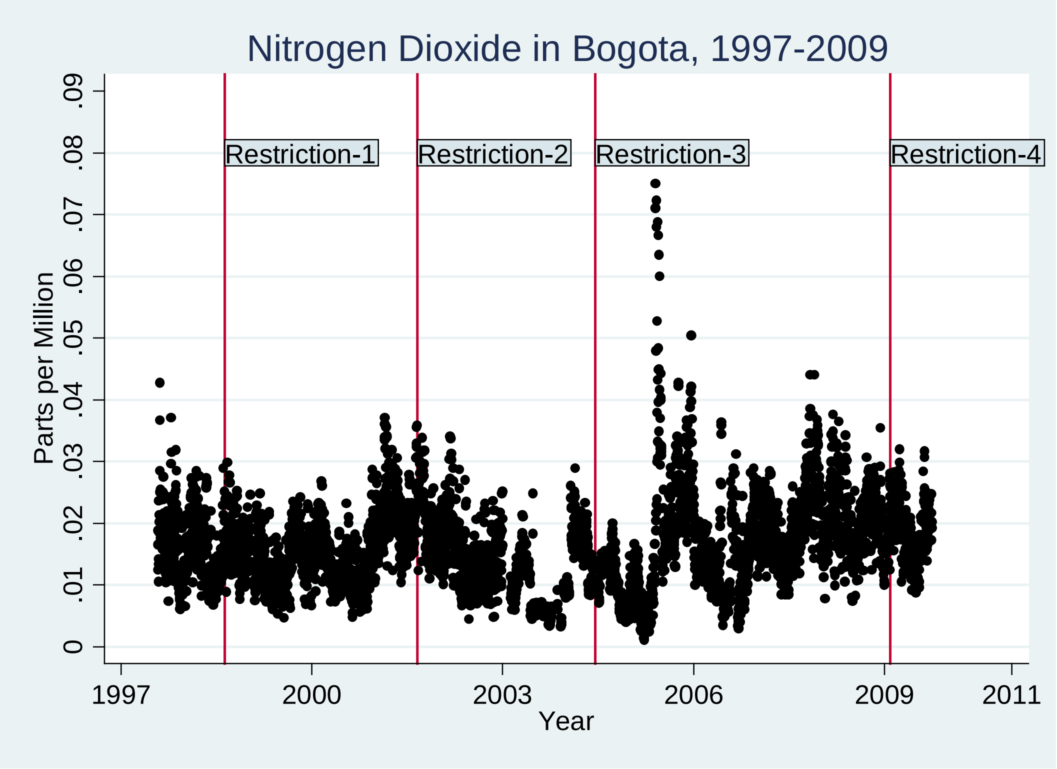
	Observations	Mean	Standard Deviation	Minimum	Maximum
CO	227481	1.70	1.54	0.00	21.40
PM_{10}	530008	67.44	47.16	0.00	988.00
NO	298391	0.02	0.03	0.00	0.52
NO_2	299454	0.02	0.01	0.00	0.37
NOx	299143	0.04	0.03	0.00	0.53
O_3	202528	0.01	0.01	0.00	0.19
SO_2	430209	0.01	0.01	0.00	0.31
Temperature	326112	13.94	3.17	-25.80	29.50
Humidity	18945	66.68	12.57	14.80	89.80
Wind speed	576636	1.68	1.50	0.00	24.30

Note: PM10 is in micrograms per cubic meter, and other pollutants are in parts per million.


Carbon Monoxide in Bogota, 1997-2009
Parts per Million
0
1
2
3
4
5
6
7
8
9
10
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Particulate Matter in Bogota, 1997-2009
Micrograms per Cubic Meter
0
20
40
60
80
100
120
140
160
180
200
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Nitrogen Monoxide in Bogota, 1997-2009
Parts per Million
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.11
.12
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Nitrogen Dioxide in Bogota, 1997-2009
Parts per Million
0
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Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
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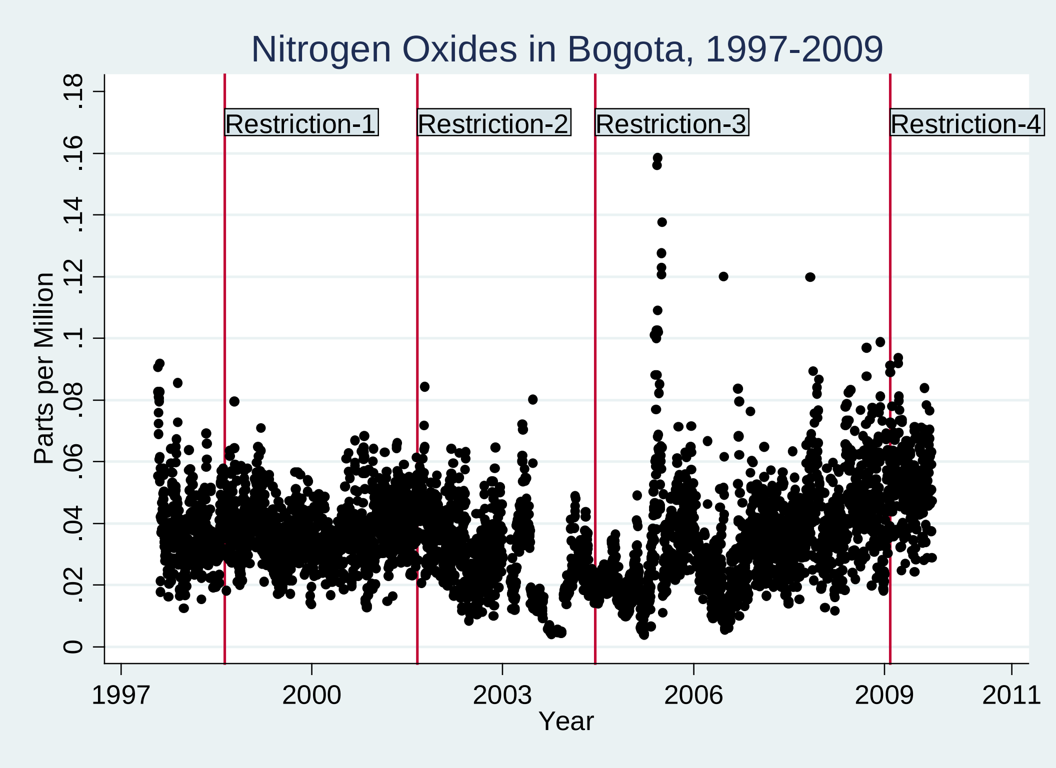
2011
Year


Nitrogen Oxides in Bogota, 1997-2009
Parts per Million
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.1
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Restriction-1
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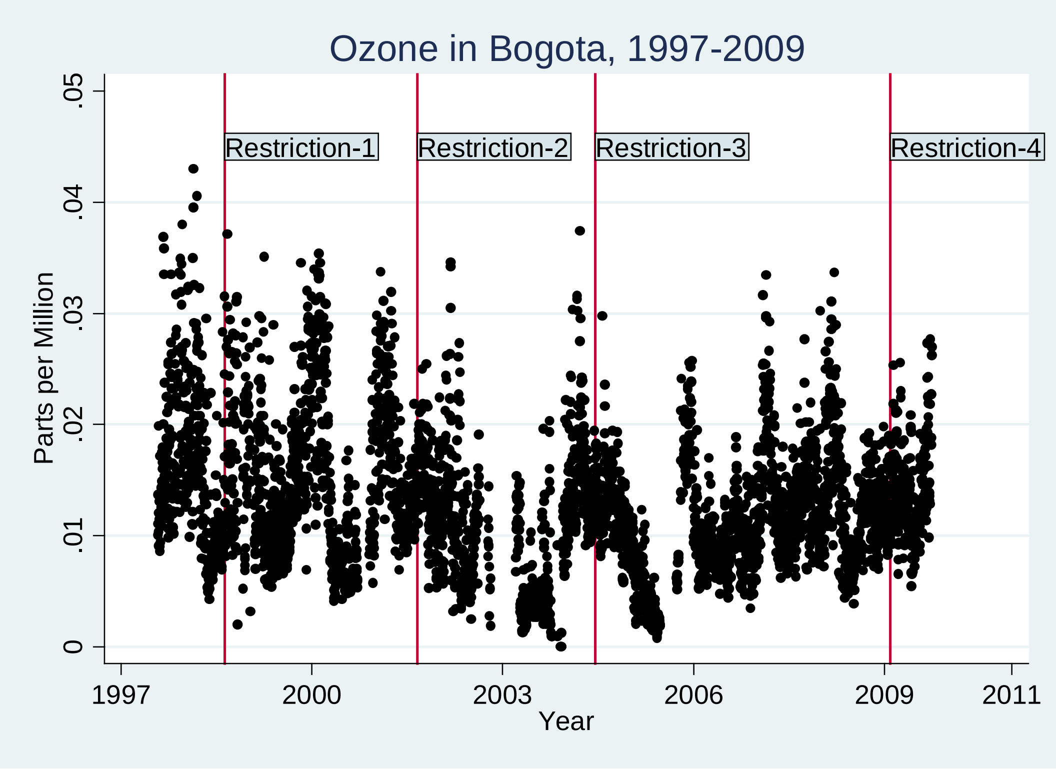
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Ozone in Bogota, 1997-2009
Parts per Million
0
.01
.02
.03
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.05
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year

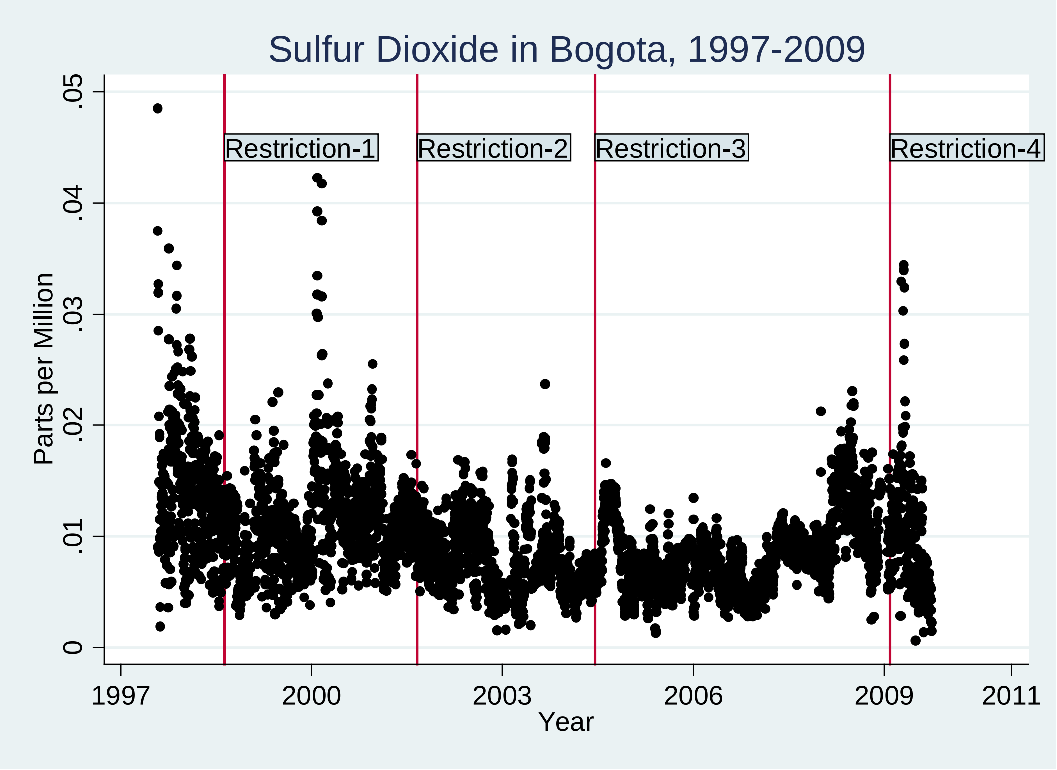


Figure 2: Air quality in Bogotá, 1997-2009

Table 6

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Least Squares

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.069	0.097	0.181	0.038	0.115	0.035	0.038
	(0.104)	(0.054)	(0.094)	(0.059)	(0.064)	(0.043)	(0.089)
Restriction-2	-0.117	0.326**	0.057	0.102	0.028	-0.444***	-0.164
	(0.171)	(0.111)	(0.236)	(0.156)	(0.196)	(0.064)	(0.130)
Restriction-3	-0.406	0.378**	0	0.387*	0.205	-0.285**	-0.043
	(0.211)	(0.132)	(0.229)	(0.177)	(0.206)	(0.090)	(0.140)
Restriction-4	-0.388	0.249	0.753**	0.432*	0.566**	-0.211**	-0.550
	(0.242)	(0.173)	(0.249)	(0.208)	(0.226)	(0.077)	(0.333)

Note: This table reports estimates from seven separate regressions. The dependent variable is the pollution level in logs.

The reported coefficients correspond to the indicator variables equal to one when the driving restriction was effective during the time periods:

8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 7a

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Seventh-order time trend)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.140**	0.071**	0.141*	0.096**	0.117*	-0.016	0.043
	(0.051)	(0.026)	(0.064)	(0.030)	(0.048)	(0.024)	(0.026)
Restriction-2	-0.018	0.012	0.112	-0.075	-0.024	-0.126**	-0.226*
	(0.099)	(0.027)	(0.081)	(0.117)	(0.100)	(0.046)	(0.095)
Restriction-3	0.026	0.080*	0.006	0.094	0.069	-0.037	-0.002
	(0.075)	(0.037)	(0.118)	(0.069)	(0.086)	(0.050)	(0.061)
Restriction-4	0.203***	0.151**	0.115	-0.022	0.028	-0.107	0.053
	(0.039)	(0.056)	(0.144)	(0.052)	(0.084)	(0.095)	(0.101)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A seventh-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one when the driving restriction was effective during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 7b

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Eighth-order time trend)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.142*	0.077**	0.144*	0.103**	0.123**	-0.014	0.054*
	(0.055)	(0.024)	(0.064)	(0.030)	(0.047)	(0.023)	(0.027)
Restriction-2	-0.004	0.036	0.14	-0.003	0.039	-0.105*	-0.132
	(0.081)	(0.027)	(0.081)	(0.082)	(0.072)	(0.047)	(0.073)
Restriction-3	0.025	0.076*	0.004	0.09	0.066	-0.036	-0.011
	(0.075)	(0.037)	(0.121)	(0.069)	(0.088)	(0.049)	(0.061)
Restriction-4	0.198***	0.143**	0.108	-0.042	0.012	-0.112	0.015
	(0.034)	(0.058)	(0.154)	(0.051)	(0.087)	(0.097)	(0.101)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A eighth-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one when the driving restriction was effective during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 7c

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Ninth-order time trend)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.140*	0.077**	0.144*	0.108**	0.126**	-0.013	0.061*
	(0.059)	(0.025)	(0.062)	(0.033)	(0.046)	(0.024)	(0.028)
Restriction-2	-0.02	0.042	0.141	0.030	0.060	-0.052	-0.082
	(0.077)	(0.024)	(0.092)	(0.095)	(0.072)	(0.068)	(0.089)
Restriction-3	0.026	0.076*	0.004	0.087	0.064	-0.041	-0.013
	(0.074)	(0.037)	(0.120)	(0.070)	(0.088)	(0.047)	(0.060)
Restriction-4	0.179**	0.152*	0.11	0.006	0.042	-0.077	0.099
	(0.049)	(0.073)	(0.157)	(0.081)	(0.111)	(0.094)	(0.095)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A ninth-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one when the driving restriction was effective during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 8

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Fixed-effect Model

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.139*	0.079**	0.144*	0.109**	0.127**	-0.012	0.063*
	(0.058)	(0.025)	(0.061)	(0.031)	(0.044)	(0.023)	(0.029)
Restriction-2	-0.049	0.052*	0.154	0.025	0.068	-0.064	-0.086
	(0.075)	(0.021)	(0.083)	(0.093)	(0.063)	(0.073)	(0.090)
Restriction-3	0.056	0.085*	0.012	0.069	0.056	-0.043	-0.004
	(0.056)	(0.038)	(0.122)	(0.070)	(0.089)	(0.049)	(0.057)
Restriction-4	0.158*	0.141*	0.11	-0.001	0.043	-0.068	0.051
	(0.066)	(0.068)	(0.138)	(0.073)	(0.101)	(0.102)	(0.119)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. All estimates are from a RD specification with a ninth-order time trend. The reported coefficients correspond to the indicator variables equal to one when the driving restriction was effective during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 9

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Least Squares (including both direct and indirect effects)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	-0.31	0.146	0.124	-0.096	0.031	0.017	-0.078
	(0.302)	(0.171)	(0.226)	(0.101)	(0.138)	(0.068)	(0.217)
Restriction-2	-0.374	0.486*	0.064	0.05	0.02	-0.495***	-0.250
	(0.397)	(0.229)	(0.352)	(0.184)	(0.256)	(0.053)	(0.255)
Restriction-3	-0.792	0.516	0.085	0.359	0.231	-0.325***	-0.122
	(0.450)	(0.266)	(0.353)	(0.209)	(0.269)	(0.060)	(0.248)
Restriction-4	-0.774	0.333	0.787*	0.403	0.579*	-0.187**	-0.687*
	(0.460)	(0.225)	(0.331)	(0.245)	(0.283)	(0.066)	(0.299)

Note: This table reports estimates from seven separate regressions. The dependent variable is the pollution level in logs.

The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 10a

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Seventh-order time trend, including both direct and indirect Effects)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.118	-0.296**	0.013	0.084	0.054	0.043	-0.238
	(0.201)	(0.092)	(0.399)	(0.202)	(0.184)	(0.227)	(0.305)
Restriction-2	0.149	-0.254	0.022	0.002	-0.043	-0.015	-0.636
	(0.286)	(0.184)	(0.376)	(0.302)	(0.204)	(0.227)	(0.374)
Restriction-3	-0.494	-0.153	0.274	1.031	0.725*	0.602	0.038
	(0.758)	(0.241)	(0.305)	(0.737)	(0.336)	(0.603)	(0.898)
Restriction-4	-0.128	-0.157	0.266	0.785	0.561	0.734	0.126
	(0.626)	(0.239)	(0.273)	(0.779)	(0.293)	(0.724)	(1.122)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A seventh-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 10b

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Eighth-order time trend, including both direct and indirect effects)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.319	-0.211	0.045	0.195	0.147	0.022	-0.075
	(0.275)	(0.172)	(0.422)	(0.183)	(0.266)	(0.184)	(0.345)
Restriction-2	0.443	-0.143	0.075	0.187	0.111	-0.044	-0.381
	(0.297)	(0.255)	(0.421)	(0.154)	(0.266)	(0.201)	(0.390)
Restriction-3	-0.499	-0.112	0.269	1.015	0.712**	0.586	0.153
	(0.830)	(0.257)	(0.336)	(0.645)	(0.289)	(0.588)	(0.867)
Restriction-4	-0.239	-0.135	0.242	0.703	0.492	0.725	0.132
	(0.685)	(0.239)	(0.307)	(0.753)	(0.282)	(0.720)	(1.120)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A eighth-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 10c

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Regression Discontinuity (Ninth-order time trend, including both direct and indirect effects)

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.387	-0.198	0.030	0.438*	0.279	0.382	0.161
	(0.415)	(0.117)	(0.376)	(0.184)	(0.308)	(0.260)	(0.203)
Restriction-2	0.551	-0.122	0.051	0.571	0.318	0.488	-0.004
	(0.557)	(0.216)	(0.336)	(0.386)	(0.360)	(0.464)	(0.246)
Restriction-3	-0.425	-0.096	0.252	1.283*	0.854*	0.921**	0.424
	(1.026)	(0.260)	(0.338)	(0.540)	(0.373)	(0.353)	(0.744)
Restriction-4	-0.126	-0.112	0.213	1.162*	0.738	1.197**	0.642
	(0.986)	(0.313)	(0.353)	(0.553)	(0.395)	(0.422)	(0.920)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. A ninth-order polynomial time trend is added in the regressions.

The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

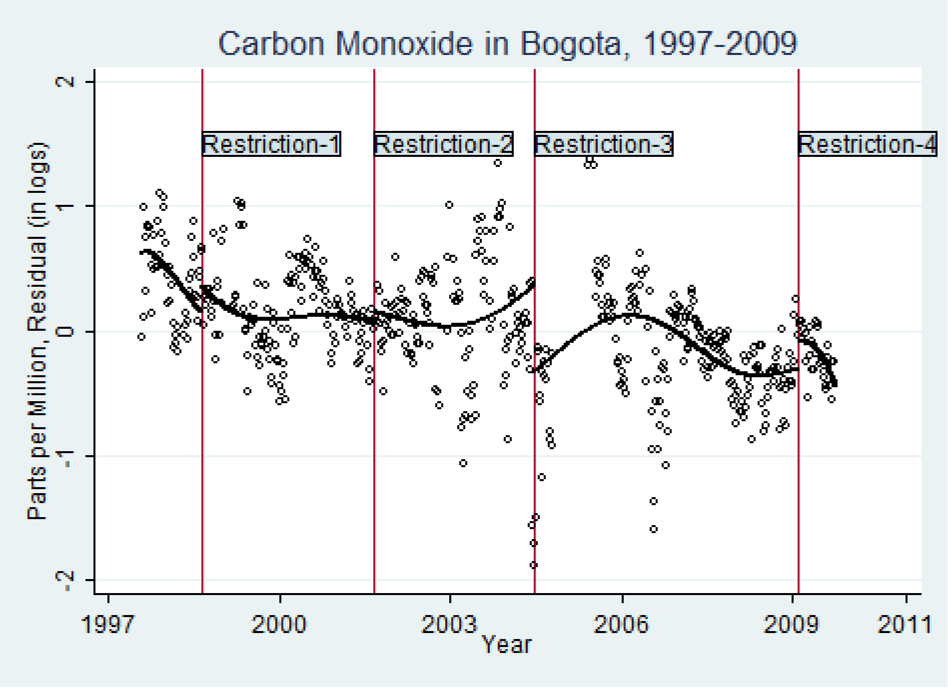
Table 11

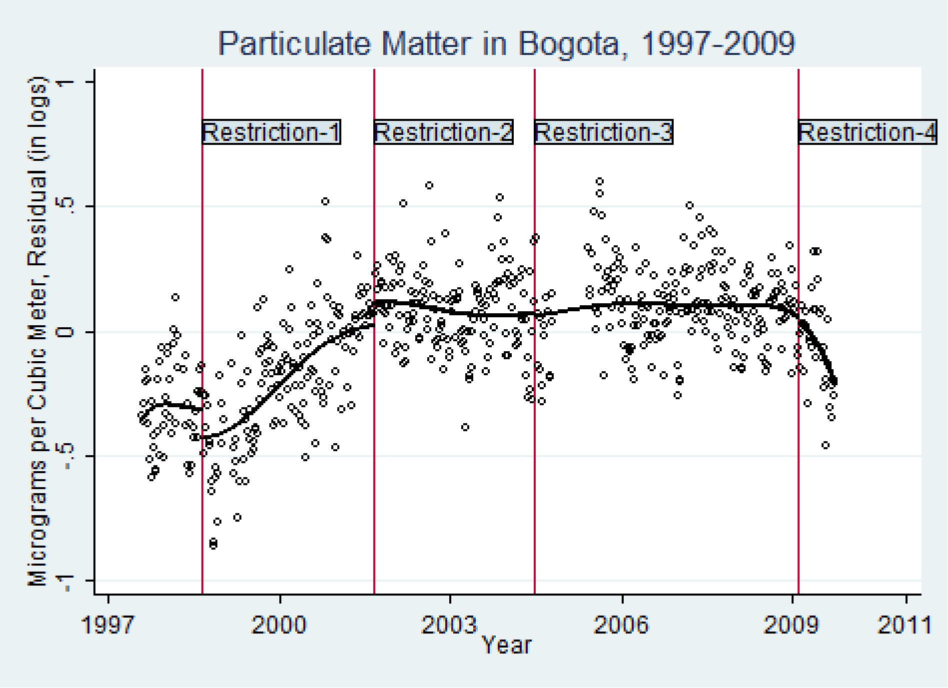
Effect of *Pico y Placa* on Pollution Levels of Bogotá: Fixed-effect Model (including both direct and indirect effects)

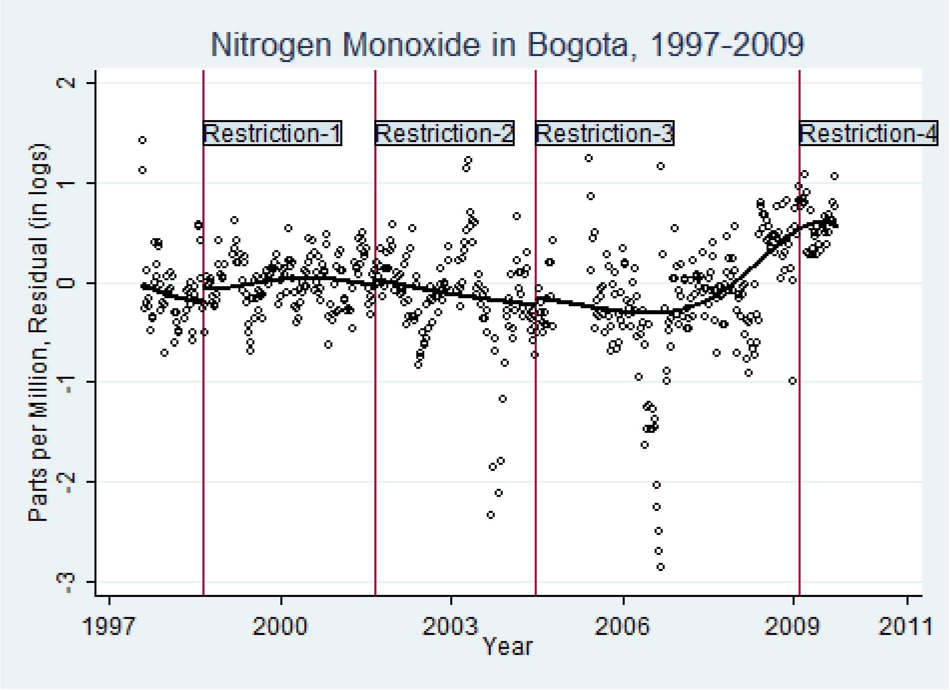
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.475	-0.161	0.024	0.396***	0.286	0.375	0.212
	(0.410)	(0.088)	(0.336)	(0.090)	(0.246)	(0.228)	(0.205)
Restriction-2	0.606	-0.028	0.061	0.434	0.303	0.447	0.023
	(0.585)	(0.181)	(0.312)	(0.290)	(0.304)	(0.409)	(0.282)
Restriction-3	-0.064	0.043	0.217	0.918	0.653*	1.008**	0.514
	(0.932)	(0.236)	(0.366)	(0.473)	(0.335)	(0.383)	(0.785)
Restriction-4	0.112	0	0.128	0.789*	0.531	1.335**	0.511
	(0.986)	(0.338)	(0.350)	(0.399)	(0.303)	(0.426)	(1.076)

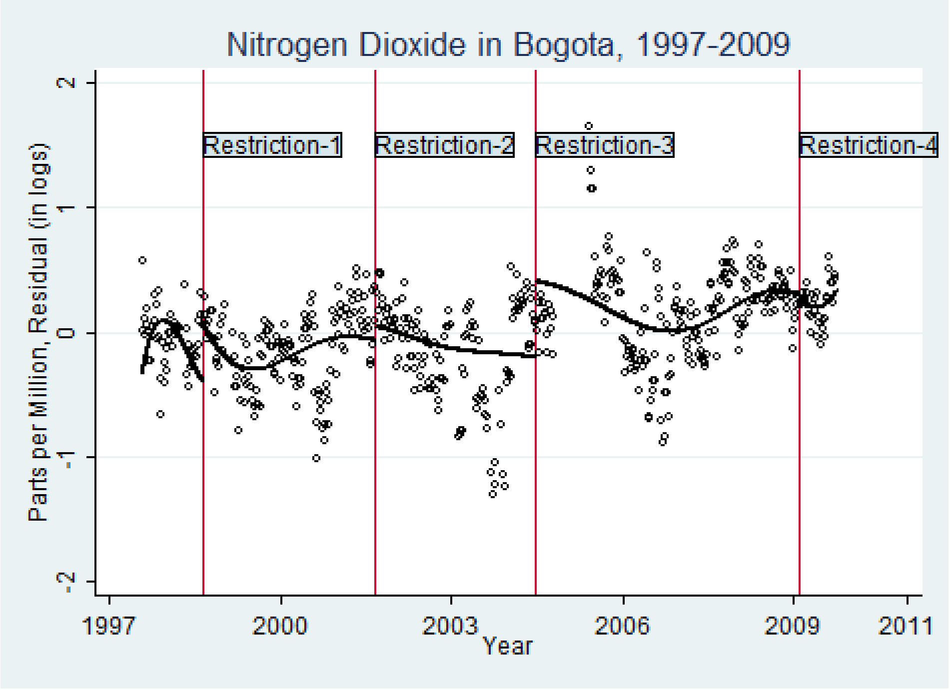
Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. All estimates are from a RD specification with a ninth-order time trend. The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses, are cluster robust.

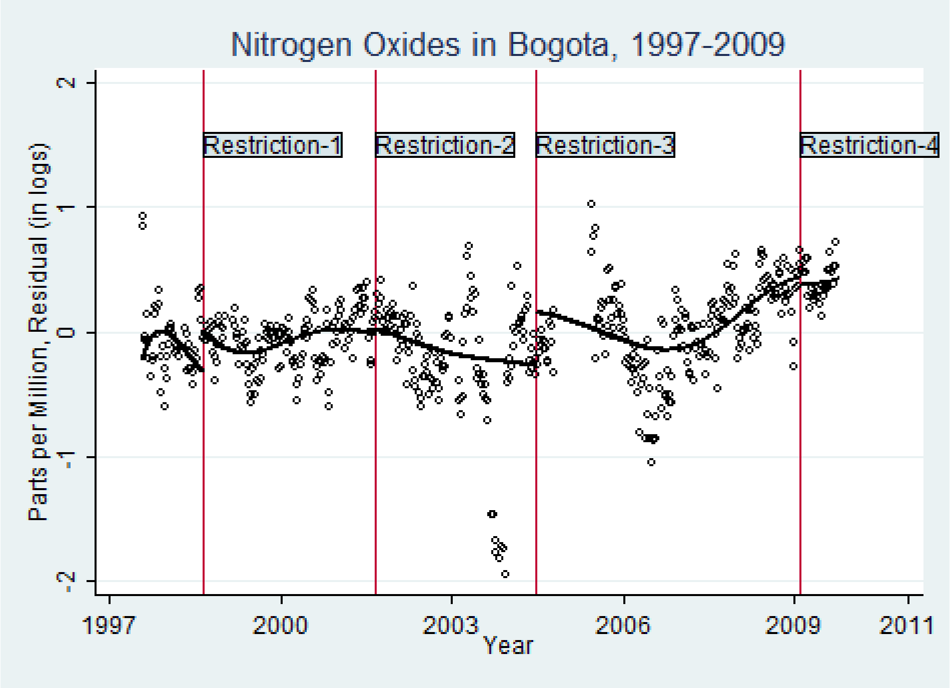
* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

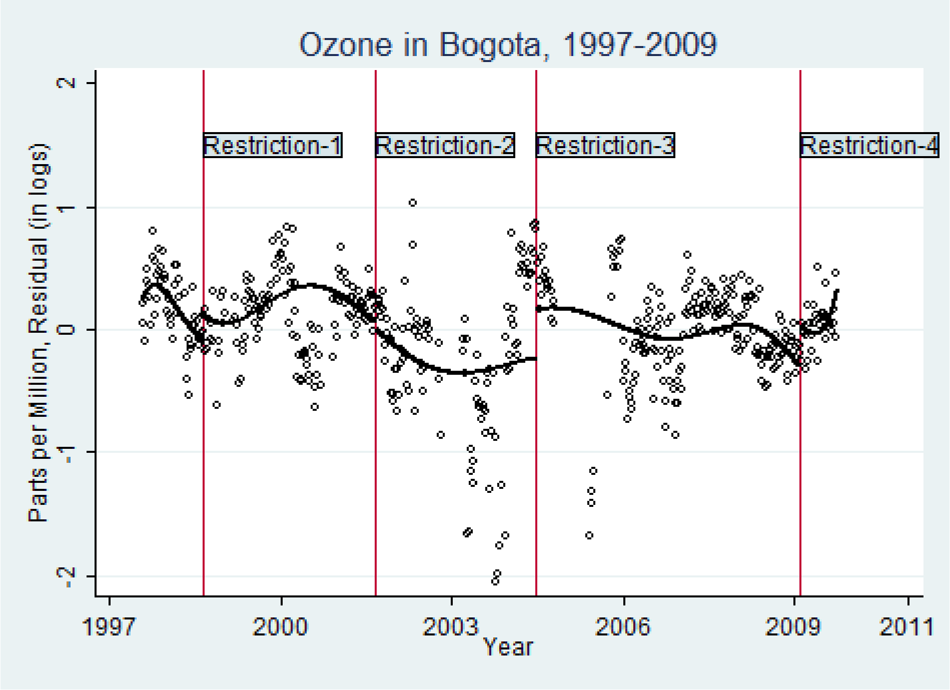

Carbon Monoxide in Bogota, 1997-2009
Parts per Million, Residual (in logs)
-2
-1
0
1
2
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Particulate Matter in Bogota, 1997-2009
Micrograms per Cubic Meter, Residual (in logs)
-1
-.5
0
.5
1
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Nitrogen Monoxide in Bogota, 1997-2009
Parts per Million, Residual (in logs)
-3
-2
-1
0
1
2
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Nitrogen Dioxide in Bogota, 1997-2009
Parts per Million, Residual (in logs)
-2
-1
0
1
2
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Nitrogen Oxides in Bogota, 1997-2009
Parts per Million, Residual (in logs)
2
1
0
-1
-2
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year


Ozone in Bogota, 1997-2009
Parts per Million, Residual (in logs)
2
1
0
-1
-2
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year

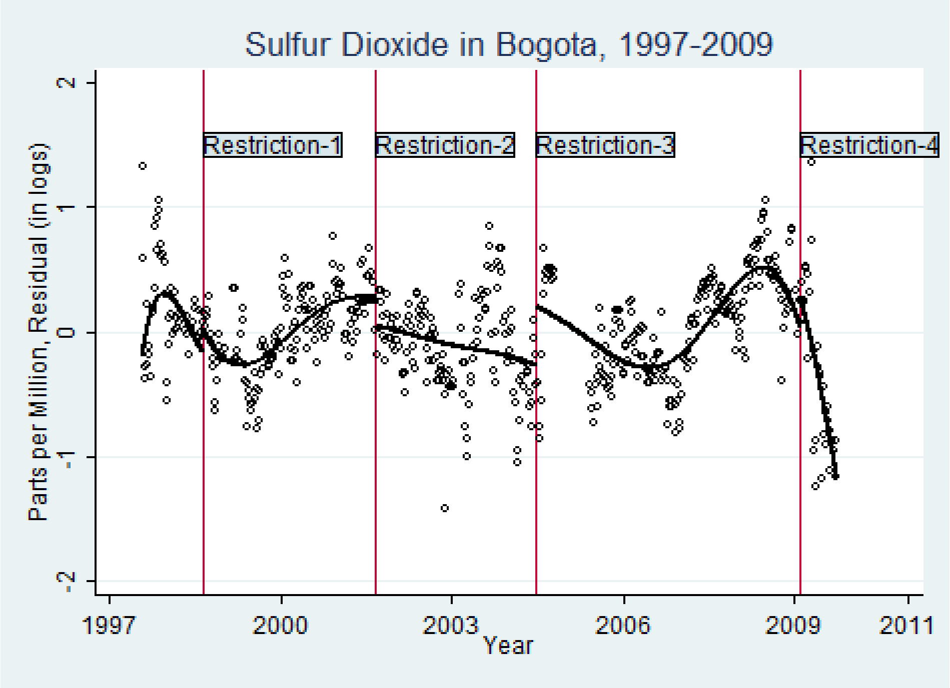


Figure 3: Mean weekly pollution level in Bogotá, ninth-order polynomial time trend

Table 12a

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Week nights

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	-0.191	-0.201***	-0.279*	-0.203**	-0.224**	0.201**	-0.071**
	(0.120)	(0.039)	(0.125)	(0.061)	(0.085)	(0.061)	(0.029)
Restriction-2	0.096	-0.114***	-0.267*	-0.142**	-0.197**	0.101	-0.114
	(0.107)	(0.018)	(0.134)	(0.055)	(0.078)	(0.073)	(0.080)
Restriction-3	-0.184	-0.144***	-0.045	-0.109	-0.091	0.134**	-0.029
	(0.102)	(0.033)	(0.163)	(0.082)	(0.112)	(0.047)	(0.060)
Restriction-4	-0.089	-0.261***	-0.212	-0.102	-0.141	0.273**	-0.033
	(0.155)	(0.050)	(0.187)	(0.066)	(0.117)	(0.102)	(0.059)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. All estimates are from a RD specification with a ninth-order time trend. The reported coefficients correspond to the indicator variables equal to one for week nights, when the driving restrictions were not effective, i.e. 10:00 p.m.-5:00 a.m. from Mondays to Fridays for 8/18/1998-8/28/2001 and from Mondays to Saturdays after 8/28/2001. Standard errors, in parentheses are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 12b

Effect of *Pico y Placa* on Pollution Levels of Bogotá: Weekends

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	-0.04	-0.046*	-0.059	-0.025	-0.037	0.003	0.016
	(0.025)	(0.021)	(0.032)	(0.049)	(0.033)	(0.027)	(0.063)
Restriction-2	0.052	0.015	-0.132	-0.018	-0.067	0.017	0.008
	(0.041)	(0.025)	(0.083)	(0.037)	(0.049)	(0.065)	(0.093)
Restriction-3	-0.069	-0.032	-0.081	0.029	-0.023	0.078**	0.127
	(0.083)	(0.031)	(0.070)	(0.041)	(0.047)	(0.024)	(0.067)
Restriction-4	-0.088	-0.041	-0.105	-0.062**	-0.095**	0.134***	-0.035
	(0.078)	(0.048)	(0.064)	(0.024)	(0.034)	(0.035)	(0.059)

Note: This table reports estimates from seven separate regressions. The dependent variable is pollution level in logs. All estimates are from a RD specification with a ninth-order time trend. The reported coefficients correspond to the indicator variables equal to one for weekends, i.e. Saturdays and Sundays for 8/18/1998-8/28/2001 and Sundays after 8/28/2001. Standard errors, in parentheses are cluster robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 12c
Effect of *Pico y Placa* on Pollution Levels of Bogotá: Daily maximum

	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.095*	-0.258***	0.073	0.353***	0.135**	0.644***	-0.105
	(0.054)	(0.053)	(0.086)	(0.073)	(0.065)	(0.121)	(0.065)
Restriction-2	0.148*	-0.198***	0.083	0.423***	0.156*	0.596***	-0.012
	(0.082)	(0.068)	(0.123)	(0.096)	(0.093)	(0.157)	(0.084)
Restriction-3	-0.754***	-0.280***	0.718***	0.853***	0.711***	0.998***	0.508***
	(0.120)	(0.072)	(0.147)	(0.105)	(0.111)	(0.168)	(0.092)
Restriction-4	-0.508***	-0.480***	0.693***	0.894***	0.653***	1.203***	0.930***
	(0.136)	(0.089)	(0.166)	(0.115)	(0.126)	(0.175)	(0.123)

Note: This table reports estimates from seven separate regressions. The dependent variable is daily maximum pollution level in logs. All estimates are from a RD specification with a ninth-order time trend.

The reported coefficients correspond to the indicator variables equal to one for every hour during the time periods: 8/18/1998 to 8/28/2001, 8/29/2001 to 6/14/2004, 6/15/2004 to 2/5/2009 and 2/6/2009 to 9/30/2009. Standard errors, in parentheses are heteroskedasticity robust.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

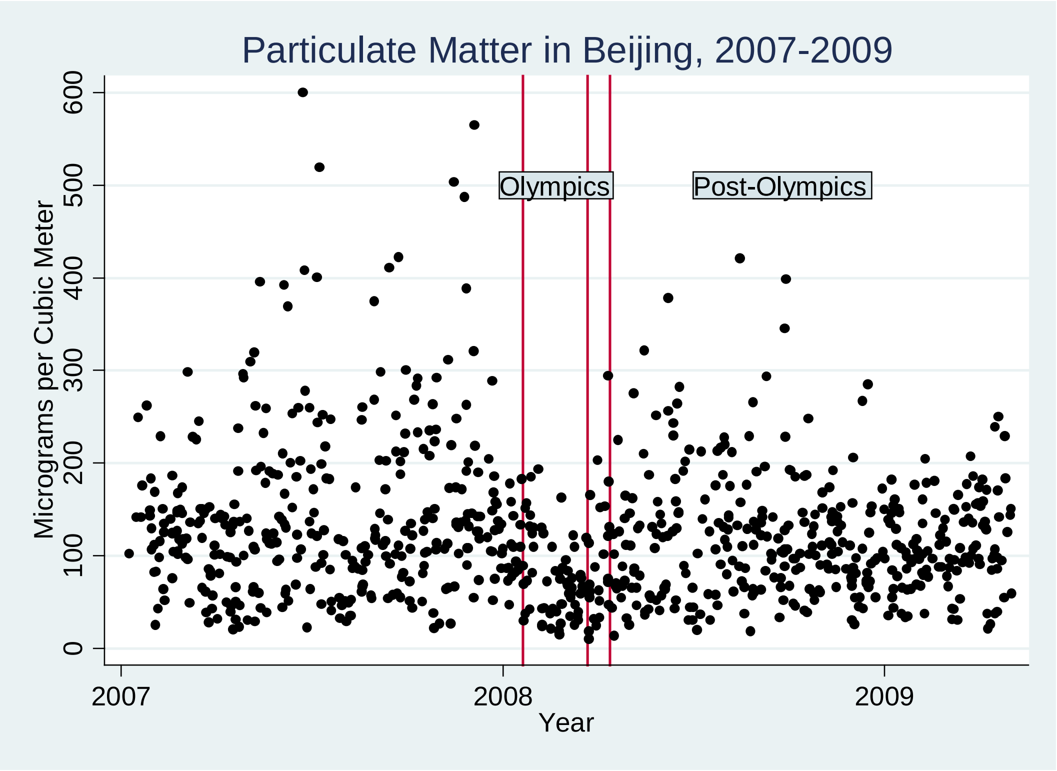


Figure 4: Particulate matter in Beijing, 2007-2009

Table 13

PM_{10} in Beijing 2007-2009: Summary Statistics

	Observations	Mean	Standard Deviation	Minimum	Maximum
PM_{10}	816	125.10	78.59	12.00	600.00
Temperature	835	13.72	10.90	-10.00	31.11
Humidity	835	58.09	19.60	15.00	98.00
Wind speed	835	2.36	1.71	0.00	12.52

Note: PM_{10} is in micrograms per cubic meter. Temperature is in Celcius and wind speed is in meters per second.

PM_{10} are converted from daily Air Pollution Index (API) for the period 7/20/2007-10/31/2009. APIs less than 50 are treated as PM_{10} concentrations.

Table 14a

Effect of the Driving Restrictions on PM_{10} in Beijing: 2007-2009

	OLS	Seventh-order	Eighth-order	Ninth-order
During the Olympics	-0.496***	-0.387***	-0.489***	-0.431***
	(0.078)	(0.108)	(0.106)	(0.105)
After the Olympics	-0.055	0.568***	0.563***	0.517***
	(0.039)	(0.162)	(0.157)	(0.157)

Note: This table reports estimates from four separate regressions. The dependent variable is PM_{10} in logs. The reported coefficients correspond to the indicator variable equal to one for the period 7/20-9/20/2008 and after 10/11/2008 respectively .

* p<0.05, ** p<0.01, *** p<0.001.

Table 14b

Effect of the Driving Restrictions on PM_{10} in Beijing: 2007-2009, excluding the days with APIs less than 50

	OLS	Seventh-order	Eighth-order	Ninth-order
During the Olympics	-0.340***	-0.196**	-0.288***	-0.238**
	(0.070)	(0.097)	(0.094)	(0.094)
After the Olympics	-0.081**	0.333**	0.354**	0.320**
	(0.032)	(0.149)	(0.143)	(0.144)

Note: This table reports estimates from four separate regressions. The dependent variable is PM_{10} in logs.

The reported coefficients correspond to the indicator variable equal to one for the period 7/20-9/20/2008

and after 10/11/2008 respectively .

* p<0.05, ** p<0.01, *** p<0.001.

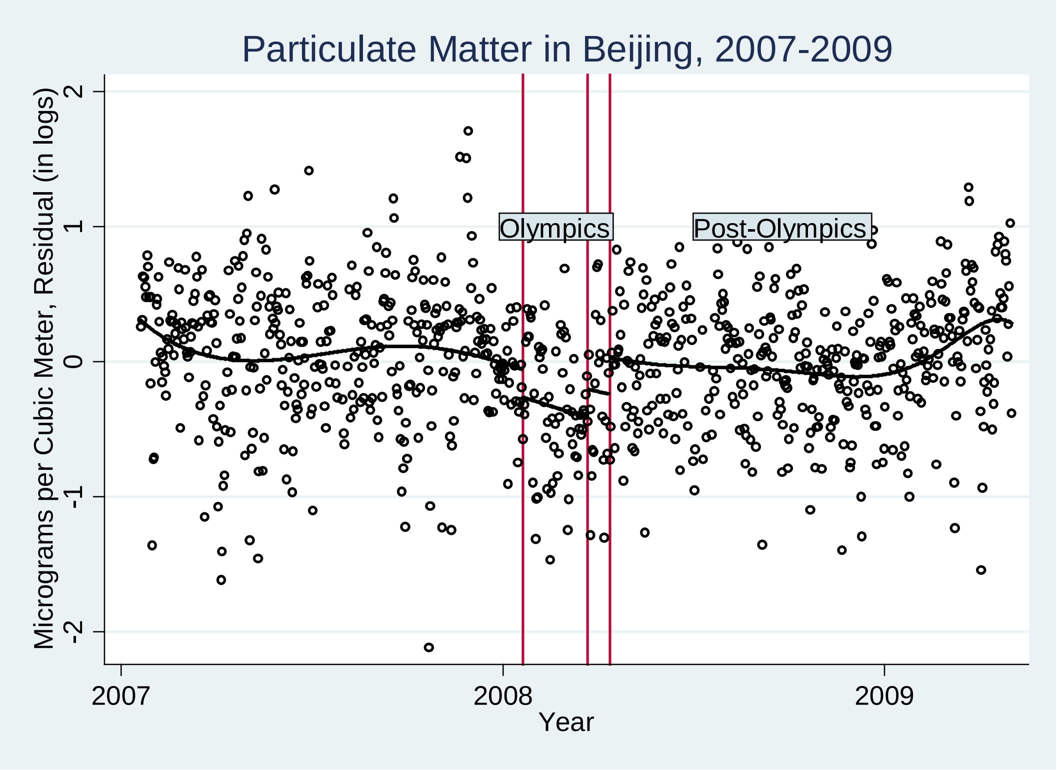


Figure 5: Particulate matter in Beijing, ninth-order polynomial time trend

Table 15

PM_{10} in Tianjin 2007-2009: Summary Statistics

	Observations	Mean	Standard Deviation	Minimum	Maximum
PM_{10}	658	98.79	55.45	17.00	503.00
Temperature	835	14.73	10.83	-10.00	32.22
Humidity	835	65.77	19.81	14.00	100.00
Wind speed	835	2.51	1.65	0.00	12.52

Note: PM_{10} is in micrograms per cubic meter. Temperature is in Celcius and wind speed is in meters per second.

PM_{10} are converted from daily API for the period 7/20/2007-10/31/2009. APIs less than 50 are treated as PM_{10} concentrations.

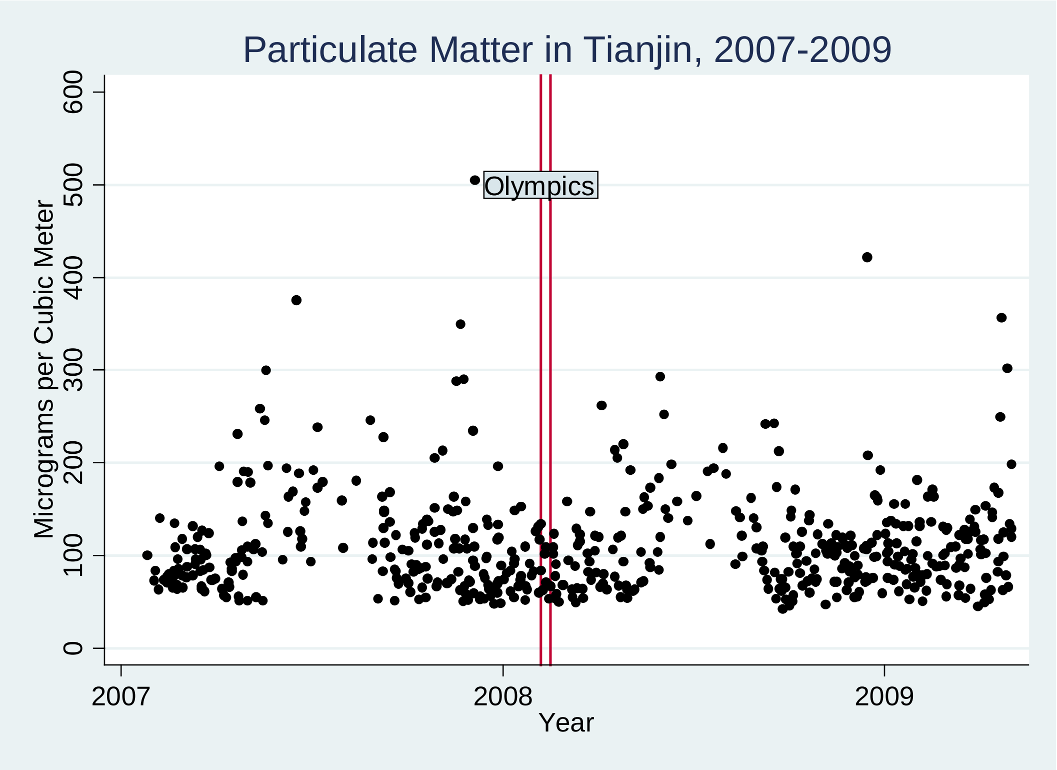


Figure 6: Particulate matter in Tianjin, 2007-2009

Table 16a

Effect of the Driving Restriction on PM_{10} in Tianjin: 2007-2009

	OLS	Seventh-order	Eighth-order	Ninth-order
During the Olympics	-0.227	-0.175	-0.165	-0.003
	(0.147)	(0.144)	(0.144)	(0.144)

Note: This table reports estimates from four separate regressions. All results are for 2007-2009. The dependent variable is PM_{10} in logs. The reported coefficients correspond to the indicator variable equal to one for the period 8/6-8/15-2008.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 16b
Effect of the Driving Restriction on PM_{10} in Tianjin: 2007-2009, excluding the days with APIs less than 50

	OLS	Seventh-order	Eighth-order	Ninth-order
During the Olympics	-0.143	-0.121	-0.118	0.054
	(0.143)	(0.142)	(0.142)	(0.140)

Note: This table reports estimates from four separate regressions. All results are for 2007-2009. The dependent variable is PM_{10} in logs. The reported coefficients correspond to the indicator variable equal to one for the period 8/6-8/15-2008.

* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

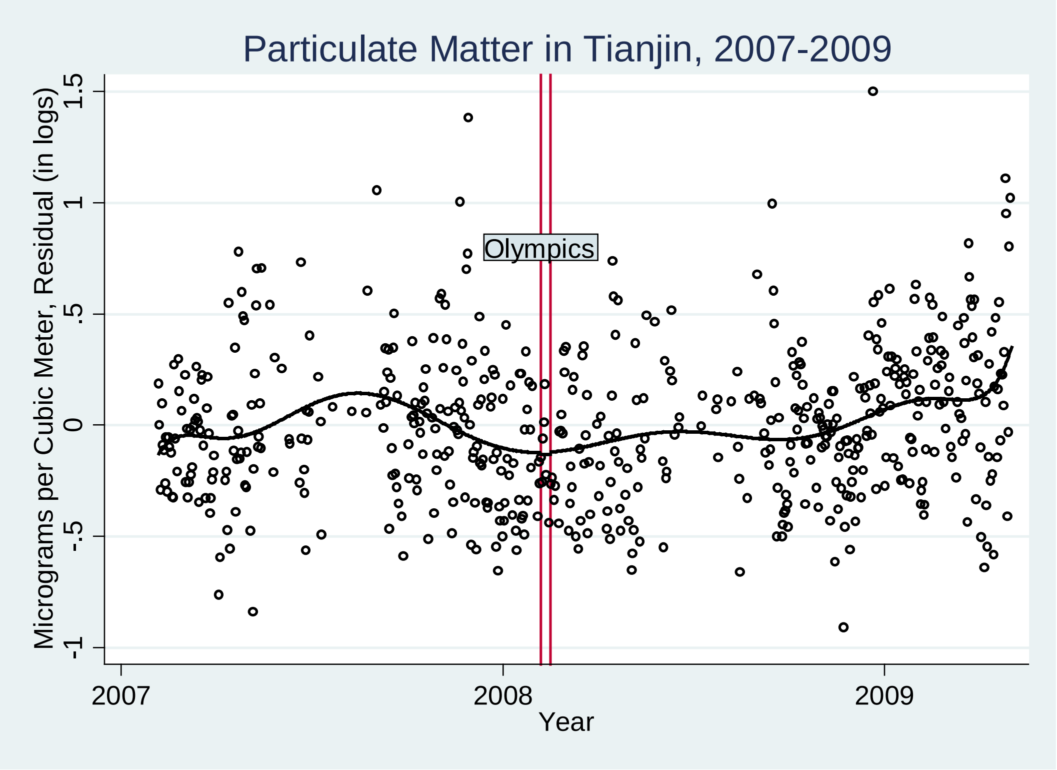


Figure 7a: Particulate matter in Tianjin, ninth-order polynomial time trend

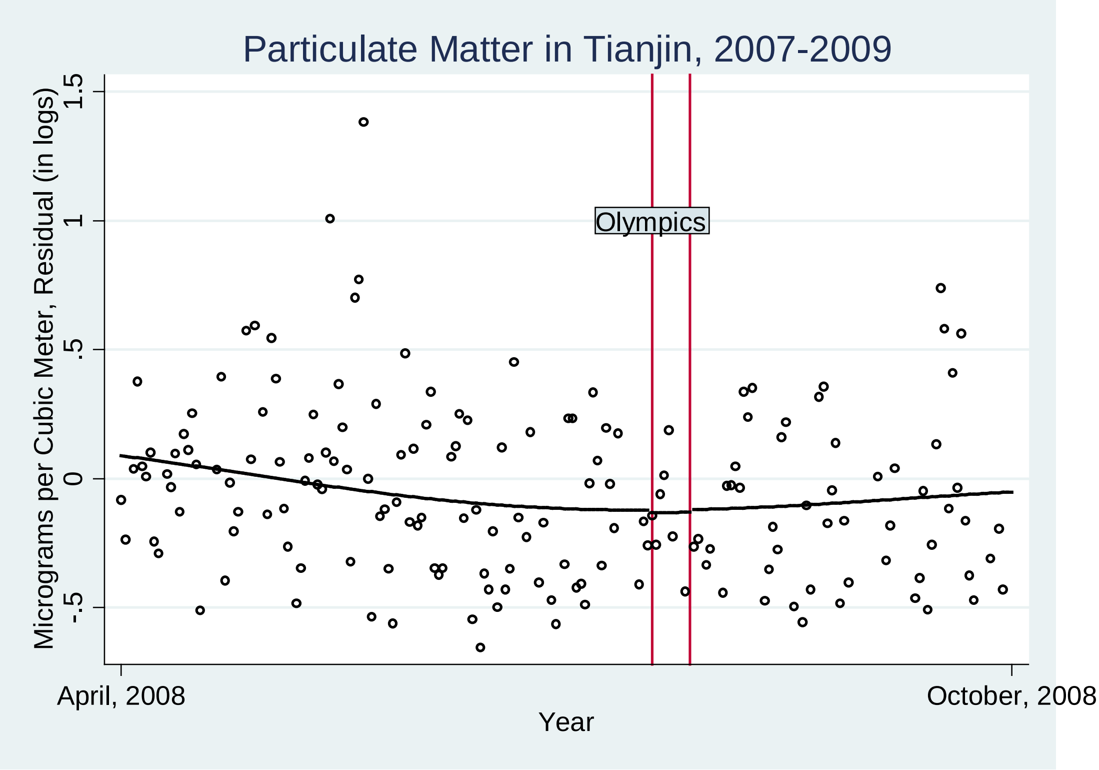


Figure 7b: Particulate matter in Tianjin, 2008 and ninth-order polynomial time trend