The Effects of License Plate-Based Driving Restrictions on Air Quality: Theory and Empirical Evidence[1]

Wei Zhang,[2] C.-Y. Cynthia Lin Lawell,[3] Victoria I. Umanskaya[4]

December 2016

Abstract

A typical driving restriction prohibits drivers from using their vehicles on given weekdays, based on the last digits of their vehicles' license plates. A number of cities in developing countries have used license plate-based driving restrictions as a policy for reducing urban air pollution and traffic congestion. This paper develops a theoretical model of the effects of license plate-based driving restrictions on air quality that combines an economic model with information about the sources and atmospheric chemistry of different air pollutants. We then draw upon suggestive empirical evidence from license plate-based driving restrictions implemented in Bogotá, Colombia. Consistent with our theory model, we find suggestive empirical evidence that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for license plate-based driving restrictions to increase air pollution. Also consistent with our theory, we find that license plate-based driving restrictions may have different effects on different air pollutants, reflecting heterogeneity in the sources and atmospheric chemistry of the pollutants. In particular, owing to atmospheric chemistry, it is possible for a license plate-based driving restriction to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3.

Keywords: driving restriction, air quality
***JEL* codes:** Q58, R48, Q53

---

[1] We thank the Secretaría Distrital de Ambiente of Bogotá for providing air pollution and meteorological data and helpful information of the policies and the air quality monitoring systems. We thank Lucas Davis, Juan-Pablo Montero, Andres Moya, Dan Phaneuf, Aaron Smith, Chris Timmins, and Hendrik Wolff for valuable comments and discussions. Seminar participants at the University of California at Davis and at the AAEA Annual Meeting provided helpful comments. All errors are our own.
[2] Connecticut College.
[3] Corresponding author. University of California at Davis. Email: cclin@primal.ucdavis.edu. Lin Lawell is a member of the Giannini Foundation of Agricultural Economics.
[4] Occidental College.

1. Introduction

Vehicular emissions are an important source of air pollution and a major environmental concern in urban areas. Motor vehicles are the primary source of carbon monoxide (CO), and an important source of volatile organic compounds (VOC) and nitrogen oxides (NO_x, which consist of both nitrogen oxide (NO) and nitrogen dioxide (NO_2)) responsible for the formation of photochemical smog and ground-level ozone (O_3). Vehicular emissions also contribute to the ambient air concentrations of sulfur dioxide (SO_2) and particulate matter (PM_{10}) (U.S. EPA, 1994). Common policies addressing vehicular emissions include dirty vehicle retirement policies, policies increasing fuel economy, emissions testing standards, technology standards requiring catalytic converters, and policies altering gasoline content. This paper focuses on another such policy: vehicle driving restrictions.

A typical driving restriction prohibits drivers from using their vehicles on given weekdays, based on the last digits of their vehicles' license plates.[5] License plate-based driving restrictions have been widely used as a method to reduce urban air pollution and traffic congestion in developing countries. Santiago, Chile introduced a license plate-based driving restriction in 1986 and Mexico City, Mexico introduced a driving restriction, *Hoy No Circula*, in 1989. Following these two, several more Latin American cities have introduced license plate-based driving restrictions, including Bogotá, Colombia[6] and São Paulo, Brazil. Beijing and its neighboring city Tianjin also implemented license plate-based driving restrictions during the 2008 Olympic Games

[5] In addition to license plate-based driving restrictions, another type of driving restriction are low emission zones, which define areas that vehicles may enter only if they are classified as low emission vehicles (Wolff and Perry, 2010); and another form of driving regulation are congestion charges (Leape, 2006; Gibson and Carnovale, 2015). In this paper, we focus on license plate-based driving restrictions, and use the terms "driving restrictions" and "license plate-based driving restrictions" interchangeably.

[6] Other Colombian cities that have implemented license plate-based driving restrictions include Bucaramanga, Cartagena, Manizales, Pereira, Barranquilla, Armenia, Cali, and Medellín.

and a modified version of the restriction continued in Beijing after the Olympics. Driving restrictions have also been implemented in cities of some developed countries as well, including Paris in 2015.

In the previous literature on the effects of license plate-based driving restrictions, 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 during the period 1986-1993 by using a regression discontinuity design to control for possible confounding factors. These two studies find no evidence that *Hoy No Circula* improved air quality in Mexico City.[7]

We build upon and synthesize the existing literature by developing a theoretical model of license plate-based driving restrictions that incorporates three behavioral channels highlighted by the literature that may affect the effectiveness of a license plate-based driving restriction. One behavioral channel that may affect the effectiveness of license plate-based driving restrictions is the possibility that households may intertemporally substitute their driving during restricted hours with driving during unrestricted hours. Davis (2008) finds that estimates for the effects of *Hoy No Circula* on air pollution during nonpeak weekdays and weekends tend to be positive, consistent

[7] Moreover, Gallego, Montero and Salas (2013a,b) find in their analysis of *Hoy No Circula* that policies that may appear effective in the short run can be highly detrimental in the long run, after households have adjusted their stock of vehicles. In the literature on license plate-based driving restrictions in China, Chen et al. (2013) find that the measures that China adopted during the 2008 Olympic Games in Beijing, particularly the driving restriction and plant closure, improved the Air Pollution Index (API) of Beijing during and after the Olympics, though most of the effect faded away by the end of October 2009. The credibility of China's API data has been questioned (Andrews, 2008, Ghanem and Zhang, 2014), but Chen et al. (2013) do not find any evidence of gaming of the API in Beijing. In their analysis of the effect of Beijing's driving restrictions on pollution and economic activity, Viard and Fu (2015) find that air pollution falls 20% during the every-other-data driving restriction and 9% during the one-day-per-week driving restriction. Cao, Wang and Zhong (2014) find that although their OLS regression results show such that Beijing's driving restriction policies are effective, their regression discontinuity results show that driving restriction policies, especially the one-day-per-week restriction policy, had little impact on air pollution concentrations. Huang, Fu and Qi (forthcoming) use internet data to analyze the effects of driving restrictions on air quality in Lanzhou, China, and find that the driving restrictions are effective in the short run, but ineffective in the long run.

with intertemporal substitution toward nighttime and weekend driving when the driving restrictions are not in place.

Two other behavioral channels that may affect the effectiveness of license plate-based driving restrictions that we incorporate in our theory model are the possibility that households may purchase a second car and the possibility that households may take an alternative mode of transportation. Davis (2008) explains the lack of an improvement in air quality resulting from *Hoy No Circula* with data from vehicle registrations and automobile sales which indicate that the program led to an increase in the total number of vehicles in circulation as well as a change in the composition of vehicles toward used, and thus higher-emitting, vehicles. In addition, Davis (2008) finds no evidence of an increase in public transportation ridership.

In addition to identifying substitution, the purchase of a second car, and the use of alternative modes of transportation as three behavioral channels through which license plate-based driving restrictions may be ineffective or even potentially increase air pollution, our theoretical model also incorporates insights from differences in the sources and atmospheric chemistry of different air pollutants. We show that the complex atmospheric chemistry of ozone smog formation may further cause driving restrictions to be ineffective or even have perverse consequences. The difficulty of regulating ozone smog in particular is also examined by Auffhammer and Kellogg (2011), who find that federal gasoline standards, which allow refiners flexibility in choosing a compliance mechanism, do not reduce ozone pollution because minimizing the cost of compliance does not reduce emissions of those compounds most prone to forming ozone; and by Salvo and Wang (2016), who find that increased ethanol use in the gasoline-ethanol vehicle fleet leads to higher ozone concentrations in urban São Paulo's ambient air.

After developing a theoretical model of license plate-based driving restrictions that incorporates substitution, the possibility of purchasing a second car or taking public transit, sources of air pollutants, and atmospheric chemistry, we examine the hypotheses of our model in light of suggestive empirical evidence from the license plate-based driving restriction implemented in Bogotá, Colombia.

Consistent with our theory model, we find suggestive empirical evidence that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for license plate-based driving restrictions to increase air pollution. Also consistent with our theory, we find that license plate-based driving restrictions may have different effects on different air pollutants, reflecting heterogeneity in the sources and atmospheric chemistry of the pollutants. In particular, owing to atmospheric chemistry, it is possible for a license plate-based driving restriction to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3.

The balance of our paper proceeds as follows. In Section 2 we present our theoretical model that combines an economic model with information about the sources and atmospheric chemistry of different air pollutants. Section 3 draws upon suggestive empirical evidence from driving restrictions implemented in Bogotá. We conclude in Section 4.

2. Theoretical Model

2.1 Economic Model

We begin with an economic model of the effects of license plate-based driving restrictions on air quality that identifies three behavioral channels through which license plate-based driving restrictions may potentially increase air pollution:[8] substitution,[9] the purchase of a second car, and the use of alternative modes of transportation.[10]

Let v_{idt} denote the vehicle miles traveled by household i on day-of-the-week d during hour t. Let $v_i \equiv \{v_{idt}\}_{dt}$ denote the vector of all the vehicle miles v_{idt} for all days of the week and all hours for a given household i; v_i therefore represents household i's weekly time pattern of vehicle miles traveled.

Household i receives private benefits $B_i(v_i)$ and incurs private costs $C_i(v_i)$ from its choice v_i of when and how much to drive during the week. Private benefits to driving include the ability to travel to work or other destinations at a particular hour on a particular day. Private costs to driving include fuel costs as well as the opportunity cost of time. Household i's private utility $U_i(v_i)$, or net benefits, is therefore its private benefits minus its private costs:

$$U_i(v_i) = B_i(v_i) - C_i(v_i).$$

Benefits $B_i(\bullet)$ are concave and costs $C_i(\bullet)$ are convex in each of their elements v_{idt}, which means that utility $U_i(\bullet)$ is concave in each of its elements v_{idt}. In other words, the marginal utility to each

[8] Our focus is on the short-run effects of a driving restriction. In the medium run, households may adjust via migration patterns and location decisions. In our empirical analysis, we also run a set of regressions allowing for adjustment over time, but, as these adjustment models do not pass the placebo tests, we place less emphasis on their results, and focus instead on the short run in the empirical analysis as well.

[9] Because a detailed theoretical model of the effects of driving restrictions on the purchase of a second car and on the use of alternative modes of transportation has been well developed in Gallego et al. (2013a), we focus our theory model primarily on substitution, as to our knowledge a theory model of substitution in the context of driving restrictions has heretofore been absent in the existing literature.

[10] It is also possible that general equilibrium effects of a driving restriction may cause air pollution to increase. For example, if a driving restriction reduces congestion it may induce additional demand for automobile travel (Beaudoin, Farzin and Lin Lawell, 2016; Beaudoin and Lin Lawell, 2016b), for example by inducing more people to purchase cars, even those who previously did not own one, leading to an increase in driving and emissions. This paper does not focus exclusively on the particular channel through which driving restrictions increase air pollution, but rather on the idea that it is possible for driving restrictions to increase air pollution.

household i of driving an additional vehicle-mile on day-of-the-week d during hour t is decreasing in the vehicle-miles v_{idt} traveled by household i on day-of-the-week d during hour t.

Let $v \equiv \{v_{idt}\}_{idt}$ denote the vector of all the vehicle miles traveled v_{idt} for all households i for all hours t for all days of the week d ; v therefore represents the entire profile of aggregate vehicle miles traveled for all hours of all days of the week. The aggregate profile of vehicle miles traveled v leads to negative externalities, such as pollution, which impose damages $D(v)$.[11] Marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from vehicle miles traveled v_{idt} are non-negative for all households i, days-of-the-week d, and hours t.

In the first-best, driving during each hour t of each day d is charged a fee or tax $p_{dt} = \frac{\partial D(v)}{\partial v_{idt}}$ per vehicle mile traveled, equal to the marginal damages of an additional vehicle mile traveled during that hour of that day, so that individual households will each choose the socially optimal choice of when and how much to drive during the week.[12]

In contrast to the first-best, a license plate-based driving restriction $\{\delta_i, \tau_i\}_i$ requires that $v_{idt} = 0$ for household i for a set of days δ_i and a set of hours τ_i. The individual household's optimization problem when faced with a license plate-based driving restriction is given by:

[11] $D(v)$ can also include other costs that are not internalized by an individual household, such as congestion costs. Beaudoin, Farzin and Lin Lawell (2016) develop a theory model to evaluate whether another driving related policy, public transit investment, has a role in reducing congestion in a second-best setting; Beaudoin and Lin Lawell (2016b) empirically examine the effects of public transit investment on congestion in the U.S. In their analysis of the short-run impacts of rapid employment growth on travel time to work, Morrison and Lin Lawell (2016) find that for each additional 10 workers added per square kilometer, travel time increases by 0.171 to 0.244 minutes per one-way commute trip per commuter in the short run, which equates to \$0.07 to \$0.20 in travel time cost per commuter per day. We focus on the air pollution costs in the empirical application, as we were unable to find good data on congestion in Bogotá. We hope to empirically examine the effects of driving restrictions on congestion in future work.

[12] The first-best driving and the driving in the absence of regulation are derived in Appendix A.

$$\max_{v_i} \; U_i(v_i) = B_i(v_i) - C_i(v_i)$$
$$\text{s.t.} \quad v_{idt} = 0 \qquad : \lambda_{idt} \quad \forall d \in \delta_i \wedge t \in \tau_i,$$

where $\lambda_{idt} \geq 0$ is the multiplier associated with each constraint imposed by the driving restriction, yielding as first-order conditions for the regulated optimum $\{v_{idt}{}^R\}_{idt}$:

$$\frac{\partial B_i(v_i{}^R)}{\partial v_{idt}} = \frac{\partial C_i(v_i{}^R)}{\partial v_{idt}} \qquad \forall d \notin \delta_i, t \notin \tau_i$$
$$\frac{\partial B_i(v_i{}^R)}{\partial v_{idt}} = \frac{\partial C_i(v_i{}^R)}{\partial v_{idt}} + \lambda_{idt} \qquad \forall d \in \delta_i \wedge t \in \tau_i$$
$$v_{idt}{}^R = 0 \qquad \forall d \in \delta_i \wedge t \in \tau_i.$$

We formalize our notion of substitution as follows:

<u>Definition</u>. Driving during unrestricted hours $(d \notin \delta_i, t \notin \tau_i)$ is a *substitute* for driving during restricted hours $(d' \in \delta_i, t' \in \tau_i)$ if and only if:

$$\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}} < 0 \qquad \forall d \notin \delta_i, t \notin \tau_i, d' \in \delta_i, t' \in \tau_i.$$

An increase in the degree of substitution between driving during unrestricted hours and driving during restricted hours for household *i* would be reflected in a more negative cross-partial $\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}}$ for household *i*.

With a license plate-based driving restriction, it is possible that driving by a particular household *i* during unrestricted hours and days is higher under the driving restriction than in the absence of regulation. In particular, if driving during unrestricted hours is a substitute for driving during restricted hours, then a restriction of driving during certain hours leads to substitution and therefore increased driving during unrestricted hours. It is moreover possible that the driving restriction may cause driving during unrestricted hours to increase by more than the driving during restricted hours was decreased. As formalized in the following Lemma 1, the greater the degree of substitution between driving during unrestricted hours and driving during restricted hours for household *i*, the more a driving restriction would increase driving by household *i* during unrestricted hours. All proofs are in Appendix A.

Lemma 1. Let $d \notin \delta_i, t \notin \tau_i$, $d' \in \delta_i$, and $t' \in \tau_i$. The greater the degree of substitution between driving during unrestricted hours and driving during restricted hours for household *i*, the more a driving restriction would increase driving by household *i* during unrestricted hours.

If the substitution effect is strong enough, a driving restriction can increase total driving. The intuition is that if the decrease in driving during restricted hours as a result of the driving restriction increases the marginal utility of driving during unrestricted hours high enough (and in particular, more than it would have increased the marginal utility of driving during restricted hours), it is possible that the driving restriction may cause driving during unrestricted hours to increase by more than the decrease in driving during restricted hours. This result is formalized in Theorem 1.

Theorem 1. For each household *i*, a restriction of driving during certain hours causes driving during unrestricted hours by household *i* to increase by more vehicle miles than driving during restricted hours was decreased if and only if driving during unrestricted hours is a substitute for driving during restricted hours and the magnitude of the cross derivative in the utility function is greater than the magnitude of the concavity of the utility function:

$$\frac{\partial v_{idt}}{\partial v_{id't'}} < -1 \Leftrightarrow \frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}} < 0 \wedge \left| \frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}} \right| > \left| \frac{\partial^2 U_i(v_i)}{\partial v_{idt}{}^2} \right|.$$

An illustrative example of how a driving restriction may cause driving during unrestricted hours to increase by more than how much the driving during restricted hours was decreased would be the following. Let's suppose that the private benefits $B_i(v_i)$ household i receives from its choice v_i of when and how much to drive during the week include the ability to travel to the grocery store at a particular hour on a particular day. If individuals in the household are restricted from driving to a grocery store during certain hours, then it is likely that they will want drive to a grocery store during unrestricted hours. However, if they drive to a grocery store during unrestricted hours, it might be the case that their preferred grocery store is closed during unrestricted hours so that they will now need to go to a grocery store farther away instead. As a consequence, their driving during unrestricted hours would increase by more than how much their driving during restricted hours decreased.

Continuing the example, it might also be the case that if the individuals in the household are driving to a different grocery store located in a different, further location during different hours, it might turn out that near the new location and during the new time of day, it now becomes desirable for them to also go to another destination as well, perhaps because near the new grocery store there is a clothing store that is also open during unrestricted hours, or because the new grocery store does not have all the items the household needs from a grocery store. As a consequence, it may be possible that while driving to the different grocery store during unrestricted hours, the household may choose to also drive to additional stores or destinations as well. Thus, a driving restriction may further cause their driving during unrestricted hours to increase by more than how much their driving during restricted hours decreased.

A driving restriction does not necessarily result in lower air pollution and lower total damages, for it is possible for the restriction to lead to increased driving in unrestricted hours, and, if the marginal damage from driving during restricted hours is small relative to the marginal damage from driving during unrestricted hours, this may lead to an increase in total damages as well. The following theorem provides the condition for when a driving restriction may actually increase the total damages from household *i*.

<u>Theorem 2</u>. Let $d \notin \delta_i, t \notin \tau_i$, $d' \in \delta_i$, and $t' \in \tau_i$. A driving restriction increases total damages from air pollution from household *i* if and only if the degree of substitution is large (i.e., $\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}}$ is more negative) relative to the ratio of the marginal damage from driving during restricted hours to the marginal damage from driving during unrestricted hours:

$$dD(v) > 0 \Leftrightarrow \frac{\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}}}{\frac{\partial^2 U_i(v_i)}{\partial v_{idt}{}^2}} > \frac{\frac{\partial D(v)}{\partial v_{id't'}}}{\frac{\partial D(v)}{\partial v_{idt}}}.$$

Thus, since $U_i(\bullet)$ is concave, if the cross derivative $\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}}$ in the utility function is negative enough (so that the substitution effect is strong) and the marginal damage $\frac{\partial D(v)}{\partial v_{id't'}}$ from driving during restricted hours is small enough relative to the marginal damage $\frac{\partial D(v)}{\partial v_{idt}}$ from driving during unrestricted hours, then it is possible for a driving restriction to increase the total damage from pollution.

The second-best driving restriction is therefore one that imposes a ban when the marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ are high and permits households to drive when the marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ are low. If, for example, marginal damages are high during the day but low during the night, then it is best to restrict driving during the day.

If the driving restriction restricts driving on different days for different households, then if the substitution effect is strong enough for all households, it is possible that there is more total driving. The following theorem provides a sufficient condition for this to be the case.

Theorem 3. Suppose that for all i,

$$\frac{\partial^2 U_i(v_i)}{\partial v_{id_i t_i} \partial v_{id_i' t_i'}} < 0 \wedge \left| \frac{\partial^2 U_i(v_i)}{\partial v_{id_i t_i} \partial v_{id_i' t_i'}} \right| > \left| \frac{\partial^2 U_i(v_i)}{\partial v_{id_i t_i}{}^2} \right|,$$

where $d_i \notin \delta_i, t_i \notin \tau_i, d_i' \in \delta_i$, and $t_i' \in \tau_i$. Then total driving under the driving restriction is higher than total driving in the absence of regulation:

$$\sum_{idt} v_{idt}{}^R > \sum_{idt} v_{idt}{}^*.$$

Similarly, if the driving restriction restricts driving on different days for different households, then if the substitution effect is strong enough, it is possible that the driving restriction leads higher air pollution and greater total damages from air pollution. The following theorem provides a sufficient condition for this to be the case.

Theorem 4. Suppose that for all i,

$$\frac{\dfrac{\partial^2 U_i(v_i)}{\partial v_{id_i t_i} \partial v_{id_i' t_i'}}}{\dfrac{\partial^2 U_i(v_i)}{\partial v_{id_i t_i}{}^2}} > \frac{\dfrac{\partial D(v)}{\partial v_{id_i' t_i'}}}{\dfrac{\partial D(v)}{\partial v_{id_i t_i}}},$$

where $d_i \notin \delta_i, t_i \notin \tau_i, d_i' \in \delta_i$, and $t_i' \in \tau_i$. Then total damages from air pollution under the driving restriction is higher than total damages in the absence of regulation:

$$D(v^R) > D(v^*).$$

Thus, if the degree of substitution is large enough and the marginal damages during unrestricted hours and days are high enough relative to the marginal damage from driving during restricted hours, driving restrictions can lead to higher ambient air pollution and greater total pollution damage throughout the day. The intuition is that if a driving restriction leads households to drive more during unrestricted hours, and if the marginal damages from their increased driving during unrestricted hours is higher than the (foregone) marginal damages from their decreased driving during restricted hours, then driving restrictions can increase total air pollution damage throughout the day.[13]

There can be heterogeneity in how a driving restriction affects different pollutants due to differences in the atmospheric chemistry of the different pollutants, including factors such as the lifetime of the pollutants in the atmosphere, how the pollutants are formed, and how different quantities of the pollutant emitted at different points in time affect the total damages caused by the pollutants; as well as differences in the extent to which changes in driving affect the ambient concentrations of the pollutant. These factors are reflected in different damage functions $D(\bullet)$ for each pollutant.[14]

[13] It is possible that households may respond to the driving restriction not only by intertemporally substituting their driving to unrestricted days and hours, but also by spatially substituting their driving by taking routes outside of the city instead of inside of the city in order to avoid the driving restriction. In their study of the air pollution and traffic effects of another type of driving regulation, a congestion charge, implemented in Milan, Gibson and Carnovale (2015) find that drivers respond to the congestion charge by intertemporally substituting toward the unpriced period; by substituting toward motorcycles, which are exempt from the charge; and by spatially substituting toward unpriced roads. It is also possible that this spatial substitution leads to pollution outside of the city that then spills over to the city itself. While our empirical application focuses on intertemporal substitution, our theory model of substitution can apply to spatial substitution as well. For example, our results that driving and air pollution can increase if the degree of intertemporal substitution is high enough can be easily extended to show that driving and air pollution can increase if the degree of spatial substitution is high enough. However, spatial substitution may not be a large concern for air quality in practice: in his study of Europe's Low Emission Zones, Wolff (2014) finds that avoidance behavior of driving around Low Emissions Zones does not lead to significant spatial spillover effects in air pollution. Owing to data availability constraints and to Wolff's (2014) finding that spatial spillover effects in air pollution may not be significant, our empirical analysis focuses on intertemporal substitution.

[14] In the empirical analysis, we focus on the effects of driving restrictions on the quantity of air pollution rather than

In particular, pollutants that have different damage functions $D(\bullet)$ may have different marginal damages $\frac{\partial D(v)}{\partial v_{id't'}}$ from driving during restricted hours and different marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from driving during unrestricted hours, so that for some pollutants the condition in Theorem 2 for a driving restriction to increase the total damages from a particular pollutants is satisfied, while for other pollutants the condition is not satisfied.[15] Theorem 5 formalizes the intuition.

---

on air pollution damages, since air pollution is easier to measure while air pollution damages depend on other factors such as the size of the exposed population. Differences in damage functions in the empirical application therefore reflect differences in the atmospheric chemistry of the different pollutants, including factors such as the lifetime of the pollutants in the atmosphere and how the pollutants are formed; as well as differences in the extent to which changes in driving affect the ambient concentrations of the pollutant. This paper focuses on heterogeneity among different pollutants; the total effect of a driving restriction would entail aggregating the damages over all pollutants.

[15] Similarly, if the damages were from congestion instead of air pollution, congestion may have different marginal damages $\frac{\partial D(v)}{\partial v_{id't'}}$ from driving during restricted hours and different marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from driving during unrestricted hours compared to those from air pollution. It is also possible for the pollution-related marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from driving, which depend in part on the emissions rate of vehicles, to depend on congestion levels. The emissions rate of vehicles is a function of travel speed, which is dependent upon the degree of congestion (Beaudoin, Farzin and Lin Lawell, 2015; Beaudoin and Lin Lawell, 2016a). Barth and Boriboonsomsin (2009) summarize the empirical relationship between travel speeds and vehicle emissions, and Berechman (2009, pp. 259) discusses how "low speeds from gridlock conditions, which characterize many urban commuting patterns, are major contributors to emissions and therefore to air pollution." Anas and Lindsey (2011, pp. 69) mention that the emissions rate is a "flat-bottomed, U-shaped function of speed with a minimum at an intermediate speed that depends on the pollutant" and that heavy congestion yields travel speeds that are below this minimum speed. Beevers and Carslaw (2005) also highlight the importance of considering the effects of both traffic volume and travel speeds on emissions. There may also be heterogeneity in how congestion affects vehicle emission rates for different pollutants.

If a driving restriction leads households substitute from driving during restricted hours to driving during unrestricted hours, then congestion during restricted hours would decrease and congestion during unrestricted hours would increase. A decrease in congestion during restricted hours would likely decrease the pollution-related marginal damages $\frac{\partial D(v)}{\partial v_{id't'}}$ from driving during restricted hours, while an increase in congestion during unrestricted hours would likely increase the pollution-related marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from driving during unrestricted hours, making it more likely to satisfy the conditions in Theorems 2 and 4 for a driving restriction to increase total air pollution. However, if the damage function is convex in the number of cars in the streets, it is possible that substitution of cars from restricted to unrestricted hours may decrease total pollution damage. If this is the case, our empirical evidence on substitution would be a lower bound on the amount of substitution that has actually taken place, since even if pollution weakly decreases, it is still possible that substitution has taken place. We hope to find the data to empirically examine the effects of driving restrictions on congestion in future work.

Theorem 5. Let the damage function for pollutant A be given by $D_A(\bullet)$ and the damage function for pollutant B be given by $D_B(\bullet)$. Suppose that for all *i*,

$$\frac{\dfrac{\partial D_A(v)}{\partial v_{id_i't_i'}}}{\dfrac{\partial D_A(v)}{\partial v_{id_it_i}}} < \frac{\dfrac{\partial^2 U_i(v_i)}{\partial v_{id_it_i}\partial v_{id_i't_i'}}}{\dfrac{\partial^2 U_i(v_i)}{\partial v_{id_it_i}^{\;2}}} < \frac{\dfrac{\partial D_B(v)}{\partial v_{id_i't_i'}}}{\dfrac{\partial D_B(v)}{\partial v_{id_it_i}}}$$

where $d_i \notin \delta_i, t_i \notin \tau_i, d_i' \in \delta_i$, and $t_i' \in \tau_i$. Then total damages from pollutant A under the driving restriction is higher than total damages from pollutant A in the absence of regulation:

$$D_A(v^R) > D_A(v^*),$$

but total damages from pollutant B under the driving restriction is lower than total damages from pollutant B in the absence of regulation:

$$D_B(v^R) < D_B(v^*).$$

If the driving restriction is too restrictive, the households would have an incentive to purchase a second car or to take another mode of transportation, such as public transit or a taxi, instead of driving. Theorem 6 formalizes the intuition. For a more detailed theoretical model of the effects of driving restrictions on the purchase of a second car and on the use of alternative modes of transportation, see Gallego et al. (2013a).

Theorem 6. Let v_i^* denote the optimal driving profile for household *i* in the absence of regulation and v_i^R denote the optimal driving profile for household *i* in the presence of a driving restriction. Suppose the household can avoid the driving restriction by purchasing a second car or by taking an alternative mode of transportation at cost φ_i. Then a household will purchase the second car or take the alternative mode of transportation, and therefore avoid the driving restriction if $U_i(v_i^*) - \varphi_i \geq U_i(v_i^R)$.

Theorem 6 has potential implications for air quality. If the household purchases a second car, this second car is likely to be a used and higher emitting car since used and higher emitting cars have lower costs φ_i. Moreover, owing to budget constraints, the purchase of a second car as a response to the driving restriction will also mean that the first car will be upgraded to a newer cleaner car more slowly. If the household takes an alternative mode of transportation, the potential effects on air quality are mixed. While some forms of public transit may be cleaner than driving, other alternative modes of transportation such as taxis may emit more pollution than the household's own vehicle (Davis, 2008).

2.2 Heterogeneity in Air Pollutants

In order to examine the heterogeneity in air pollutants in more detail, we now combine our economic model with information about the sources and atmospheric chemistry of different air pollutants. One source of heterogeneity between different air pollutants is that they each have different marginal damages $\frac{\partial D(v)}{\partial v_{idt}}$ from driving, owing in part to whether automobile emissions is the primary source of emissions for that pollutant. If automobile emissions are not the primary source for a particular air pollutant, changes in driving caused by a driving restriction may have little effect on these pollutants.

Automobile emissions are a primary source of emissions of carbon monoxide (CO). In the U.S., mobile sources constitute 74.4% of CO emissions (U.S. EPA, 2015a), while on-road mobile sources constitute 33.9% of CO emissions (U.S. EPA, 2015b; Beaudoin and Lin Lawell, 2016a). The transport sector is responsible for 73% of CO emissions in the UK ("Air Pollution Emissions in the UK", 2015), 59% of anthropogenic CO emissions worldwide, 53% of anthropogenic CO emissions in developing countries, and 69-90% of anthropogenic CO emissions in Latin America

(Onursal and Gautam, 1997; OECD/IEA, 1991). In Bogotá, mobile sources constitute 99.9% of CO emissions (Robra, 2010), and traffic is the source of over 95% of CO emissions (Zárate, 2007).

Automobile emissions are not a primary source of emissions of PM_{10}. In the U.S., PM_{10} comes primarily from dust (60.4%) and agriculture (24.8%); only 3.3% of PM_{10} emissions in the U.S. come from mobile sources (U.S. EPA, 2015a) and only 1.8% of PM_{10} emissions in the U.S. come from on-road mobile sources (U.S. EPA, 2015b; Beaudoin and Lin Lawell, 2016a). In the UK, only 24% of PM_{10} emissions come from transport ("Air Pollution Emissions in the UK", 2015). In Bogotá, traffic is the source of approximately 35% of PM_{10} emissions (Zárate, 2007).

Automobile emissions are a primary source of emissions of nitrogen oxides (NO_x, which consist of both NO and NO_2). In the U.S., 59.4% of NO_x emissions are from mobile sources (U.S. EPA, 2015a) and 38.0% of NO_x emissions are from on-road mobile sources (U.S. EPA, 2015b; Beaudoin and Lin Lawell, 2016a). The transport sector accounts for 50% of NO_x emission in the UK ("Air Pollution Emissions in the UK", 2015), 43% of anthropogenic NO_x emissions worldwide, and 49% of anthropogenic NO_x emissions in Latin America (Onursal and Gautam, 1997; OECD/IEA, 1991). In Bogotá, mobile sources constitute 95.8% of NO_x emissions (Robra, 2010), vehicles are responsible for 92% of NO_x emissions (CIIA, 2008), and traffic is the source of over 75% of NO_x emissions (Zárate, 2007).

Automobile emissions are not a primary source of emissions of SO_2. In the U.S., SO_2 comes primarily from fuel combustion (86.6%); only 2.5% of SO_2 emissions come from mobile sources (U.S. EPA, 2015a) and only 0.5% of SO_2 emissions come from on-road mobile sources (U.S. EPA, 2015b; Beaudoin and Lin Lawell, 2016a). The transport sector accounts for only 1% of SO_2 emissions in the UK ("Air Pollution Emissions in the UK", 2015) and 2-6% of SO_2 emissions worldwide (Onursal and Gautam, 1997). In Bogotá, mobile sources constitute 86.2%

of SO_2 emissions (Robra, 2010), but traffic is the source of only 30% of SO_2 emissions (Zárate, 2007).

The possible effects of changes in driving on ozone (O_3) are more complicated. A secondary pollutant, ozone is not emitted directly but is formed in ambient air in the presence of sunlight by chemical reactions involving nitrogen oxides (NO_x), which consist of nitrogen oxide (NO) and nitrogen dioxide (NO_2); and volatile organic compounds (VOCs) (Lin, 2000; Lin et al., 2000; Lin, Jacob and Fiore, 2001; Lin, 2010). The rate of ozone production shows a nonlinear and non-monotonic dependence on precursor concentrations. There are two different photochemical regimes: a NO_x-limited regime, in which the rate of ozone formation increases with increasing NO_x and is insensitive to changes in VOC; and a VOC-limited regime, in which the rate of ozone formation increases with increasing VOC and may even decrease with increasing NO_x (Sillman, 1999). Thus, higher emissions of NO_x do not always result in higher levels of ozone pollution; in some cases, higher NO_x emissions may actually *decrease* ozone, a phenomenon known as NO_x titration (Lin, 2010).[16]

Since ozone formation requires sunlight, ozone concentrations peak during hours of maximum sunlight, around the middle of the day (Allen, 2002). In urban areas, peak ozone concentrations typically occur in the early afternoon, shortly after solar noon when the sun's rays are most intense (California Environmental Protection Agency, 2015). The marginal damages from driving are therefore higher for ozone around noon. Thus, if a driving restriction does not restrict driving during noon-time or early afternoon and induces substitution towards driving around noon or early afternoon, it is possible that the driving restriction may increase ozone concentrations. As seen in Theorem 2, if the substitution effect is strong and the marginal damage

[16] For a scientific explanation of NO_x titration, see Lin (2000).

$\frac{\partial D(v)}{\partial v_{id't'}}$ from driving during restricted hours is small enough relative to the marginal damage $\frac{\partial D(v)}{\partial v_{idt}}$ from driving during unrestricted hours, then it is possible for a driving restriction to increase the total damage from pollution.

Moreover, owing to atmospheric chemistry, it is possible for a driving restriction to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3. In the absence of volatile organic compounds (VOCs), which are pollutants emitted by cars, the photostationary steady-state concentration of O_3 is governed by a cycle between NO and NO_2, as illustrated in Figure 1(a). NO_2 combines with sunlight and oxygen (O_2) to form O_3 and NO, leading to O_3 production. NO combines with O_3 to form O_2 and NO_2, leading to O_3 loss. Thus, in the absence of VOCs, NO and NO_2 cycle back and forth with each other, producing O_3 when NO_2 cycles to NO and losing O_3 when NO cycles back to NO_2, and there is no net change in concentrations of O_3, NO, or NO_2 (Jacob, 1999; Barker, 1995).

However, if there are VOCs present, for example from emissions for cars, net O_3 production occurs. As illustrated in Figure 1(b), VOC oxidation increases the NO_2/NO ratio by converting NO to NO_2 without O_3 loss (Jacob, 1999; Barker, 1995). VOC reaction sequences are initiated by reactions that involve hydrocarbons (Seinfeld, 1995). Thus, VOC emissions from cars can increase both NO_2 and O_3 and can decrease NO. From Theorems 3 and 4, if the driving restriction restricts driving on different days for different households, then if the substitution effect is strong enough for all households, it is possible that a driving restriction can lead to more total driving, higher air pollution, and greater total damages from air pollution. Thus, it is possible that a driving restriction can lead to more total driving and more VOC emissions, and therefore higher concentrations of NO_2 and O_3 and lower concentrations of NO.

Vehicles fueled by gasoline have different effects on air pollution than do vehicles fueled by diesel, and these effects vary by air pollutant. In the absence of particle traps, diesel CO emissions are similar to those from gasoline. However, "modern" diesel vehicles with particle traps have lower CO emissions and lower hydrocarbon emissions than gasoline vehicles (Jacobson et al., 2004). Diesel vehicles with or without a particle trap and without a NO_x control device emit 4-30 times more NO_x than do gasoline vehicles (Jacobson et al., 2004). In addition, diesel vehicles have higher particulate matter emission rates than gasoline vehicles (Onursal and Gautam, 1997; Faiz, Weaver, and Walsh 1996).

Diesel vehicles with or without a particle trap and without a NO_x control device also emit a higher ratio of NO_2 to NO than do gasoline vehicles, and as a consequence, may increase O_3 particularly when the photochemical regime is a NO_x-limited regime (Jacobson et al., 2004). This is because, as seen in Figure 1, when NO_x is emitted continuously as NO_2, O_3 is produced directly when NO_2 cycles to NO. In contrast, when the same NO_x is emitted as NO, O_3 is lost when NO cycles to NO_2, thus destroying some of the O_3 that is created (Jacobson et al., 2004; Jacob, 1999; Barker, 1995). Thus, the higher ratio of NO_2 to NO in diesel vehicles relative to gasoline vehicles leads to higher O_3, particularly when the photochemical regime is a NO_x-limited regime (Jacobson et al., 2004).

2.3 Hypotheses from Theoretical Model

Combining our economic model with information about the sources and atmospheric chemistry of different air pollutants, we arrive at the following hypotheses, each of which has implications for the expected sign of the coefficient on the driving restriction in our empirical model. Table 1 summarizes these hypotheses and the expected sign of the coefficient on the driving restriction implied by each.

Hypothesis 1 is that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for driving restrictions to increase air pollution. If this hypothesis were true, we would expect that for some air pollutants, some coefficients on driving restrictions will be significant and positive.

Hypothesis 2 is that any increase in driving as a result of driving restrictions (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) will have less of an impact on PM_{10} and SO_2, and more of an impact on CO and NO_x. If automobile emissions are not the primary source for a particular air pollutant, changes in driving may have little effect on these pollutants. If this hypothesis were true, then we would expect more positive coefficients on driving restrictions for CO and NO_x than for PM_{10} and SO_2.

Hypothesis 3 is that if the photochemical regime is a NO_x-limited regime, then increases in NO_x as a result of increased driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) will lead to increases in O_3. If this hypothesis were true, then we would expect positive coefficients on driving restrictions for both NO_x and O_3.

Hypothesis 4 is that if the photochemical regime is a VOC-limited regime, then increases in NO_x as a result of increased driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) may decrease O_3. If this hypothesis were true, then we would expect a positive coefficient on driving restrictions for NO_x and a negative coefficient on driving restrictions for O_3.

Hypothesis 5 is that if a driving restriction does not restrict driving during noon-time or early afternoon and induces substitution towards driving around noon or early afternoon, it is possible that the driving restriction may increase O_3 concentrations. If this hypothesis were true, then we would expect a positive coefficient on driving restrictions that do not restrict driving during noon-time or early afternoon for O_3.

Hypothesis 6 is that owing to atmospheric chemistry, it is possible for a driving restriction that increases driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3. If this hypothesis were true, then we would expect positive coefficients on driving restrictions for NO_2, NO_x, and O_3; and a negative coefficient on driving restrictions for NO.

Hypotheses 7-10 are a step towards distinguishing among the three behavioral channels through which driving restrictions may potentially increase air pollution: substitution, the purchase of a second car, and the use of alternative modes of transportation.

Hypothesis 7 is that driving restrictions may increase driving during unrestricted hours, total driving, and air pollution due to substitution. If this hypothesis were true, then we would expect positive coefficients on driving restrictions for daily maximum concentrations and for non-restricted hours, and an insignificant or negative coefficient on driving restrictions during restricted hours.

Hypothesis 8 is that driving restrictions may increase air pollution due to the purchase of a second car. If this hypothesis were true, then we would expect a positive coefficient on driving restrictions that restrict both driving during all daylight hours (to reduce substitution) and driving by alternative modes of transportation (to reduce the effect of using alternative modes of transportation).

Hypothesis 9 is that driving restrictions may increase air pollution due to the use of alternative modes of transportation. If this hypothesis were true, then we would expect a positive coefficient on driving restrictions that do not restrict driving by alternative modes of transportation.

Hypothesis 10 is that if driving restrictions lead to the purchase of a second car or the use of alternative modes of transportation, and if the second car or alternative mode of transportation uses diesel instead of gasoline, then O_3, the NO_2/NO ratio, and PM_{10} may increase, and, if these diesel vehicles have a particle trap, CO may decrease. If this hypothesis were true, then we would expect positive coefficients on driving restrictions for O_3, NO_2, and PM_{10}; and possibly negative coefficients on driving restrictions for CO and NO.

3 Suggestive Empirical Evidence from Bogotá

We now examine our hypotheses in light of suggestive empirical evidence from Bogotá. We choose Bogotá because there have been few, if any, empirical analyses of the driving restriction in Bogotá and because the different versions of the driving restriction in Bogotá can be exploited to examine our hypotheses. Owing to data and other limitations, clean natural experiments were difficult to find, and therefore our empirical results provide evidence that is suggestive as best.

Driving restrictions were first implemented in Bogotá in August 1998 as part of the program called *Pico y Placa*. On each weekday, 40% of private vehicles were restricted from operating in the city between 7:00 a.m. and 9:00 a.m. and between 5:30 p.m. and 7:30 p.m. Thus, every vehicle was banned from the roads during peak hours on 2 days per week. In August 2001, some forms of public transportation in Bogota, including some buses, minibuses, and taxis, became subject to driving restrictions as well: 20% of the public vehicles were banned from the roads between 5:30 a.m. and 9:00 p.m. from Monday to Saturday (El Tiempo, 2001). TransMilenio buses, school buses, commuter shuttles, and tour buses were exempted from driving restrictions. In June 2004, the driving restriction for private vehicles was extended to cover the hours between 6:00 a.m. and 9:00 a.m. and between 4:00 p.m. and 7:00 p.m. (Mahendra, 2008). In February 2009, the driving restriction for private cars was again extended to be in effect from 6:00 a.m. to 8:00 p.m. on each weekday. The various versions of the *Pico y Placa* driving restriction are summarized in Table 2.[17]

The schedule of the *Pico y Placa* changes once a year. The grouping of the four digits that designate the 40% of private vehicles that are restricted on a particular weekday does not change, even though the restriction day changes for each group once in a year. For example, cars with license plates ending in 5, 6, 7, and 8 were restricted on Fridays in 2011, but on Mondays in 2012. If a family has two cars with last digits 2 and 8, for example, they can drive every day since these two digits fall in different four-digit groups.

Bogotá has an air quality monitoring network since 1997, administered by the District Administrative Department of the Environment (Departamento Técnico Administrativo del Medio Ambiente, DAMA). The network currently has 14 stations monitoring air pollution and weather (Zárate et al., 2007). We use hourly pollution records from this monitoring network from 1997 to

[17] There is evidence that the driving restrictions were enforced. In 2010, during the first day when new rotation numbers started, the Department of Transportation recorded 287 drivers who failed to abide by the restriction, while in 2009, 442 were counted (El Tiempo, 2011). There were 11,088 recorded violations of the restriction in 2011 and 10,644 in 2012. The restriction is coded as traffic rule C14. In 2012, violators were fined an amount equivalent to a 15-day statutory minimum wage and their vehicle was immobilized (Secretaría Distrital de Movilidad, 2013). We did not find any evidence that either the fines or the amount of money or resources put into enforcement changed during the sample period, nor any evidence that either the fines or the amount of money or resources put into enforcement changed for the different versions of the driving restriction.

2009 for seven air pollutants:[18] carbon monoxide (CO), particulate matter (PM_{10}), nitrogen oxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NO_x, which consist of both NO and NO_2), ozone (O_3), and sulfur dioxide (SO_2).[19] Our sample consists of observations from seven stations that were in use during the entire study period. We exclude observations from the stations that were added or removed from the network to prevent compositional changes from biasing the results. Since the stations included in our sample did not monitor weather, we averaged the hourly data on temperature, relative humidity, and wind speed over other stations from the same monitoring system. Table 3 presents summary statistics for the pollution and weather variables in our data set. Figure B1 in Appendix B plots mean daily pollution levels for each of the seven pollutants for the time period 1997 to 2009; these graphs are described in Appendix B.

To analyze the impact of the driving restriction on air quality, we use a regression discontinuity design. A regression discontinuity design can be used when observations can be ordered according to a forcing (or running) variable and then the treatment is assigned above a given threshold. In our case, the forcing variable is time and the threshold is the date the restriction was implemented (Percoco, 2014). Previous studies that have used a regression discontinuity design with time as the forcing variable to evaluate environmental and energy policy include Davis (2008), Auffhammer and Kellogg (2011), and Salvo and Wang (2016). In a regression discontinuity design, there is no value of the forcing variable at which we observe both treatment and control observations; instead, we extrapolate across covariate values, at least in a neighborhood of the discontinuity (Angrist and Pischke, 2009; Imbens and Lemieux, 2008).

[18] The time period of the data set was determined by the availability of the data. Air quality was not monitored before 1997, and the end date of our period of analysis was the most recent data we were able to obtain. To our knowledge, VOCs were not monitored.
[19] It is also possible for driving restrictions to increase the concentration of global pollutants such as CO_2. However, since it is nearly impossible to tease out the effect of the driving restriction in Bogotá on the concentration of a global pollutant worldwide, since the concentration of a global pollutant can be affected by emissions from anywhere around the world, not just from Bogotá, we do not analyze global pollutants in our empirical analysis.

In particular, we use the following regression discontinuity design for each pollutant *j*:

$$\ln y_{ijt} = \beta_1 D_{1t} + \beta_2 D_{2t} + \beta_3 D_{3t} + \beta_4 D_{4t} + x_t ' \beta_4 + \alpha_i + \varepsilon_{ijt}, \qquad (1)$$

where y_{ijt} is the amount of pollutant *j* measured at station *i* at hour *t*, D_{nt} is a driving restriction indicator variable which equals one for all the hours for all the days covered by driving restriction version *n* and zero otherwise, x_t is a vector of covariates, and α_i is a station fixed effect. We include four driving restriction indicators D_{nt} in the specification, one for each of the four versions of the driving restriction listed in Table 2. The vector of covariates x_t includes indicator variables for month of the year, day of the week, and hour of the day; fourth-order polynomials in temperature, relative humidity, and wind speed; and a ninth-order polynomial time trend.[20] The coefficients of interest are the coefficients β_n on the four versions *n* of the driving restriction, as they capture the effect of the different versions of *Pico y Placa* on air quality.

Our regression discontinuity design addresses the potential bias caused by time-varying omitted variables. 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 in effect provide a comparison group for observations when *Pico y Placa* was in effect. Our station fixed effects control for time-invariant station heterogeneity.

Results are shown in Table 4. For each pollutant, each row reports coefficients corresponding to different driving restriction indicator variables. Following Davis (2008), we

[20] The validity of regression discontinuity estimates of causal effects depends on whether the polynomial models provide an adequate description of the counterfactual conditional mean of the dependent variable, conditional on time. If not, then what may look like a jump due to treatment might simply be an unaccounted-for nonlinearity in the counterfactual conditional mean function (Angrist and Pischke, 2009). We therefore use a higher order polynomial to account for any nonlinearities in the counterfactual conditional mean function. We use a ninth-order polynomial time trend because the ninth-order time trend term is often significant, and because our results are robust to whether we also include a tenth-order time trend term.

report standard errors that are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Since we analyze the effects of the driving restrictions on 7 different pollutants, we apply the Bonferroni correction to adjust for multiple hypothesis testing (Bland and Altman, 1995; Napierala, 2012). According to the results, the various versions of the driving restriction caused significant positive increases in hourly NO_2 and O_3, but did not have any significant effect on hourly CO, PM_{10}, NO, NO_x, or SO_2. There are some negative coefficients on some versions of the driving restriction for CO and PM_{10}, but none of them are significant.[21]

To analyze the effects of the driving restriction during restricted and unrestricted hours, we run one regression discontinuity model of the effect of *Pico y Placa* during the hours when driving was restricted and another regression discontinuity model for the two hours before and the two hours after the restricted hours. We control for a ninth-order polynomial time trend, station fixed effects, month of the year, day of the week, and hour of the day, as well as fourth-order polynomials in weather variables. For these regressions, we restrict the sample to the period 1997 to 2001, which covers the period before any version of the driving restriction was implemented as well as the period during which the first driving restriction (Restriction-1) was implemented. We do so because we are focusing on the hours during which the restriction is in effect, and the first version of the driving restriction is the only version in which only private vehicles were restricted. In the subsequent versions of the driving restriction, public vehicles were also restricted, and the hours when the public vehicles were restricted were different from the hours when the private vehicles restricted. The first driving restriction is therefore the only version of the driving restriction that provides the cleanest delineation between restricted and unrestricted hours.

[21] Figure B2 in Appendix B plots residuals from a regression of log pollution levels on weather and seasonality covariates and station fixed effects for each of the pollutants; these graphs are analyzed in Appendix B.

Table 5 reports results from a regression discontinuity model of the effect of the first driving restriction (Restriction-1) during the hours when driving was restricted and a second regression discontinuity model for the two hours before and the two hours after the restricted hours. According to the results, during the hours when the restriction was in effect, the restriction caused a significant decrease in NO and a significant increase in NO_2. During the hours before and after the driving restriction, the restriction caused a significant increase in NO_2. There are some additional negative coefficients for PM_{10} and SO_2, but they are not significant.

The result from Table 5 that the restriction caused a significant decrease in NO and a significant increase in NO_2 is consistent with Hypothesis 6 that owing to atmospheric chemistry, it is possible for a driving restriction that increases driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3. Thus, it is possible that the driving restriction led to more total driving and more VOC emissions, and therefore higher concentrations of NO_2 and lower concentrations of NO, both during the hours when the restriction was in effect and also during the hours before and after the driving restriction.[22]

An underlying assumption for regression discontinuity designs is that the forcing variable, which in our case is time, should be balanced around the cutoff, which in the case of our regression discontinuity model of the effect of the first driving restriction in Table 5 is the implementation of the first driving restriction on August 18, 1998 (Imbens and Lemieux, 2008; Lee and Lemieux, 2010; Beach and Jones, 2015). To examine the distribution of the forcing variable (time) at the threshold (the implementation of the first driving restriction on August 18, 1998), we plot the

[22] To further examine any differences in pollution between restricted and unrestricted hours, Figure C1 in Appendix C plots residuals from a regression of log pollution levels on weather and seasonality covariates and station fixed effects for each of the pollutants by hour of day, using data from both before and during the first driving restriction. We explain and analyze these graphs in Appendix C.

number of observations per week against the week away from August 18, 1998 for each pollutant. The results for all pollutants are in Figure D1 in Appendix D; the results for each pollutant are in Figure D2 of Appendix D. As these graphs show, the distribution is continuous around the threshold, so the forcing variable is balanced around the cutoff. This continuity of the distribution around the threshold is evidence against any manipulation of whether air quality measurements were taken before or after the driving restriction.

To examine if there were any discontinuous changes in the control variables at the time the various versions of the driving restrictions were implemented, Table D1 in Appendix D presents results of regression discontinuity analyses of our hourly weather variables: temperature, relative humidity, and wind speed. None of the driving restrictions had any significant effect on any of the weather variables.[23]

In addition to our analyses using hourly observations, we also estimate the effect of *Pico y Placa* on daily average pollution levels in Bogotá. For each station and each day, we average the hourly pollution levels across each hour of the day for that station. We then estimate a regression discontinuity model with a ninth-order time trend, station fixed effects, weather covariates, and indicator variables for month of the year and day of the week.

Table 6 reports the results of the regression discontinuity analysis using daily average pollution levels. According to the results, various versions of the driving restriction had significant positive effects on the daily average concentrations of NO_x and O_3. There are some negative coefficients for CO and PM_{10}, but they are not significant.

[23] In addition, changes in public transportation were gradual and did not occur discontinuously at the time the various versions of the driving restrictions were implemented. The TransMilenio Bus Rapid Transit system started in December 2000 with only 14 km connected; other lines were added gradually (Hidalgo, 2011). Similarly, bike paths were gradually constructed (Secretaría Distrital de Movilidad, 2016; Hidalgo, 2014).

In addition to daily average pollution levels, we also analyze the effects of the driving restrictions on daily maximum pollution levels. For some pollutants, daily maximum pollution levels may be what matters most in determining the damages from pollution, as there may be some nonlinearities in the relationship between pollution and health (Davis, 2008). We construct the daily maximum pollution levels by averaging across monitoring stations for each hour and then taking the maximum for each day. We then estimate a regression discontinuity model with a ninth-order time trend, station fixed effects, weather covariates, and indicator variables for month of the year and day of the week. As shown in Table 7, the results of the regression discontinuity analysis using daily maximum pollution levels are similar to those using daily average pollution levels in Table 6.

The magnitudes of our significant coefficients in Tables 4-7 range from 0.301 to 1.363, meaning that the respective version of the driving restriction can increase the level of the respective pollutant by 30.1 to 136.3 percentage points. As seen in the summary statistics in Table 3, the maximum concentrations of each pollutant range from between 988 to 6467 times the minimum concentration of the respective pollutant. Thus, increases in pollution concentrations of 30.1 to 136.3 percentage points as a result of the driving restriction are reasonable, since the range in pollutant concentrations is orders of magnitude much higher.[24]

To examine the robustness of our results, we run placebo tests for each of our regression discontinuity regression models using placebo restriction dates instead of the actual driving

[24] Moreover, looking at the plots of mean weekly air pollution levels in Bogotá in Figure B2 in Appendix B, the magnitudes of our significant coefficients seem plausible. For example, in the graph of NO_2 in Figure B2, there are large increases in NO_2 when Restriction-1 and Restriction-3 are implemented, consistent with the respective significant positive coefficients in Table 4. Similarly, in the graph of O_3 in Figure B2, there are large increases in O_3 when Restriction-3 and Restriction-4 are implemented, consistent with the respective significant positive coefficients in Table 4.

restriction dates as the treatment. If we do not find significant treatment effects where there has been no treatment, then this means that our results are robust to our tests.

Since the implementation of the first driving restriction on August 18, 1998 and the implementation of the third driving restriction on June 15, 2004 both took place on the third Tuesday of the month, we choose as our placebo restriction date a third Tuesday of the month, and, following Imbens and Lemieux (2008), one that was roughly in the middle of the relevant sample period, for each of our Placebo Before Restriction-1, Placebo Before Restriction-2, Placebo Before Restriction-3, and Placebo Before Restriction-4 regressions.

The 7 Placebo Before restriction-1 regressions use a placebo restriction date of Tuesday, April 21, 1998 and use data from before the first driving restriction only (i.e., from August 1, 1997 to August 17, 1998). The 7 Placebo Before Restriction-2 regressions use a placebo restriction date of Tuesday, October 19, 1999 and use data from after the first driving restriction but before the second restriction only (i.e., from August 19, 1998 to August 28, 2001). The 7 Placebo Before Restriction-3 regressions use a placebo restriction date of Tuesday, July 15, 2003 and use data from after the second driving restriction but before the third restriction only (i.e., from August 30, 2001 to June 14, 2004). The 7 Placebo Before Restriction-4 regressions use a placebo restriction date of Tuesday, June 19, 2007 and use data from after the third driving restriction but before the fourth restriction only (i.e., from June 16, 2004 to February 5, 2009).

The results of the placebo tests are presented in Appendix E. The placebo tests of the regression discontinuity models using hourly pollution levels in Table 4 are presented in Table E1. The placebo tests of the analysis of the effects of the first driving restriction by time of day in Table 5 are presented in Table E2. The placebo tests of the regression discontinuity models using daily average pollution levels in Table 6 are presented in Table E3. The placebo tests of the regression discontinuity models using daily maximum pollution levels in Table 7 are presented in Table E4.

As seen in Tables E1-E4 of Appendix E, none of the placebo treatment effects are significant for any of the pollutants for any of the regression discontinuity models. Thus, since we do not find significant treatment effects where there has been no treatment, this means that our results are robust to our tests.[25]

In order to test the hypotheses of our theory model, and as alternative to the Bonferroni correction to solve the multiple-inference problem, we conduct summary index tests following the procedure described by Anderson (2008). In particular, we choose a specific set of outcomes based on the hypotheses of our theory model, and then implement summary index tests in the outcome areas.

Based on our theory model, we define the following primary outcome areas *k*. The first primary outcome area consists of the less auto-related pollutants: PM_{10} and SO_2 (Hypothesis 2). The second primary outcome area consists of the more auto-related pollutants: CO and NO_x (Hypothesis 2). The third primary outcome area consists of the pollutants on which any increase in driving should have the same direction of effect if the photochemical regime is a NO_x-limited regime: NO_x and O_3 (Hypothesis 3). The fourth primary outcome area consists of the pollutants we hypothesize may increase, based on the atmospheric chemistry of ozone, if there is an increase in driving and/or the use of diesel as a result of a driving restriction: NO_2 and O_3 (Hypotheses 6 and 10). The fifth primary outcome area consists of the pollutants we hypothesize may decrease

[25] We also run a set of regressions allowing for adjustment over time. For these regressions, we use a regression discontinuity design which adapts a model developed by Gallego, Montero and Salas (2013b). The model and results are presented in Appendix F. However, as these adjustment models do not pass the placebo tests, this evidence is weak at best and we place less emphasis on these results.

if the driving restriction leads to an increase in the use of diesel vehicles with a particle trap as a substitute for gasoline vehicles: CO and NO (Hypothesis 10).

For each pollutant *j*, we calculate the transformed effect size $\tilde{y}_{ijkt}$ of pollutant *j* in outcome area *k* measured at station *i* at hour *t* by demeaning its level y_{ijt} and dividing by the standard deviation of the demeaned values of the respective pollutant *j* before the first driving restriction. Then, for each of the 5 primary outcome areas *k* above, we construct a summary index s_{ikt} for each station *i* at hour *t*, which is the weighted average of the transformed effects $\tilde{y}_{ijkt}$ of each pollutant *j* in outcome area *k*. In particular, the summary index s_{ikt} for primary outcome *k* is given by $s_{ikt} = (l'\hat{\Sigma}_k^{-1}l)^{-1}(l'\hat{\Sigma}_k^{-1}\bar{\tilde{y}}_{ijkt})$, where *l* is a column vector of 1's of length the number of pollutants *j* in outcome area *k*; $\hat{\Sigma}_k^{-1}$ is the inverted covariance matrix of the transformed effects for outcome area *k*; and $\bar{\tilde{y}}_{ijkt}$ is a column vector of transformed effects $\tilde{y}_{ijkt}$ for all pollutants *j* in outcome area *k* measured at station *i* at hour *t*. We then run our regression discontinuity regressions for each outcome area *k* using the summary index s_{ikt} as the dependent variable.

Tables 8-11 present the results of our summary index tests for hourly pollution, for the effects of the first driving restriction by time of day, for daily average pollution, and for daily maximum pollution, respectively. As expected, none of the driving restrictions had any significant effect on the outcome area consisting of less auto-related pollutants (Hypothesis 2). Also as expected, even though the first version of *Pico y Placa* decreased the summary index of hourly pollution for the more auto-related pollutants during restricted hours (Table 9), both the first and second versions of the driving restriction increased the summary index of daily average pollution

(Table 10) and of daily maximum pollution (Table 11) for the more auto-related pollutants (Hypothesis 2), providing evidence that the driving restriction led to an increase in air pollution.

Some of the driving restrictions had a significant positive effect on the summary index of daily maximum pollution for pollutants in the NO_x-limited outcome area, providing evidence that the photochemical regime is a NO_x-limited regime (Hypothesis 3).

As predicted, for pollutants we hypothesize may increase, based on the atmospheric chemistry of ozone, if there is an increase in driving and/or the use of diesel as a result of a driving restriction (Hypotheses 6 and 10), the first version of *Pico y Placa* increased the summary index of hourly pollution for these pollutants both during restricted hours and during the two hours before and two hours after restricted hours (Table 9); and the fourth driving restriction increased the summary index of daily average pollution and of daily maximum pollution for these pollutants.

Although the first version of *Pico y Placa* decreased the summary index of hourly pollution for the pollutants we hypothesize may decrease if the driving restriction leads to an increase in the use of diesel vehicles with a particle trap (Table 9), both the first and second versions of the driving restriction increased the summary index of daily average pollution (Table 10) and of daily maximum pollution (Table 11) for these pollutants, providing evidence for substitution towards more driving using vehicles without a particle trap during unrestricted hours, leading to an increase in air pollution (Hypothesis 10).

To further examine differences in the effects of the different versions of the driving restriction, we also run a set of regressions in which we include an indicator variable for driving restrictions that is equal to 1 during the entire time period when any driving restriction is in place, and 0 otherwise; and then include indicator variables for the second, third, and fourth versions of the driving restriction, which measure the incremental effect of these subsequent versions of the driving restriction, respectively, over and above the effect of the first version of the driving restriction. We therefore replace the indicator variable for the first driving restriction with an indicator variable for having any driving restriction. In addition, since SO_2 may be more related to industrial activity than to driving behavior, following Gallego, Montero and Salas (2013b), we include SO_2 as a control variable rather than as a dependent variable, in order to control for any changes in industrial activity that may have been correlated with the driving restrictions.[26]

Tables H1-H3 in Appendix H present the results our analysis of the effects of different versions of the driving restrictions for hourly pollution, for daily average pollution, and for daily maximum pollution when we include SO_2 as a control variable. As seen in these results, driving restrictions have a significant positive effect on daily average and daily maximum O_3. In addition, the second version of the driving restriction had an additional significant positive effect on hourly, daily average, and daily maximum PM_{10}; the third version of the driving restriction had an additional significant negative effect on daily average and daily maximum CO; and the fourth version of the driving restriction had an additional significant positive effect on hourly and daily average O_3. These results are robust to whether we use a tenth-order time trend instead of a ninth-order time trend (Tables H4-H6 of Appendix H) and whether we use SO_2 as a dependent variable instead of a control variable (Tables H7-H9 of Appendix H).

The additional significant positive effect of the second version of the driving restriction on hourly, daily average, and daily maximum PM_{10} is consistent with an increase in driving and an increase in the use of diesel. The additional significant negative effect of the third version of the

[26] As seen in Tables G1-G4 of Appendix G, our results in Tables 4-7 for hourly pollution, for the effects of the first driving restriction by time of day, for daily average pollution, and for daily maximum pollution, respectively, are robust to whether we include SO_2 as a control variable. In particular, we still find that the implementation of *Pico y Placa* (Restriction-1) led to a decline in NO during the restricted hours; and that various versions of the policy have led to significant increases in NO_2 and O_3.

driving restriction on daily average and daily maximum CO suggests that by the time of the third driving restriction, there may have been some particle traps on some of the diesel vehicles whose use may have increased as a result of the driving restriction.

We present some suggestive data regarding alternative transport use and fuel use in Bogotá in Appendix I. Unfortunately, the limited data available preclude us from running a rigorous regression discontinuity analysis. As described in more detail in Appendix I, there does not appear to be any particularly noticeable trend in the percentage of the population in Bogotá using private transportation (including private vehicles and motorcycles), public transportation (including buses and taxis), and walking or biking over the years 1998-2007 (Figure I1). However, the number of private passenger cars in Bogotá has been increasing (Figure I2); there appears to be somewhat of a downward trend in utilization rates for buses and an upward trend in utilization rates for taxis and motorcycles (Figure I3); and the number of motorcycles in Bogotá has been increasing rapidly (Figure I4). Although motorcycles may be more energy efficient than automobiles, depending on the engine motorcycles can be more polluting in terms of carbon monoxide (CO) and hydrocarbons (Chiou et al., 2009; Estupiñan et al., 2015). Although motorcycles are not currently covered by the driving restriction in Bogotá, there have been recent discussions about possibly including them in the restriction (Caracol Radio, 2016).

In terms of the types of fuel used in Bogotá, sales of gasoline in Bogotá declined from around 25,000 barrels per day to 16,000 barrels per day from 2000 to 2006 (Secretaría Distrital de Planeación, 2008). From 1996 to 2005, consumption of diesel in Bogotá increased by 296% for the taxis fleet and 126% for private cars (Secretaría Distrital de Planeación, 2008). It is unlikely that many diesel vehicles in Bogotá had particle traps during our sample period, as it was not until 2015 that an environmental program was introduced by the Department of the Environment in

Bogotá to install diesel particulate filters in TransMilenio and Integrated Mass Transit System (SITP) buses (Secretaría Distrital de Ambiente, 2015; Alcaldiá Mayor de Bogotá, 2014).

4 Conclusion

This paper develops a theoretical model of the effects of license plate-based driving restrictions on air quality that combines an economic model with information about the sources and atmospheric chemistry of different air pollutants. We then draw upon suggestive empirical evidence from driving restrictions implemented in Bogotá. Owing to data and other limitations, clean natural experiments were difficult to find, and therefore our empirical results provide evidence that is suggestive as best. Even so, the suggestive empirical evidence appears to support the hypotheses from our theory.

Our results show that the implementation of *Pico y Placa* (Restriction-1) led to a decline in NO, in a summary index of more auto-related pollutants (CO and NO_X), and in a summary index of pollutants that may decrease if there is an increase in use of diesel vehicles with particle traps (CO and NO) during the restricted hours. We also find that the third version of the driving restriction had an additional significant negative effect on daily average and daily maximum CO. However, across different versions of the policy, we do not see a statistically significant overall improvement in air quality. None of the versions of the driving restriction had any significant impact on SO_2. Instead, various versions of the policy have led to significant increases in NO_2, NO_x, O_3, and PM_{10}.

Our result that various versions of the policy have led to significant increases in NO_2, NO_x, and O_3 is consistent with Hypothesis 1 of our theory model that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for driving restrictions to increase air pollution.

If automobile emissions are not the primary source for a particular air pollutant, changes in driving may have little effect on these pollutants. Our result that driving restrictions had a significant positive effect on NO_x and on a summary index of the daily average and daily maximum of more auto-related pollutants (CO and NO_x), but no significant effect on SO_2 or on a summary index of the less auto-related pollutants (PM_{10} and SO_2) is therefore consistent with Hypothesis 2 that any increase in driving as a result of driving restrictions (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) will have less of an impact on PM_{10} and SO_2, and more of an impact on CO and NO_x.[27]

Our result that various versions of the driving restriction led to significant increases in NO_x, O_3, and a summary index of NO_x and O_3 is consistent with the photochemical regime in Bogotá being a NO_x-limited regime (Hypothesis 3) and not a VOC-limited regime (Hypothesis 4).

The positive effect of Restriction-1 on daily average and daily maximum O_3; and the positive effect of Restriction-3 on hourly, daily average, and daily maximum O_3 are consistent with Hypothesis 5 that if a driving restriction does not restrict driving during noon-time or early afternoon and induces substitution towards driving around noon or early afternoon, it is possible that the driving restriction may increase O_3 concentrations.

Our result that various versions of the policy have led to a significant decrease in NO and significant increases in NO_2, NO_x, O_3, and a summary index of NO_2 and O_3 is consistent with

[27] Our result that driving restrictions had a significant positive effect on NO_x but no significant effect on SO_2 is also evidence against omitted variables and any policy or behavioral changes unrelated to driving that may affect pollution levels and are correlated with the implementation of the driving restrictions.

Hypothesis 6 that owing to atmospheric chemistry, it is possible for a driving restriction to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3.

We also take a step towards distinguishing among the three behavioral channels through which driving restrictions may potentially increase air pollution: substitution, the purchase of a second car, and the use of alternative modes of transportation. We find suggestive evidence in support of all three channels.

Pico y Placa was in effect during only peak hours before Restriction-4 was implemented in 2009, which makes it easy to substitute displaced trips towards unrestricted hours. Several of our results provide suggestive evidence that households may be substituting by driving more during unrestricted hours (Hypothesis 7). First, the positive effect of driving restrictions that do not restrict driving during noon-time or early afternoon on O_3 are consistent with households substituting by driving more during hours of peak ozone formation. Second, the lower NO during restricted hours and higher NO_2 during the two hours before and the two hours after restricted hours are consistent with substitution away from restricted hours towards unrestricted hours. Third, even though reductions in hourly air pollution levels happened during restricted hours, daily average and daily maximum pollution levels did not decrease.

While *Pico y Placa* requires the restricted last digits associated with each day to change every year, the grouping of the digits does not change.[28] However, two cars with certain last digit combinations, such as 2 and 8, could still enable driving on each day. Between 1999 and 2008, more than 496,000 vehicles were added to the fleet, and by 2009 over one million cars were running in Bogotá (*El Tiempo* 2009), suggesting that, similar to the situation in Mexico City,

[28] For example, from July 2010 to June 2011, *Pico y Placa* applied to the following last digits of license plates: {9,0,1,2} on Monday, {3,4,5,6} on Tuesday, {7,8,9,0} on Wednesday, {1,2,3,4} on Thursday, and {5,6,7,8} on Friday. From July 2011 to June 2012, the policy applied to {5,6,7,8} on Monday, {9,0,1,2} on Tuesday, {3,4,5,6} on Wednesday, {7,8,9,0} on Thursday, and {1,2,3,4} on Friday.

households may have circumvented the restrictions by purchasing a second car. Our result that Restriction-4, which restricts both driving during all daytime hours (to minimize substitution) and driving by public vehicles including taxis (to minimize the effect of using alternative modes of transportation), increased hourly, daily average, and daily maximum O_3, and increased a summary index of NO_2 and O_3 is consistent with Hypothesis 8 that driving restrictions may increase air pollution due to the purchase of a second car. After Restriction-4 was implemented, about 250,000 new cars were registered in Bogotá from 2009 to 2011 (El Tiempo, 2011).

Our result that Restriction-1, which does not restrict public vehicles (including some buses, minibuses, and taxis), increased NO_2, NO_x, O_3; a summary index of more auto-related pollutants (CO and NO_x); a summary index of NO_x and O_3; a summary index of NO_2 and O_3; and a summary index of CO and NO; is weakly consistent with Hypothesis 9 that driving restrictions may increase air pollution due to the use of alternative modes of transportation. However, because Restriction-1 did not restrict driving during all daytime hours, these results are also consistent with substitution.

Our results that various versions of the driving restriction have increased O_3, NO_2, PM_{10}, and a summary index of NO_2 and O_3 provide evidence for an increase in driving and/or the use of diesel as a result of the driving restriction (Hypotheses 6 and 10).

Although the first version of *Pico y Placa* decreased the summary index of hourly pollution for the pollutants we hypothesize may decrease if the driving restriction leads to an increase in the use of diesel vehicles with a particle trap, both the first and second versions of the driving restriction increased the summary index of daily average pollution and of daily maximum pollution for these pollutants, providing evidence for substitution towards more driving using vehicles without a particle trap during unrestricted hours, at least during the first and second versions of the driving restriction, leading to an increase in air pollution (Hypothesis 10). The additional significant negative effect of the third version of the driving restriction on daily average and daily maximum CO suggests that by the time of the third version of the driving restriction, however, there may have been some particle traps on some of the diesel vehicles whose use may have increased as a result of the driving restriction (Hypothesis 10).

Thus, consistent with our theory model, we find suggestive empirical evidence that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for license plate-based driving restrictions to increase air pollution. Also consistent with our theory, we find that license plate-based driving restrictions may have different effects on different air pollutants, reflecting heterogeneity in the sources and atmospheric chemistry of the pollutants. In particular, owing to atmospheric chemistry, it is possible for a license plate-based driving restriction to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3.

References

"Air pollution emissions in the UK". (2015). [Online: web]. Accessed 30 July 2015. URL: http://www.air-quality.org.uk/08.php

Alcaldiá Mayor de Bogotá. (2014). 2.500 buses del SITP y Transmilenio tendrán filtros que disminuyen la contaminación. URL: http://www.bogota.gov.co/article/2500-buses-del-sitp-y-transmilenio-tendr%C3%A1n-filtros-que-disminuyen-la-contaminaci%C3%B3n

Allen, J. (2002). Chemistry in the sunlight. NASA Earth Observatory. [Online: web]. Accessed 30 July 2015. URL: http://earthobservatory.nasa.gov/Features/ChemistrySunlight/printall.php

Anas, A. and Lindsey, R. (2011). Reducing urban road transportation externalities: Road pricing in theory and in practice. *Review of Environmental Economics and Policy* 5(1): 66-88.

Anderson, M.L. (2008). Multiple inference and gender differences in the effects of early intervention: A reevaluation of the Abecedarian, Perry Preschool, and Early Training Projects. *Journal of the American Statistical Association* 103: 1481-1495.

Andrews, S.Q. (2008). Inconsistencies in air quality metrics: "Blue Sky" days and PM10 concentrations in Beijing. *Environmental Research Letters* 3: 1-14.

Angrist, J.D., and Pischke, J.-S. (2009). *Mostly Harmless Econometrics: An Empiricist's Companion*. Princeton: Princeton University Press.

Auffhammer, M., and Kellogg, R. (2011). Clearing the air? The effects of gasoline content regulation on air quality. *American Economic Review* 101(6): 2687-2722.

Barker, J. (1995). A brief introduction to atmospheric chemistry. In J. Barker (Ed.), *Progress and problems in atmospheric chemistry* (pp. 1-33). New Jersey: World Scientific.

Barth, M. and Boriboonsomsin, K. (2009). Traffic congestion and greenhouse gases. *Access* 35. University of California Transportation Center.

Beach, B, and Jones, D. (2015). Gridlock: Ethnic diversity in government and the provision of public goods. Working paper, College of William and Mary.

Beaudoin, J., Farzin, Y.H., and Lin Lawell, C.-Y.C. (2015). Public transit investment and sustainable transportation: A review of studies of transit's impact on traffic congestion and air quality. *Research in Transportation Economics* 52: 15-22.

Beaudoin, J., Farzin, Y.H., and Lin Lawell, C.-Y.C. (2016). Public transit investment and traffic congestion policy. Working paper, University of California at Davis.

Beaudoin, J., and Lin Lawell, C.-Y.C. (2016a). Is public transit's "green" reputation deserved?: Evaluating the effects of transit supply on air quality. Working paper, University of California at Davis.

Beaudoin, J., and Lin Lawell, C.-Y.C. (2016b). The effects of public transit supply on the demand for automobile travel. Working paper, University of California at Davis.

Beevers, S. and Carslaw, D. (2005). The impact of congestion charging on vehicle emissions in London. *Atmospheric Environment* 39(1): 1-5.

Berechman, J. (2009). *The Evaluation of Transportation Investment Projects*. New York: Routledge.

Bland, J.M., and Altman, D.G. (1995). Multiple significance tests: The Bonferroni Method. *BMJ* 3010: 170.

California Environmental Protection Agency. (2015). The physics and chemistry of ozone. [Online: web]. Accessed 30 July 2015. URL: http://www.fraqmd.org/OzoneChemistry.htm

Cámara de Comercio de Bogotá. (2007). Observatorio de Movilidad de Bogotá y la Región.

Cao, J., Wang, X., and Zhong, X. (2014). Did driving restrictions improve air quality in Beijing? *China Economics Quarterly* 13(3): 1091-1126.

Caracol Radio. (2016). Alcaldía de Bogotá no descarta implementar 'pico y placa' para las motos. 31 March 2016. URL: http://caracol.com.co/emisora/2016/03/31/bogota/1459447449_427174.html

Chen, Y., Jin, G., Kumar, N., and Shi, G. (2013). The promise of Beijing: Evaluating the impact of the 2008 Olympic Games on air quality. *Journal of Environmental Economics and Management* 66: 424-443.

Chiou, Y.-C., Wen, C.-H., Tsai, S.-H., and Wang, W.-Y. (2009). Integrated modeling of automobile/motorcycle ownership, type and usage for estimating energy consumption and emissions. *Transportation Research Journal Part A: Policy and Practice* 43(7): 665-684.

CIIA. (2008). Reporte final: Definición de elementos técnicos para la formulación de políticas distritales encaminadas al mejoramiento de la calidad del aire en .

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 2001. URL: http://www.eltiempo.com/archivo/documento/MAM-464627, last accessed June 18, 2010.

El Tiempo. (2009). Revelador primer informe del Pico y Placa todo el día. 14 May 2009. URL: http://www.eltiempo.com/archivo/documento/MAM-3442939

El Tiempo. (2011). Hoy, rota el pico y placa para carros. 1 July 2011. URL: http://www.eltiempo.com/archivo/documento/MAM-4657091

Eskeland, G.S., and Feyzioglu, T. (1997). Rationing can backfire: The "Day without a Car" in Mexico City. *World Bank Economic Review* 11(3): 383–408.

Estupiñan, N., Santana, M., Palacios, A., and Rodríguez, D.A. (2015). Motorcycle ownership and use: The case of Latin America.

Faiz, A., Weaver, C.S. and Walsh, M. (1996). Air pollution from motor vehicles: Standards and technologies for controlling emissions. World Bank and United Nations Environment Programme, Washington, DC.

Gallego, F., Montero, J.-P., and Salas, C. (2013a). The effect of transport policies on car use: A bundling model with applications. *Energy Economics* 40: S85-S97.

Gallego, F., Montero, J.-P., and Salas, C. (2013b). The effect of transport policies on car use: Evidence from Latin American cities. *Journal of Public Economics* 107: 47-62.

Ghanem, D., and Zhang, J. (2014). Effortless perfection: Do Chinese cities manipulate air pollution data. *Journal of Environmental Economics and Management* 68(2): 203-225.

Gibson, M., and Carnovale, M. (2015). The effects of road pricing on driver behavior and air pollution. *Journal of Urban Economics* 89: 62-73.

Hidalgo, D. (2011). TransMilenio: A Retrospective, *The CityFix*. URL: http://thecityfix.com/blog/transmilenio-a-retrospective/

Hidalgo, D. (2014). How ciclovías contribute to mobility and quality of life in Latin America and in cities worldwide. *The CityFix*. URL: http://thecityfix.com/blog/ciclovias-mobility-quality-life-latin-america-cities-worldwide-dario-hidalgo/

Huang, H., Fu, D., and Qi, W. (forthcoming). Effect of driving restrictions on air quality in Lanzhou, China: Analysis integrated with internet data source. *Journal of Cleaner Production*.

Imbens, G.W., and Lemieux, T. (2008). Regression discontinuity designs: A guide to practice. *Journal of Econometrics* 142: 615-635.

Jacob, D.J. (1999). *Introduction to Atmospheric Chemistry*. New Jersey: Princeton University Press.

Jacobson, M.Z., Seinfeld, J.H., Carmichael, G.R., and Streets, D.G. (2004). The effect on photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel vehicles. *Geophysical Research Letters* 31, L02116, doi:10.1029/2003Gl018448.

Leape, J. (2006). The London congestion charge. *Journal of Economic Perspectives* 20 (4): 157-176.

Lee, D.S., and Lemieux, T. (2010). Regression discontinuity designs in economics. *Journal of Economic Literature* 48: 281-355.

Lin, C.-Y.C. (2000). *Trends In Ozone Smog*. Senior thesis, Harvard University.

Lin, C.-Y.C. (2010). A spatial econometric approach to measuring pollution externalities: An application to ozone smog. *Journal of Regional Analysis and Policy* 40 (1): 1-19.

Lin, C.-Y.C., Jacob, D.J., and Fiore, A.M. (2001). Trends in exceedances of the ozone air quality standard in the continental United States, 1980-1998. *Atmospheric Environment* 35: 3217-3228.

Lin, C.-Y.C., Jacob, D.J., Munger, J.W., and Fiore, A.M. (2000). Increasing background ozone in surface air over the United States. *Geophysical Research Letters*, 27 (21): 3465-3468.

Mahendra, A. (2008). Vehicle restrictions in four Latin American cities: Is congestion pricing possible? *Transport Reviews* 28(1): 105-133.

Morrison, G.M., and Lin Lawell, C.-Y.C. (2016). Does employment growth increase travel time to work?: An empirical analysis using military troop movements. *Regional Science and Urban Economics* 60: 180-197.

Napierala, M.A. (2012). What is the Bonferroni Correction? American Academy of Orthopaedic Surgeons (AAOS) Now. URL: http://www.aaos.org/news/aaosnow/apr12/research7.asp

OECD/IEA [Organization for Economic Cooperation and Development/International Energy Agency]. (1991). *Greenhouse Gas Emissions: The Energy Dimension*. OECD, Paris.

Onursal, B., and Gautam, S. (1997). Vehicular air pollution: experiences from seven Latin Mmerican urban centers. World Bank Technical Paper No. 373.

Percoco, M. (2014). *Regional Perspectives on Policy Evaluation*. Berlin: Springer.

Robra, J.P. (2010). An emissions inventory of air pollutants for the city of Bogotá, Colombia. Master's Thesis, Swiss Federal Institute of Technology Lausanne.

Salvo, A., and Wang, Y. (2016). Ethanol-blended gasoline policy and ozone pollution in Sao Paulo. Working paper, National University of Singapore.

Secretaría Distrital de Ambiente. (2015). Resolución 123 de 2015: Por la cual se establece el Programa de Filtros de Partículas Diésel para Bogotá, –BDPF-. URL: http://www.alcaldiabogota.gov.co/sisjur/normas/Norma1.jsp?i=60825#0

Secretaría Distrital de Movilidad. (2013). Análisis de alternativas complementarias para la medida de restricción de circulación a vehículos particulares Pico Y Placa.

Secretaría Distrital de Movilidad. (2016). URL: http://www.movilidadbogota.gov.co/?sec=608

Secretaría Distrital de Planeación. (2008). El transporte y el consume de hidrocarburos en Bogota.

Seinfeld, J. (1995). Chemistry of ozone in the urban and regional atmosphere. In J. Barker (Ed.), *Progress and problems in atmospheric chemistry* (pp. 34-57). New Jersey: World Scientific.

Sillman, S. (1999). The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment* 33: 1821-1845.

U.S. EPA [Environmental Protection Agency]. (1994). Automobile emissions: An overview. Fact Sheet OMS-5.

U.S. EPA [Environmental Protection Agency]. (2015a). Multipollutant Ccmparison. [Online: web]. Accessed 30 July 2015. URL: http://www.epa.gov/air/emissions/multi.htm

U.S. EPA [Environmental Protection Agency]. (2015b). National Emission Inventory.

Viard, V.B., and Fu, S. (2015). The effect of Beijing's driving restrictions on pollution and economic activity. *Journal of Public Economics* 125: 98-115.

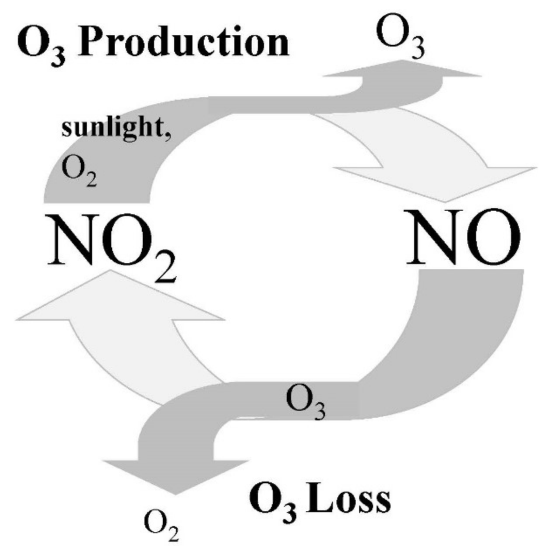
Wolff, H. (2014). Keep your clunker in the suburb: low emission zones and adoption of green vehicles. *Economic Journal* 124: F481-F512.

Wolff, H. and Perry, L. (2010). Trends in clean air legislation in Europe: Particulate matter and Low Emission Zones. *Review of Environmental Economics and Policy* 4 (2): 293-308.

Zárate, E., Belalcázar, L.C., Clappier, A., Manzi, V., and Van den Bergh, H. (2007). Air quality modeling over Bogotá, Colombia: Combined techniques to estimate and evaluate emission inventories. *Atmospheric Environment* 41: 6302-6318.

Figure 1. The Chemistry of Ozone Smog Formation

(a) Photostationary steady-state in the absence of VOCs



(b) Ozone production in the presence of VOCs

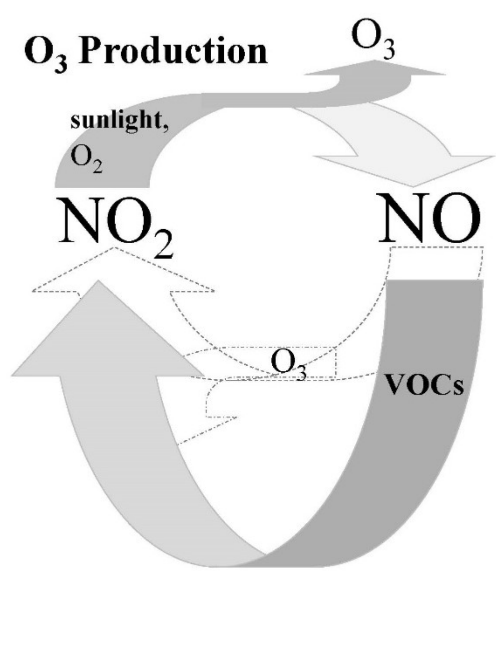


Table 1. Hypotheses from Theoretical Model

	Hypothesis	**Expected sign of coefficient on driving restriction**
1	Under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for driving restrictions to increase air pollution.	For some air pollutants, some coefficients on driving restrictions will be significant and positive.
2	Any increase in driving as a result of driving restrictions (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) will have less of an impact on PM_{10} and SO_2, and more of an impact on CO and NO_x.	More positive coefficients on driving restrictions for CO and NO_x than for PM_{10} and SO_2.
3	If the photochemical regime is a NO_x-limited regime, then increases in NO_x as a result of increased driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) will lead to increases in O_3.	Positive coefficients on driving restrictions for both NO_x and O_3.
4	If the photochemical regime is a VOC-limited regime, then increases in NO_x as a result of increased driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) may decrease O_3.	Positive coefficient on driving restrictions for NO_x and negative coefficient on driving restrictions for O_3.
5	If a driving restriction does not restrict driving during noon-time or early afternoon and induces substitution towards driving around noon or early afternoon, it is possible that the driving restriction may increase O_3 concentrations.	Positive coefficient on driving restrictions that do not restrict driving during noon-time or early afternoon for O_3.
6	Owing to atmospheric chemistry, it is possible for a driving restriction that increases driving (e.g., due to substitution, the purchase of a second car, or the use of alternative modes of transportation) to cause a significant decrease in NO and a significant increase in NO_2, NO_x, and O_3.	Positive coefficients on driving restrictions for NO_2, NO_x, and O_3; and a negative coefficient on driving restrictions for NO.

7	Driving restrictions may increase driving during unrestricted hours, total driving, and air pollution due to substitution.	Positive coefficients on driving restrictions for daily maximum concentrations and for non-restricted hours, and insignificant or negative coefficient on driving restrictions during restricted hours.
8	Driving restrictions may increase air pollution due to the purchase of a second car.	Positive coefficient on driving restrictions that restrict both driving during all daylight hours and driving by alternative modes of transportation.
9	Driving restrictions may increase air pollution due to the use of alternative modes of transportation.	Positive coefficient on driving restrictions that do not restrict driving by alternative modes of transportation.
10	If driving restrictions lead to the purchase of a second car or the use of alternative modes of transportation, and if the second car or alternative mode of transportation uses diesel instead of gasoline, then O_3, the NO_2/NO ratio, and PM_{10} may increase, and, if these diesel vehicles have a particle trap, CO may decrease.	Positive coefficients on driving restrictions for O_3, NO_2, and PM_{10}; and possibly negative coefficients on driving restrictions for CO and NO.

Table 2. Versions of the *Pico y Placa* Driving Restriction in Bogotá

			Restricted hours for:	
	Start date	**End date**	**Private vehicles**	**Public vehicles**
Restriction-1	Aug. 18, 1998	Aug. 28, 2001	7:00am-9:00am & 5:30pm-7:30pm	
Restriction-2	Aug. 29, 2001	June 14, 2004	7:00am-9:00am & 5:30pm-7:30pm	5:30am-9:00pm
Restriction-3	June 15, 2004	Feb. 5, 2009	6:00am-9:00am & 4:00pm-7:00pm	5:30am-9:00pm
Restriction-4	Feb. 6, 2009		6:00am-8:00pm	5:30am-9:00pm

Notes: 40% of the private vehicles were restricted during the restricted hours for private vehicles. 20% of the public vehicles were restricted during the restricted hours for public vehicles.

Table 3. Summary Statistics for Bogotá, 1997-2009

	# Obs	Mean	Std. Dev.	Min	Max
CO	226,827	1.704	1.535	0.01	21.4
PM_{10}	530,001	67.44	47.157	1	988
NO	295,624	0.021	0.027	0.00014	0.518
NO_2	299,221	0.017	0.013	0.00024	0.371
NO_x	299,129	0.038	0.034	0.001	0.531
O_3	202,248	0.013	0.013	0.00003	0.194
SO_2	430,124	0.01	0.012	0.00007	0.3127
Temperature	326,108	13.94	3.174	-25.8	29.5
Humidity	18,945	66.68	12.57	14.8	89.8
Wind speed	552,481	1.749	1.486	0.02	24.3

Notes: The unit of observation is a station-hour. PM_{10} is in micrograms per cubic meter, and other pollutants are in parts per million. Temperature is in degrees Celsius and wind speed is in meters per second. Pollutant data are from the stations that were in use during the entire study period and meteorological data are the averages from the same monitoring system.

Table 4. The Effects of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.474	-0.161	0.024	0.406*	0.251	0.399	0.207
	(0.205)	(0.102)	(0.149)	(0.140)	(0.109)	(0.183)	(0.134)
Restriction-2	0.604	-0.027	0.061	0.451	0.248	0.481	0.014
	(0.283)	(0.119)	(0.218)	(0.261)	(0.189)	(0.279)	(0.200)
Restriction-3	-0.065	0.043	0.218	0.930*	0.618	1.030*	0.508
	(0.344)	(0.124)	(0.298)	(0.333)	(0.263)	(0.313)	(0.355)
Restriction-4	0.110	0.001	0.128	0.810	0.474	1.363*	0.499
	(0.395)	(0.140)	(0.340)	(0.358)	(0.294)	(0.334)	(0.471)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The reported coefficients correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 5. The Effects of the First Version of *Pico y Placa* on Hourly Pollution Levels in Bogotá by Time of Day, 1997-2001

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restricted hours	0.127	-0.018	-0.462*	0.656*	0.090	0.316	-0.017
	(0.127)	(0.081)	(0.126)	(0.159)	(0.093)	(0.139)	(0.141)
The two hours before and the two hours after restricted hours	0.293	0.098	-0.361	0.695*	0.169	0.267	0.066
	(0.143)	(0.062)	(0.147)	(0.154)	(0.104)	(0.112)	(0.178)

Notes: This table reports estimates from 14 separate regression discontinuity specifications, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The first specification (restricted hours) for each pollutant includes observations from the 8th-9th and 18th-20th hours in the sample period. The second specification (the two hours before and the two hours after restricted hours) for each pollutant includes observations from the 6th-7th, 10th-11th, 16th-17th, and 21st-22nd hours in the sample period. The reported coefficients correspond to indicator variables that equal one for every hour after the implementation of the first driving restriction on August 18, 1998. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 6. The Effects of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log daily average pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.397	-0.209	0.167	0.348	0.301*	0.489*	0.241
	(0.181)	(0.112)	(0.139)	(0.145)	(0.107)	(0.162)	(0.112)
Restriction-2	0.507	-0.090	0.150	0.408	0.311	0.515	0.078
	(0.250)	(0.130)	(0.219)	(0.273)	(0.197)	(0.261)	(0.172)
Restriction-3	-0.303	-0.006	0.471	0.894	0.624	1.126*	0.621
	(0.326)	(0.130)	(0.304)	(0.336)	(0.270)	(0.324)	(0.340)
Restriction-4	-0.113	-0.108	0.375	0.783	0.437	1.386*	0.606
	(0.372)	(0.145)	(0.343)	(0.367)	(0.305)	(0.342)	(0.444)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 7. The Effects of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log daily maximum pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.355	-0.243	0.278	0.257	0.316*	0.644*	0.158
	(0.146)	(0.119)	(0.121)	(0.173)	(0.095)	(0.171)	(0.078)
Restriction-2	0.446	-0.101	0.325	0.332	0.380	0.560	0.061
	(0.203)	(0.141)	(0.245)	(0.293)	(0.206)	(0.295)	(0.137)
Restriction-3	-0.222	-0.034	0.698	0.903	0.757	1.224*	0.650
	(0.271)	(0.141)	(0.329)	(0.350)	(0.282)	(0.366)	(0.287)
Restriction-4	-0.027	-0.233	0.483	0.753	0.499	1.473*	0.521
	(0.316)	(0.151)	(0.353)	(0.392)	(0.313)	(0.381)	(0.353)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table 8. The Effects of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009: Summary Index Tests

	Dependent variable is summary index of log hourly pollution for:				
Primary outcome area	Less auto-related	More auto-related	NO_x-limited	Ozone chemistry	Diesel with particle trap
Hypothesis	2	2	3	6 and 10	10
Pollutants	PM_{10} and SO_2	CO and NO_x	NO_x and O_3	NO_2 and O_3	CO and NO
	(1)	(2)	(3)	(4)	(5)
Restriction-1	0.006	0.315	0.000	0.143	0.386
	(0.076)	(0.187)	(0.104)	(0.156)	(0.201)
Restriction-2	0.031	0.305	0.032	0.177	0.446
	(0.117)	(0.232)	(0.164)	(0.265)	(0.258)
Restriction-3	0.254	-0.216	0.206	0.45	-0.265
	(0.192)	(0.290)	(0.222)	(0.328)	(0.307)
Restriction-4	0.175	-0.122	0.298	0.612	-0.235
	(0.253)	(0.308)	(0.234)	(0.334)	(0.325)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each primary outcome area, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The reported coefficients correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level.

Table 9. The Effects of the First Version of *Pico y Placa* on Hourly Pollution Levels in Bogotá by Time of Day, 1997-2001: Summary Index Tests

	Dependent variable is summary index of log hourly pollution for:				
Primary outcome area	Less auto-related	More auto-related	NO_x-limited	Ozone chemistry	Diesel with particle trap
Hypothesis	2	2	3	6 and 10	10
Pollutants	PM_{10} and SO_2	CO and NO_x	NO_x and O_3	NO_2 and O_3	CO and NO
	(1)	(2)	(3)	(4)	(5)
Restricted hours	0.013	-0.249*	-0.027	0.411*	-0.390**
	(0.092)	(0.109)	(0.101)	(0.191)	(0.112)
The two hours before and the two hours after restricted hours	0.123	-0.003	0.084	0.391*	-0.116
	(0.103)	(0.129)	(0.076)	(0.185)	(0.124)

Notes: This table reports estimates from 10 separate regression discontinuity specifications, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The first specification (restricted hours) for each outcome area includes observations from the 8^{th}-9^{th} and 18^{th}-20^{th} hours in the sample period. The second specification (the two hours before and the two hours after restricted hours) for outcome area includes observations from the 6^{th}-7^{th}, 10^{th}-11^{th}, 16^{th}-17^{th}, and 21^{st}-22^{nd} hours in the sample period. The reported coefficients correspond to indicator variables that equal one for every hour after the implementation of the first driving restriction on August 18, 1998. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level.

Table 10. The Effects of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009: Summary Index Tests

	Dependent variable is summary index of log daily average pollution for:				
Primary outcome area	Less auto-related	More auto-related	NO_x-limited	Ozone chemistry	Diesel with particle trap
Hypothesis	2	2	3	6 and 10	10
Pollutants	PM_{10} and SO_2	CO and NO_x	NO_x and O_3	NO_2 and O_3	CO and NO
	(1)	(2)	(3)	(4)	(5)
Restriction-1	-0.006	0.514*	0.174	0.412	0.595**
	(0.108)	(0.210)	(0.175)	(0.261)	(0.219)
Restriction-2	0.043	0.551*	0.208	0.420	0.677*
	(0.156)	(0.259)	(0.258)	(0.426)	(0.274)
Restriction-3	0.394	-0.144	0.503	0.972	-0.201
	(0.251)	(0.343)	(0.340)	(0.495)	(0.346)
Restriction-4	0.229	-0.064	0.545	1.180*	-0.187
	(0.329)	(0.366)	(0.376)	(0.528)	(0.371)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each outcome area, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station, and then used to calculate the summary index. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level.

Table 11. The Effects of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009: Summary Index Tests

	Dependent variable is summary index of log daily maximum pollution for:				
Primary outcome area	Less auto-related	More auto-related	NO_x-limited	Ozone chemistry	Diesel with particle trap
Hypothesis	2	2	3	6 and 10	10
Pollutants	PM_{10} and SO_2	CO and NO_x	NO_x and O_3	NO_2 and O_3	CO and NO
	(1)	(2)	(3)	(4)	(5)
Restriction-1	-0.031	0.432*	0.285*	0.113	0.396**
	(0.092)	(0.169)	(0.142)	(0.227)	(0.150)
Restriction-2	0.087	0.526*	0.238	0.129	0.545**
	(0.139)	(0.217)	(0.247)	(0.355)	(0.197)
Restriction-3	0.413	-0.200	0.672*	0.514	-0.379
	(0.212)	(0.295)	(0.318)	(0.414)	(0.288)
Restriction-4	0.155	-0.221	0.655	0.996*	-0.330
	(0.273)	(0.327)	(0.358)	(0.444)	(0.315)

Notes: This table reports estimates from five separate regression discontinuity specifications, one for each outcome area, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station, the maximum hourly pollution level is taken over all hours in that day for that station, and then used to calculate the summary index. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level.

Appendix A

A.1 Social Optimum

The social planner's problem is to choose the vehicle miles traveled for each household for each day of the week for each hour so as to maximize total welfare W, which is defined as total private benefits minus total private costs minus the total social damage from pollution:

$$\max_{\{v_{idt}\}_{idt}} W = \sum_i B_i(v_i) - \sum_i C_i(v_i) - D(v) \quad .$$

The first-order conditions to the social planner's problem are therefore to choose each household i's driving for each given day of the week d during each given hour t so that marginal private benefits equal marginal private costs plus marginal social damage:

$$\frac{\partial B_i(v_i^{FB})}{\partial v_{idt}} = \frac{\partial C_i(v_i^{FB})}{\partial v_{idt}} + \frac{\partial D(v^{FB})}{\partial v_{idt}} \qquad \forall i, d, t \quad ,$$

which yields the first-best outcome $\{v_{idt}{}^{FB}\}_{idt}$. Since marginal utility is equated to marginal damages and since utility is concave, the higher the marginal damages of driving an additional vehicle mile during a particular hour of a particular day, the lower the optimal vehicle miles traveled during that hour of that day.

In the first-best, driving during each hour t of each day d is charged a fee or tax $p_{dt} = \frac{\partial D(v)}{\partial v_{idt}}$ per vehicle mile traveled, equal to the marginal damages of an additional vehicle mile traveled during that hour of that day, so that individual households will each choose the socially optimal choice of when and how much to drive during the week.

A.2 Driving in Absence of Regulation

In the absence of regulation, and in contrast to the first-best, each household i will choose its driving to set marginal private benefits equal to marginal private costs:

$$\frac{\partial B_i(v_i^*)}{\partial v_{idt}} = \frac{\partial C_i(v_i^*)}{\partial v_{idt}} \quad \forall d,t,$$

which, since benefits are concave and costs are convex, means that the driving v_{idt}^* in the absence of regulation is weakly higher than the first-best driving for each household for each hour of each day.

A.3 Proofs

Proof of Lemma 1: The first-order condition in the absence of regulation is given by:

$$\frac{\partial U_i}{\partial v_{idt}} = 0\,.$$

Taking the derivative of both sides with respect to $v_{id't'}$ yields:

$$\frac{\partial U_i^2(v_i)}{\partial v_{idt}^{\;2}}\frac{\partial v_{idt}}{\partial v_{id't'}} + \frac{\partial^2 U_i(v_i)}{\partial v_{idt}\partial v_{id't'}} = 0\,,$$

which, after rearranging, yields that the change in driving by household *i* in unrestricted hours as a result of a driving restriction is giving by:

$$\frac{\partial v_{idt}}{\partial v_{id't'}} = \frac{-\dfrac{\partial^2 U_i(v_i)}{\partial v_{idt}\partial v_{id't'}}}{\dfrac{\partial^2 U_i(v_i)}{\partial v_{idt}^{\;2}}}\,.$$

An increase in the degree of substitution between driving during unrestricted hours and driving during restricted hours for household *i* would be reflected in a more negative cross-partial $\dfrac{\partial^2 U_i(v_i)}{\partial v_{idt}\partial v_{id't'}}$ for household *i*. Since $U_i(\bullet)$ is concave $\left(\dfrac{\partial^2 U_i(v_i)}{\partial v_{idt}^{\;2}} < 0\right)$, the more negative the cross-partial $\frac{\partial^2 U_i(v_i)}{\partial v_{idt} \partial v_{id't'}}$ for household i, the more a driving restriction would increase driving by household i during unrestricted hours. Thus, the greater the degree of substitution between driving during unrestricted hours and driving during restricted hours for household i, the more a driving restriction would increase driving by household i during unrestricted hours. □

Proof of Theorem 1: Follows from Lemma 1. □

Proof of Theorem 2: Total differentiating the damage function $D(v)$ yields:

$$dD(v) = \frac{\partial D(v)}{\partial v_{idt}} dv_{idt} + \frac{\partial D(v)}{\partial v_{id't'}} dv_{id't'}.$$

Total damages increase if $dD(v) > 0$, which means:

$$\frac{\partial D(v)}{\partial v_{idt}} dv_{idt} + \frac{\partial D(v)}{\partial v_{id't'}} dv_{id't'} > 0,$$

which, after rearranging, yields:

$$\frac{\partial v_{idt}}{\partial v_{id't'}} < \frac{-\frac{\partial D(v)}{\partial v_{id't'}}}{\frac{\partial D(v)}{\partial v_{idt}}},$$

where the right-hand-side term is weakly less than zero since marginal damages are non-negative. Substituting in Theorem 1 for the left-hand side and then multiplying both sides by -1 yields the desired result. □

Proof of Theorem 3: Follows from aggregating Theorem 1 over all households i. □

Proof of Theorem 4: Follows from aggregating Theorem 2 over all households *i*. □

Proof of Theorem 5: Follows from aggregating Theorem 2 over all households *i*. □

The proof of Theorem 6 is straightforward and is therefore omitted.

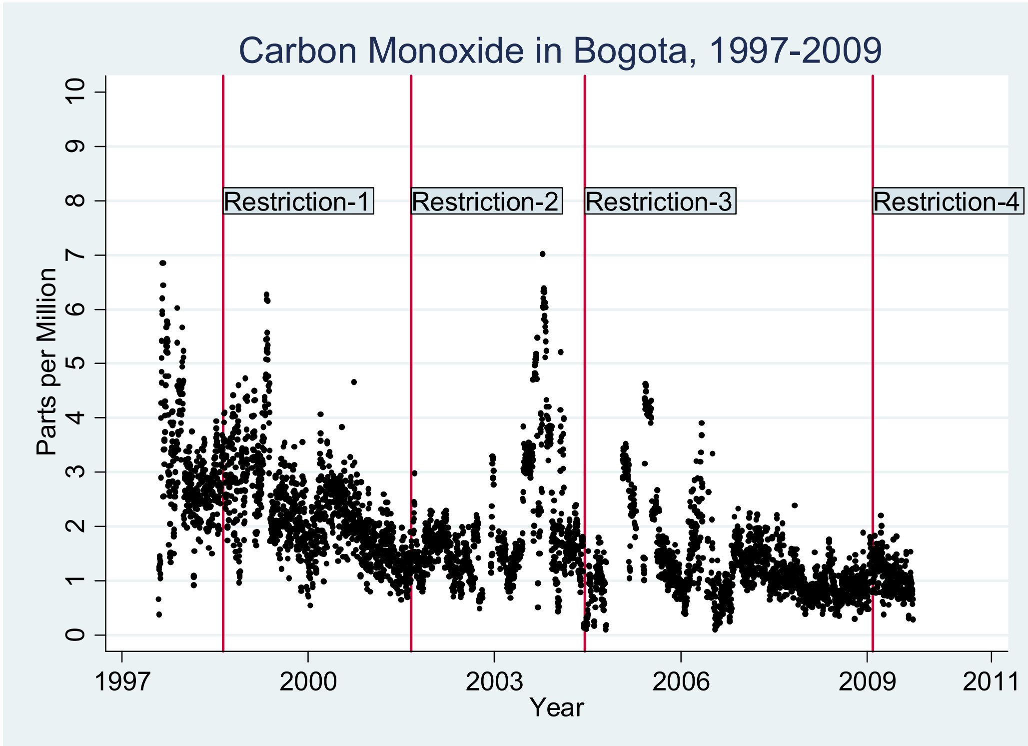
Appendix B

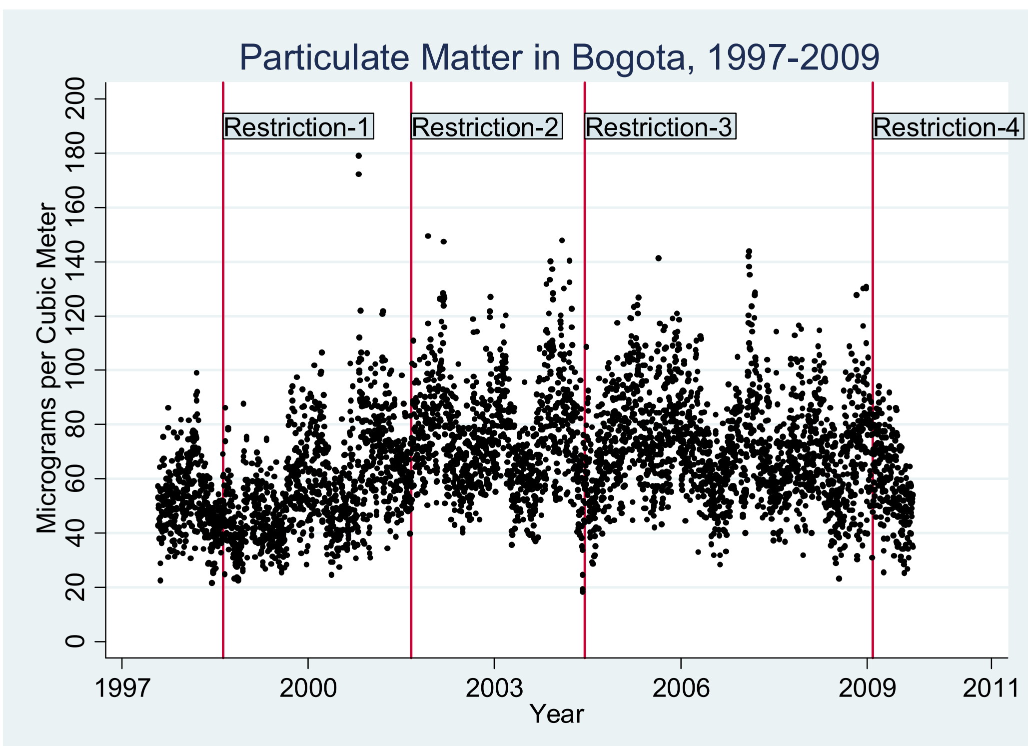
Figure B1 in Appendix B plots mean daily pollution levels for each of the seven pollutants for the time period 1997 to 2009. Mean daily pollution levels are constructed by averaging over all hours of the day and all monitoring stations. The vertical lines indicate the dates when *Pico y Placa* was implemented and subsequently modified: August 18, 1998, August 29, 2001, June 15, 2004, and February 6, 2009. According to the figures, CO levels decreased initially and then increased back in the early 2000s, while PM_{10} levels remained stable with a small increase. The levels of all other pollutants vary widely across days but exhibit no discernible long-term patterns. Moreover, there is no visible reduction in air pollution that coincides with the enactment or any expansions of *Pico y Placa*.

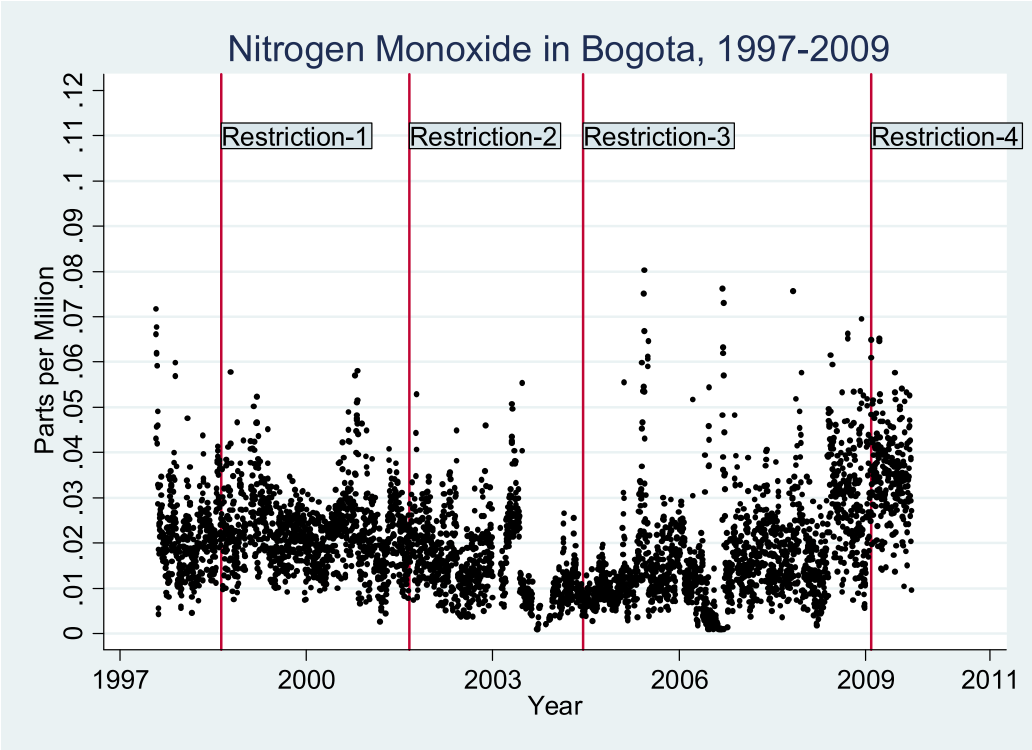
Figure B2 in Appendix B plots residuals from a regression of log pollution levels on weather and seasonality covariates and station fixed effects for each of the pollutants. These residuals are averaged across monitors within each week. The fitted lines are the predicted values of a regression of these residuals on driving restriction dummies and a ninth-order polynomial time trend. Again, the vertical lines indicate the dates when *Pico y Placa* was implemented and subsequently modified. For all pollutants, the ninth-order polynomial seems to describe the underlying time trend adequately while maintaining some degree of smoothness.

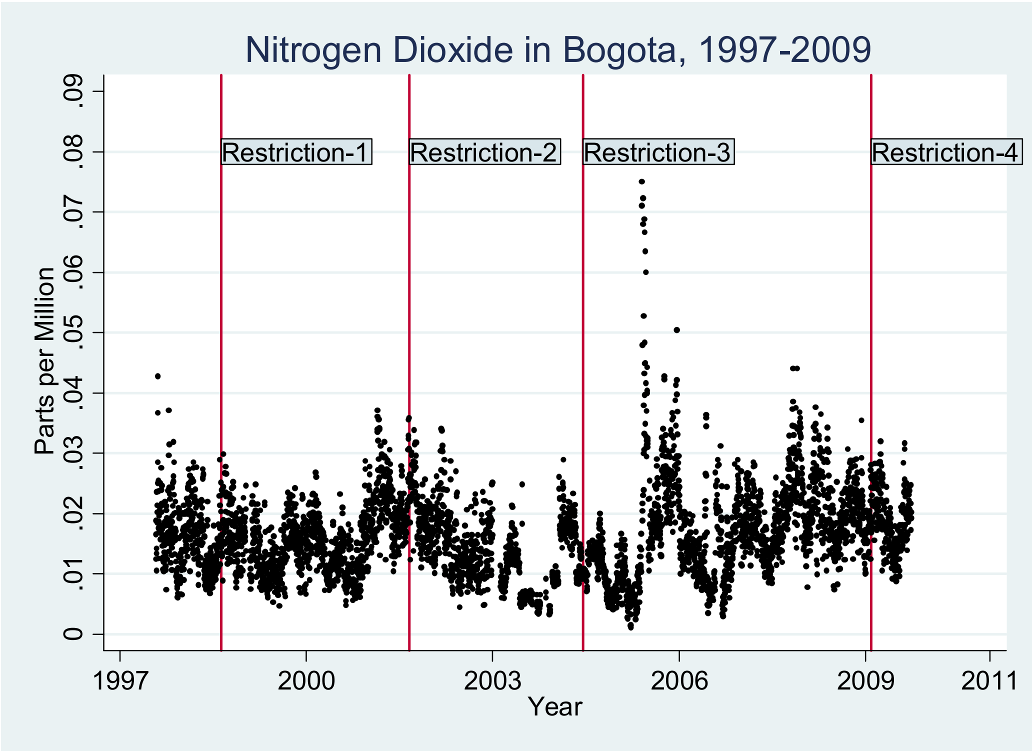
According to the figures, CO decreases with the expansion of the restriction schedule in 2004 (Restriction-3); PM_{10} decreases with the enactment of the policy (Restriction-1) but increases back afterwards; SO_2 decreases with the expansion of the schedule in 2001 (Restriction-2). The first two discontinuities are consistent with the corresponding negative point estimates in Table 4, but neither coefficient is significant. Moreover, the point estimate corresponding to the third discontinuity is neither negative nor significant. Thus, even though there are some reductions in CO and PM_{10} during the course of *Pico y Placa*, the ninth-order regression discontinuity specification provides no evidence of a statistically significant overall improvement in air quality. Instead, various versions of the driving restriction appear to have increased pollution from NO_2 and O_3. These results are consistent with Hypothesis 1 from our theory model that under certain circumstances, due to substitution, the purchase of a second car, the use of alternative modes of transportation, and/or atmospheric chemistry, it is possible for driving restrictions to increase air pollution.

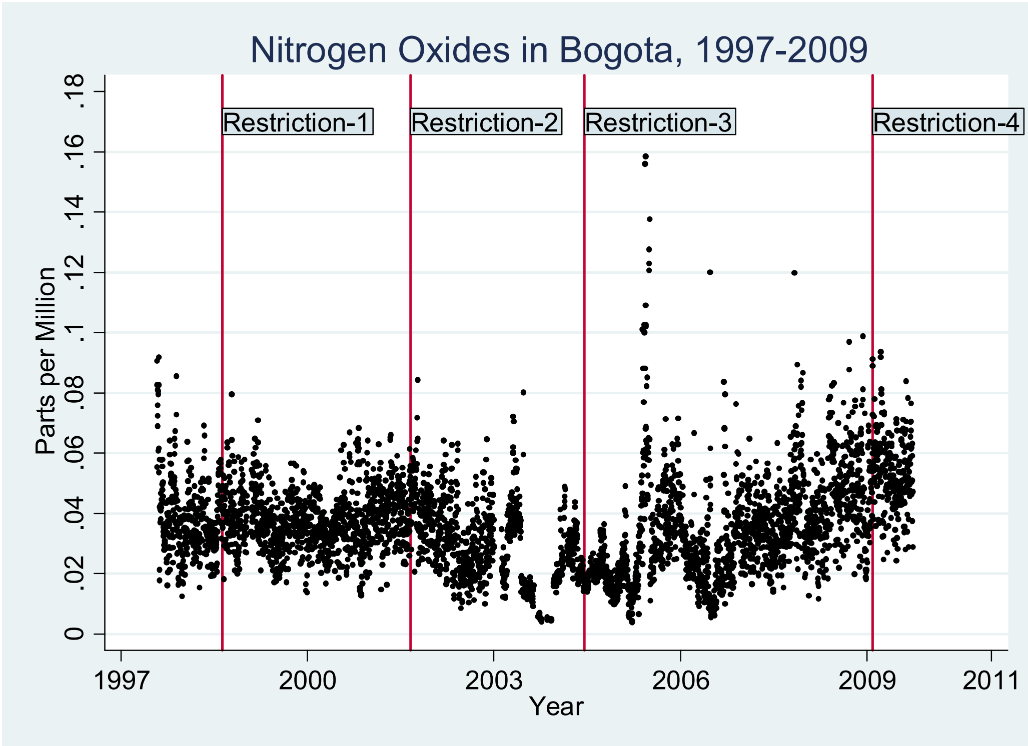
Figure B1. Mean Daily Air Pollution Levels in Bogotá, 1997-2009



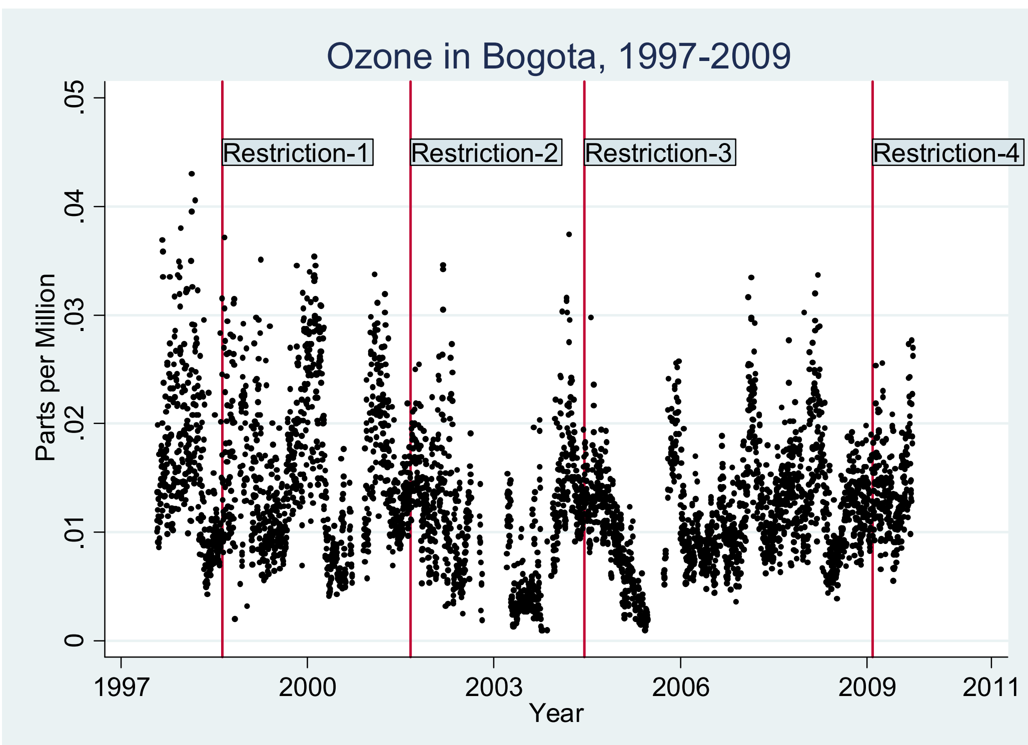



Nitrogen Monoxide in Bogota, 1997-2009
Parts per Million
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1
.11
.12
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year

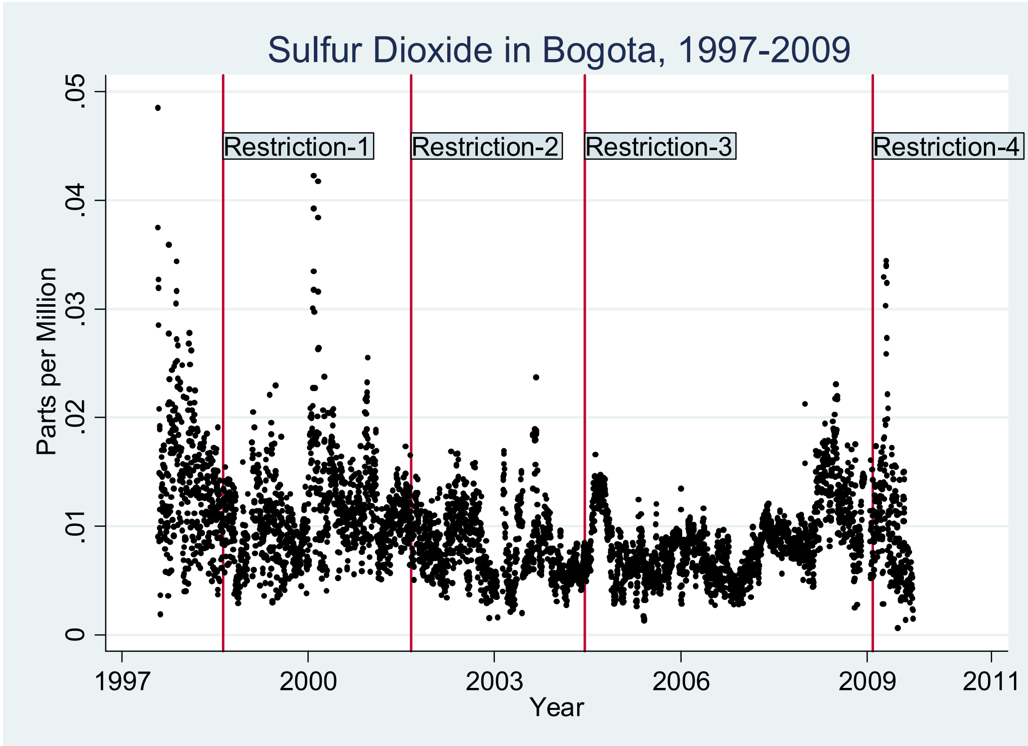

Nitrogen Dioxide in Bogota, 1997-2009
Parts per Million
0
.01
.02
.03
.04
.05
.06
.07
.08
.09
Restriction-1
Restriction-2
Restriction-3
Restriction-4
1997
2000
2003
2006
2009
2011
Year



Nitrogen Oxides in Bogota, 1997-2009
Restriction-1
Restriction-2
Restriction-3
Restriction-4
Parts per Million
0
.02
.04
.06
.08
.1
.12
.14
.16
.18
1997
2000
2003
2006
2009
2011
Year

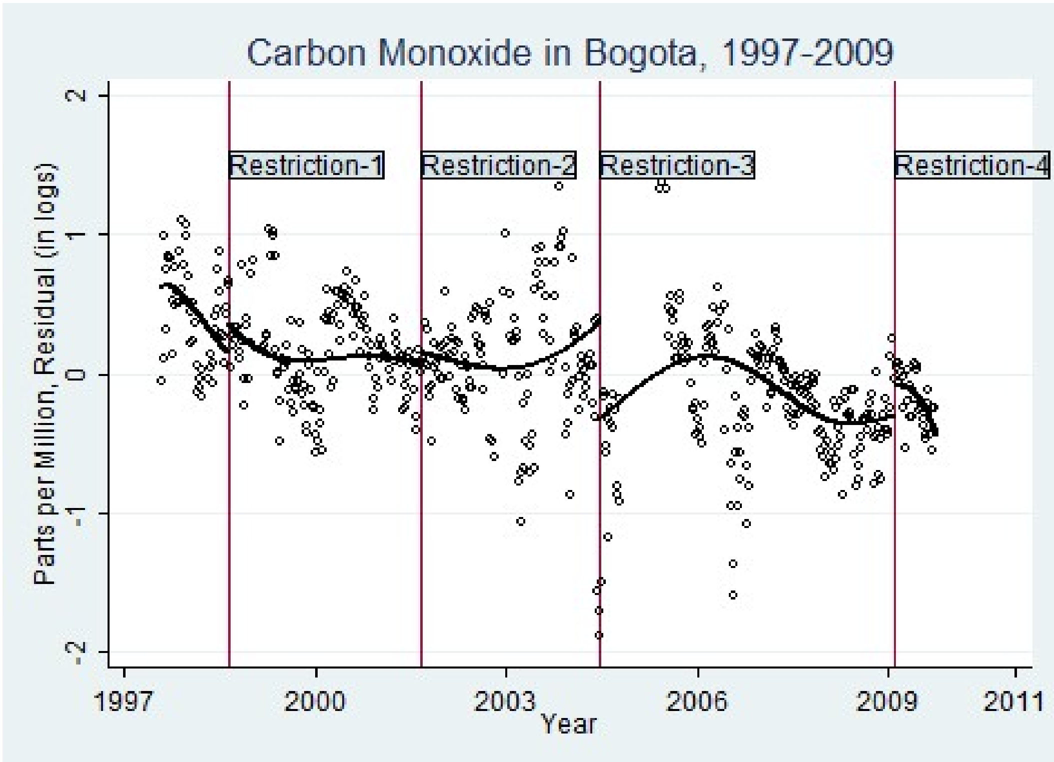


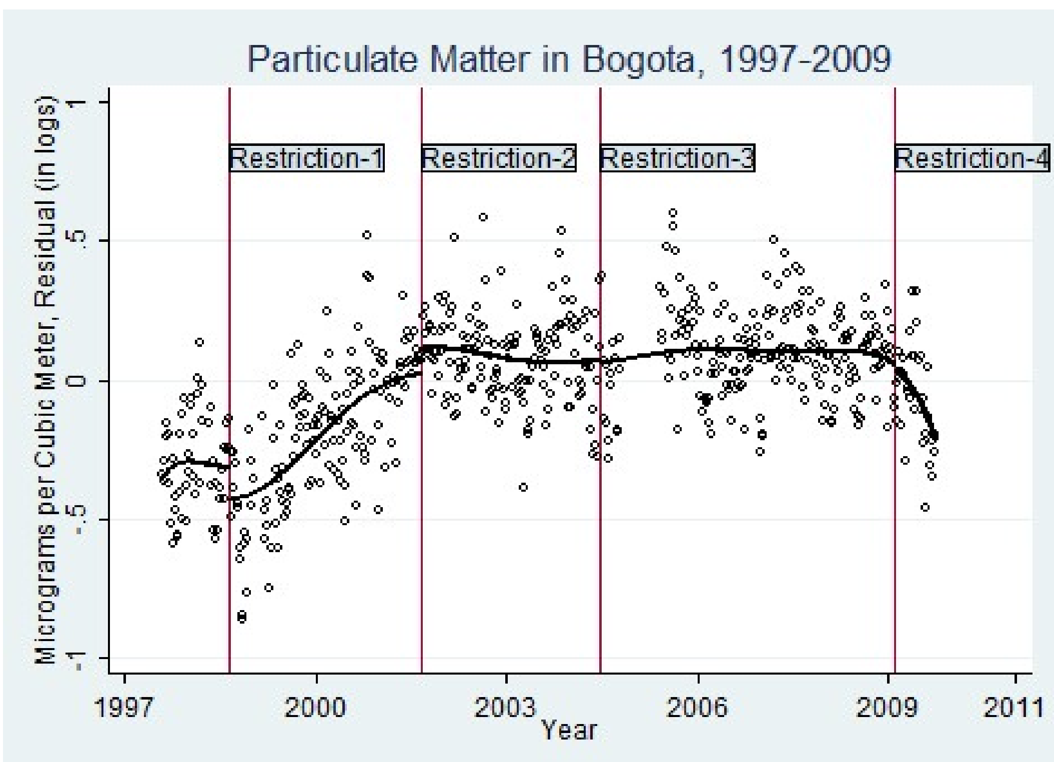
Ozone in Bogota, 1997-2009
Restriction-1
Restriction-2
Restriction-3
Restriction-4
Parts per Million
0
.01
.02
.03
.04
.05
1997
2000
2003
2006
2009
2011
Year



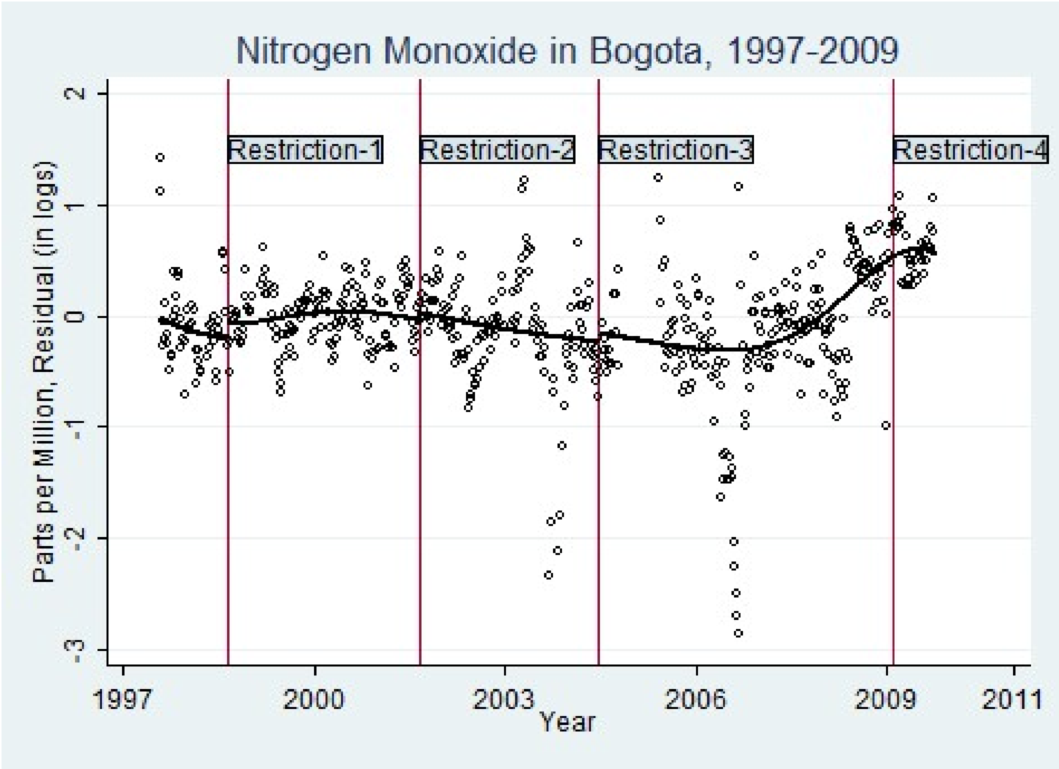
Sulfur Dioxide in Bogota, 1997-2009
Restriction-1
Restriction-2
Restriction-3
Restriction-4
Parts per Million
0
.01
.02
.03
.04
.05
1997
2000
2003
2006
2009
2011
Year

Figure B2. Mean Weekly Air Pollution Levels in Bogotá, Ninth-Order Polynomial Time Trend, 1997-2009

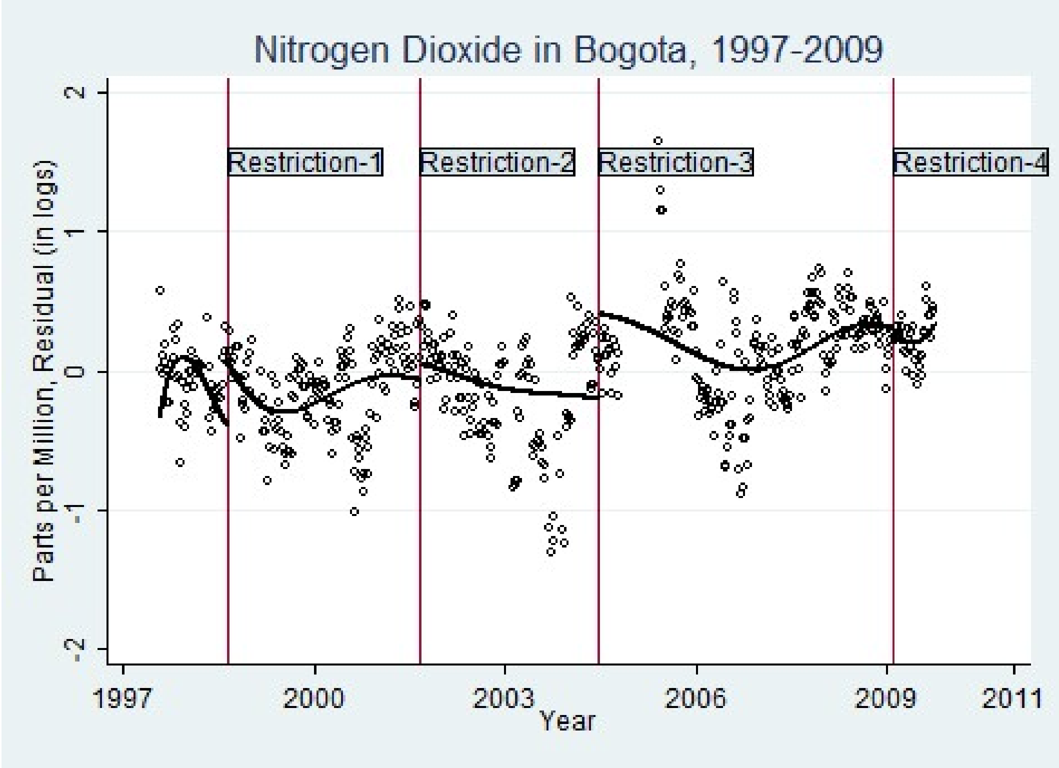




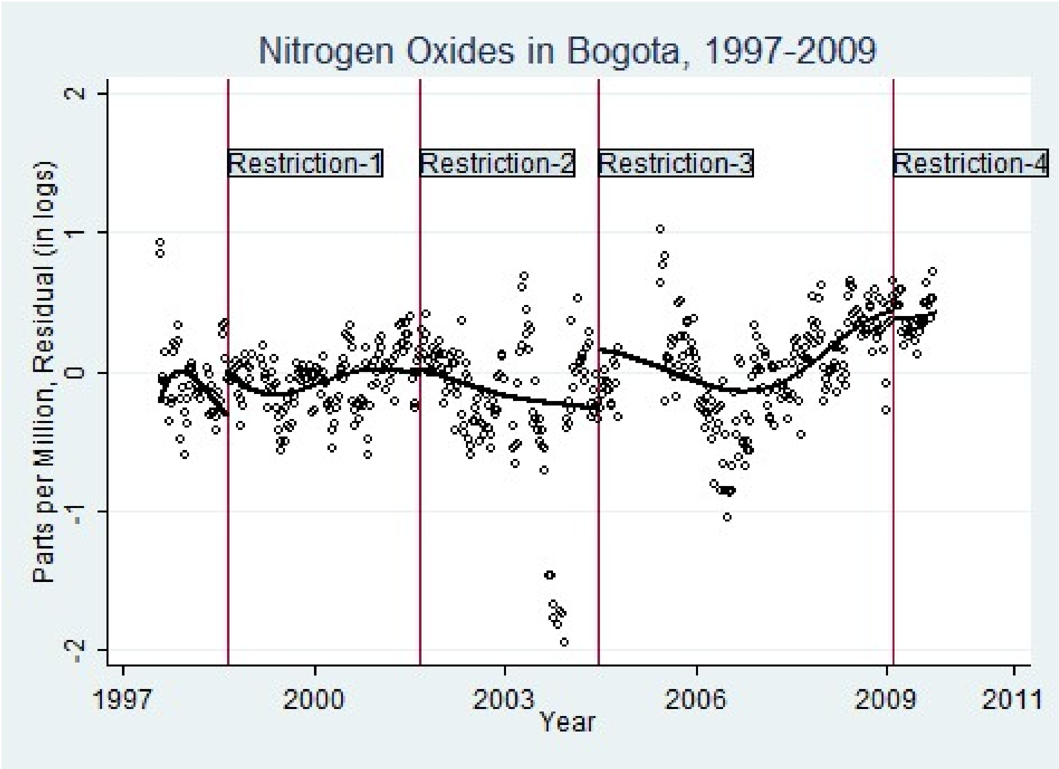
\

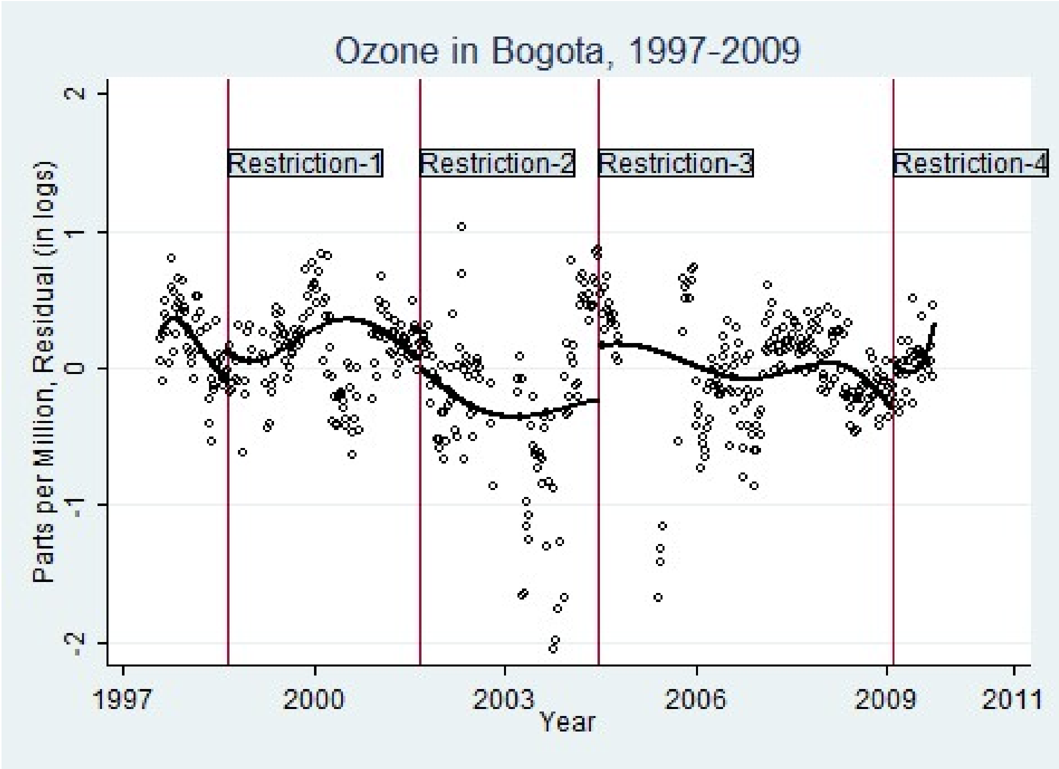


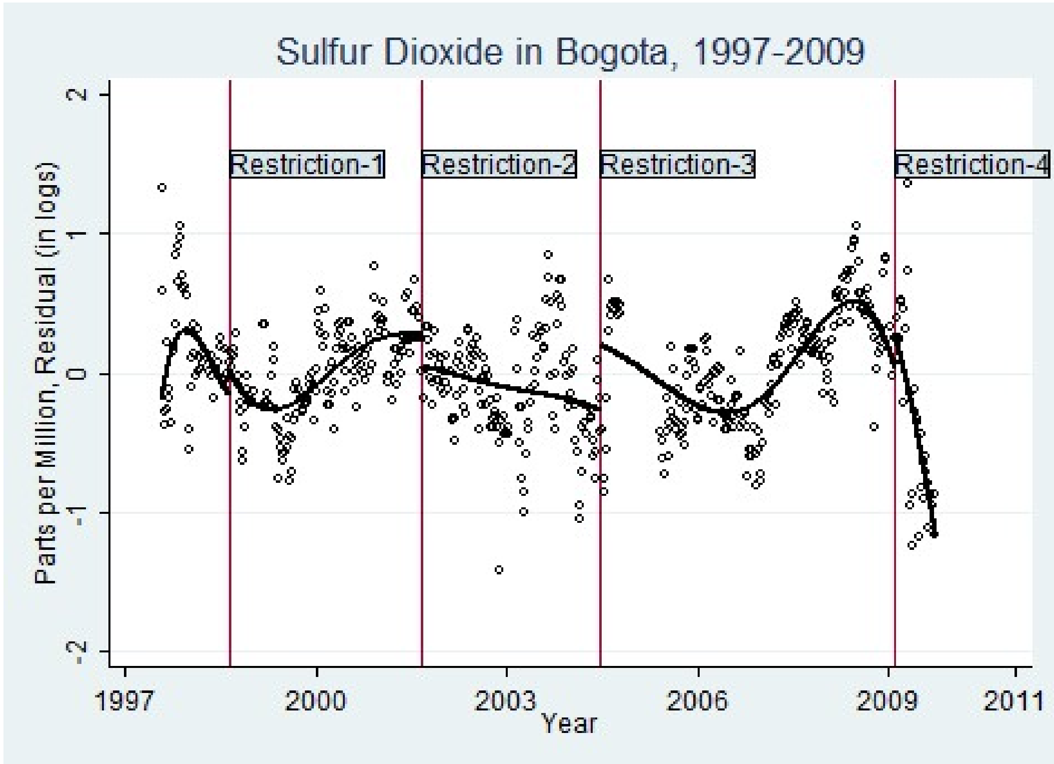
Nitrogen Monoxide in Bogota, 1997-2009
Restriction-1
Restriction-2
Restriction-3
Restriction-4
Parts per Million, Residual (in logs)
2
1
0
-1
-2
-3
1997
2000
2003
2006
2009
2011
Year



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


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


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


Sulfur 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

Appendix C

To further examine any differences in pollution between restricted and unrestricted hours,[29] Figure C1 in Appendix C plots residuals from a regression of log pollution levels on weather and seasonality covariates and station fixed effects for each of the pollutants by hour of day, once again using data from before and during the first driving restriction only. For each hour of day, these residuals are averaged across monitors within each week. The fitted lines are the predicted values of a regression of these residuals on the driving restriction dummy, a restricted hours dummy, a restricted hours dummy interacted with the driving restriction dummy, and a ninth-order polynomial in hour of day. The two sets of vertical red lines indicate the restricted hours during the first driving restriction. The blue residuals and fitted line are for observations before the first driving restriction. The green residuals and fitted line are for observations after the first driving restriction (but before the second driving restriction).

According to Figure C1 in Appendix C, the fitted line green line is below the blue line during restricted hours but above the blue line during non-restricted hours for O_3 and SO_2. This suggests that the restriction may have caused concentrations of O_3 and SO_2 to decrease during restricted hours but increase during non-restricted hours, when compared to their respective concentrations before the restriction. Thus, while the driving restriction may have been effective in decreasing concentrations of O_3 and SO_2 during restricted hours, owing to substitution, concentrations of O_3 and SO_2 increased during non-restricted hours. This result is consistent with the negative coefficient on the driving restriction during restricted hours for SO_2; and with the

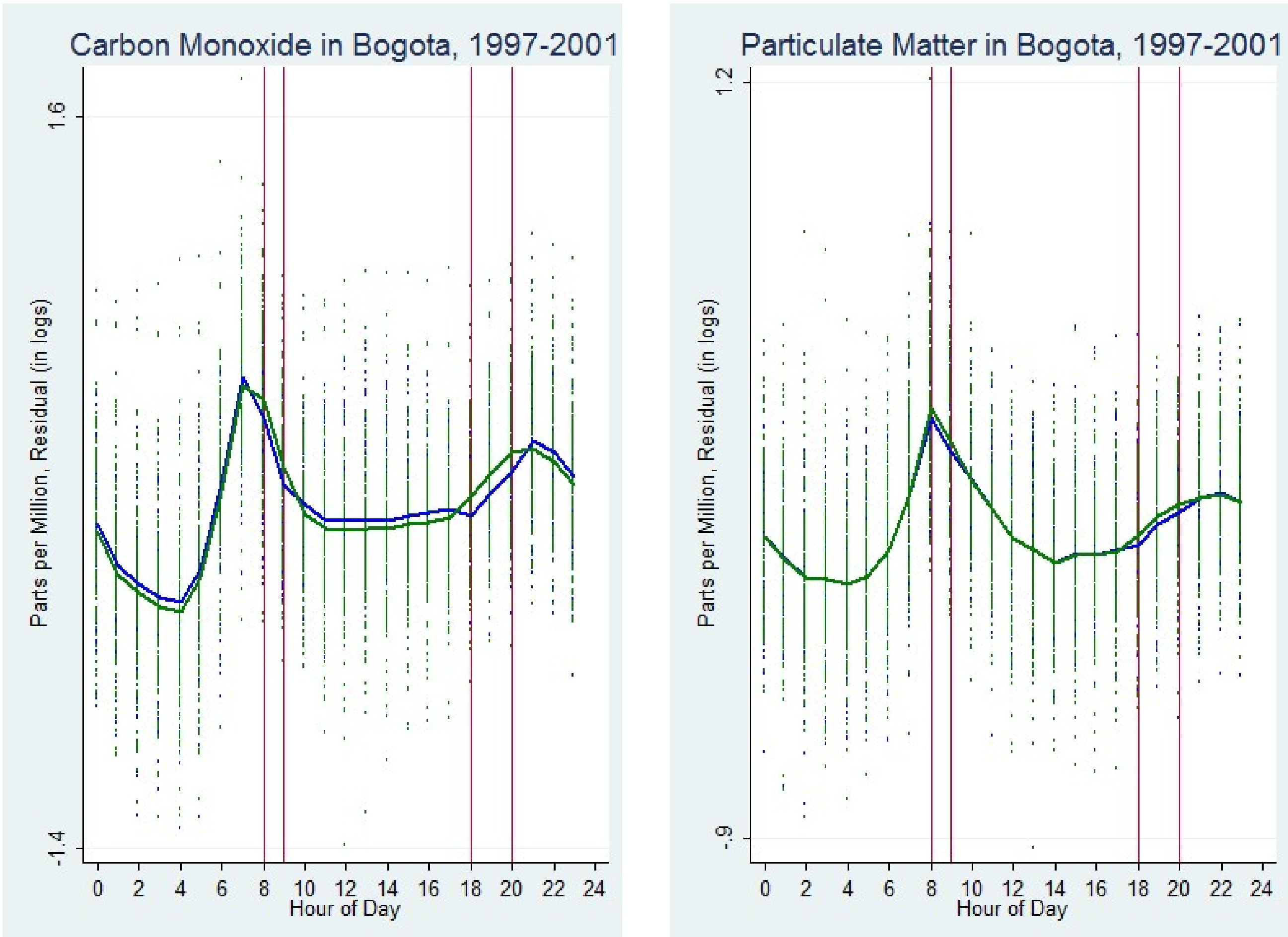
[29] For pollutants with longer lifetimes in the atmosphere, any changes in emissions between restricted and unrestricted hours may not be as sharply reflected in ambient pollution levels.

positive coefficients on the driving restriction the two hours before and the two hours after restricted hours for both O_3 and SO_2 in Table 5, but none of the coefficients on the driving restrictions are significant either during restricted hours or during the two hours before and the two hours after restricted hours, for either O_3 or SO_2.

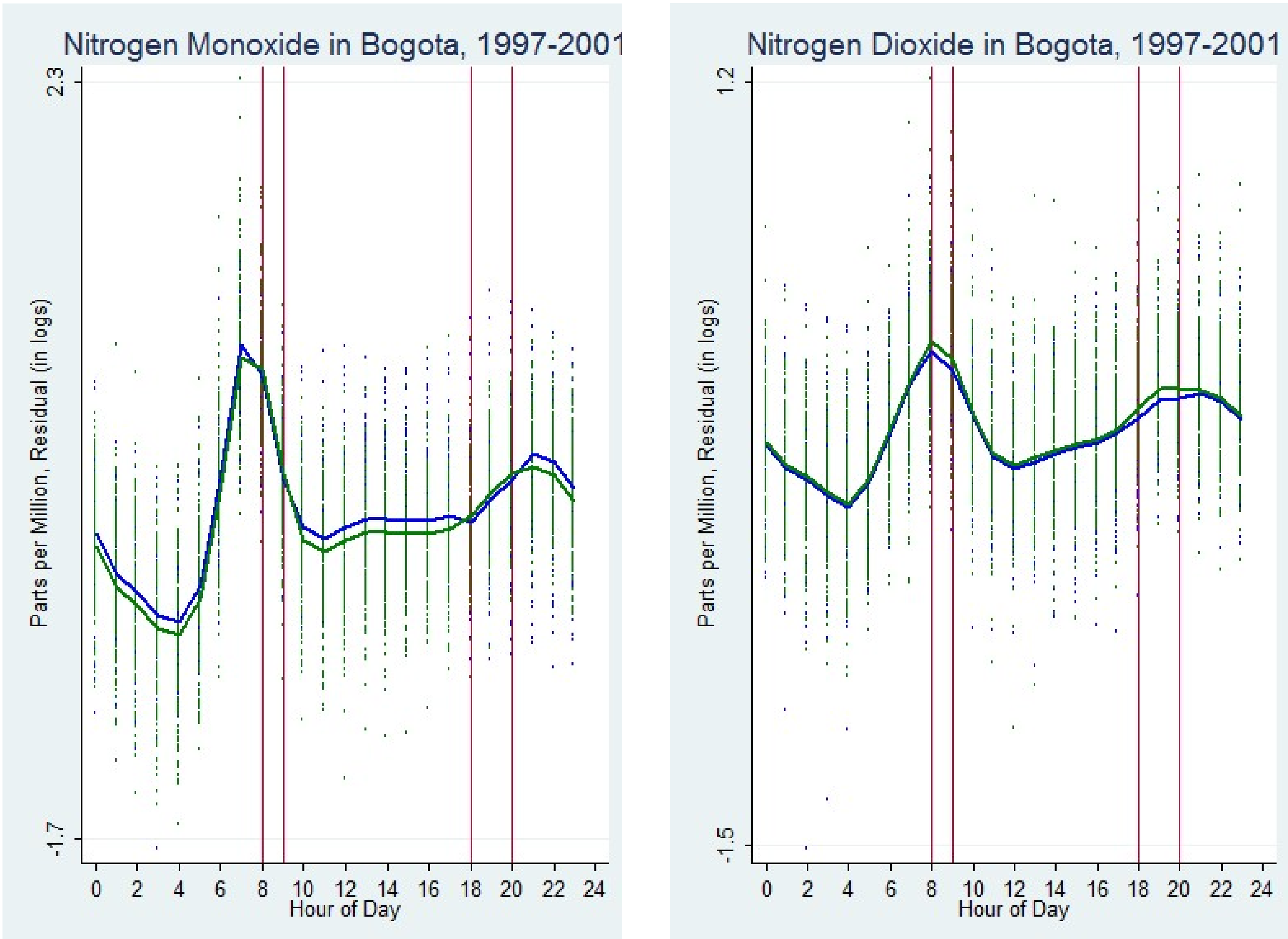
In contrast, the fitted line green line is above the blue line during restricted hours but below the blue line during non-restricted hours for CO. Thus, after the restriction, CO concentrations were higher during restricted hours but lower during non-restricted hours, when compared to their concentrations before the restriction. This result is consistent with the positive coefficient on the driving restriction during restricted hours for CO in Table 5, but the coefficient on the driving restriction is not significant for CO either during restricted hours or during the two hours before and the two hours after restricted hours.

The green line is above the blue line during restricted hours but roughly the same during non-restricted hours for NO_2 and PM_{10}. Thus, after the restriction, concentrations of NO_2 and PM_{10} were higher during restricted hours but unchanged during non-restricted hours, when compared to their concentrations before the restriction. This result is consistent with the significant positive coefficient on the driving restriction during restricted hours for NO_2 in Table 5. In Table 5, the coefficient on the driving restriction is not significant for PM_{10} either during restricted hours or during the two hours before and the two hours after restricted hours.

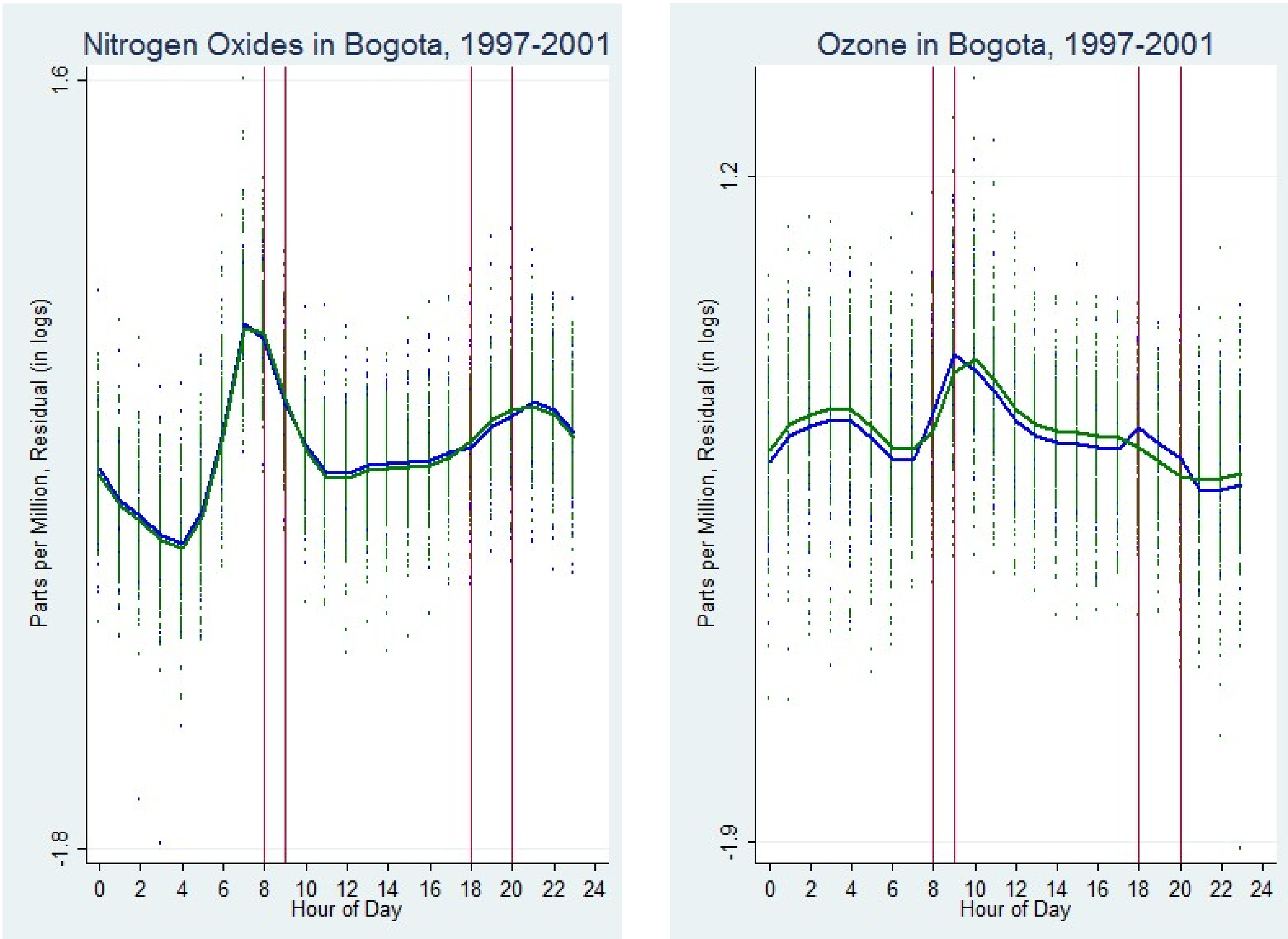
Figure C1. Mean Weekly Air Pollution Levels in Bogotá By Hour of Day, Ninth-Order Polynomial in Hour of Day, 1997-2001



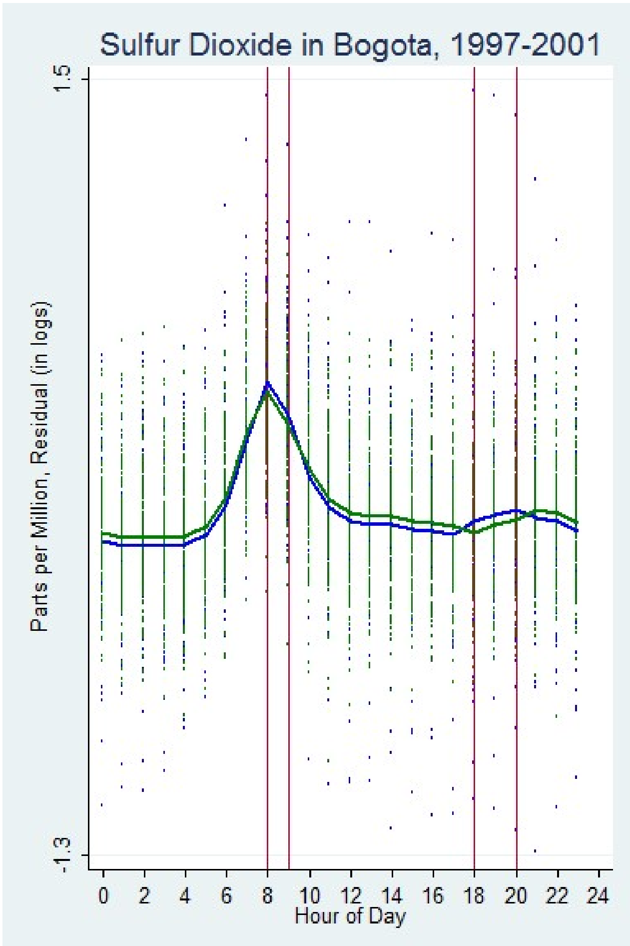
Notes: The two sets of vertical red lines indicate the restricted hours during the first driving restriction, which are the 8th-9th and 18th-20th hours of the day. The blue residuals and fitted line are for observations before the first driving restriction. The green residuals and fitted line are for observations after the first driving restriction (but before the second driving restriction).



Notes: The two sets of vertical red lines indicate the restricted hours during the first driving restriction, which are the 8th-9th and 18th-20th hours of the day. The blue residuals and fitted line are for observations before the first driving restriction. The green residuals and fitted line are for observations after the first driving restriction (but before the second driving restriction).



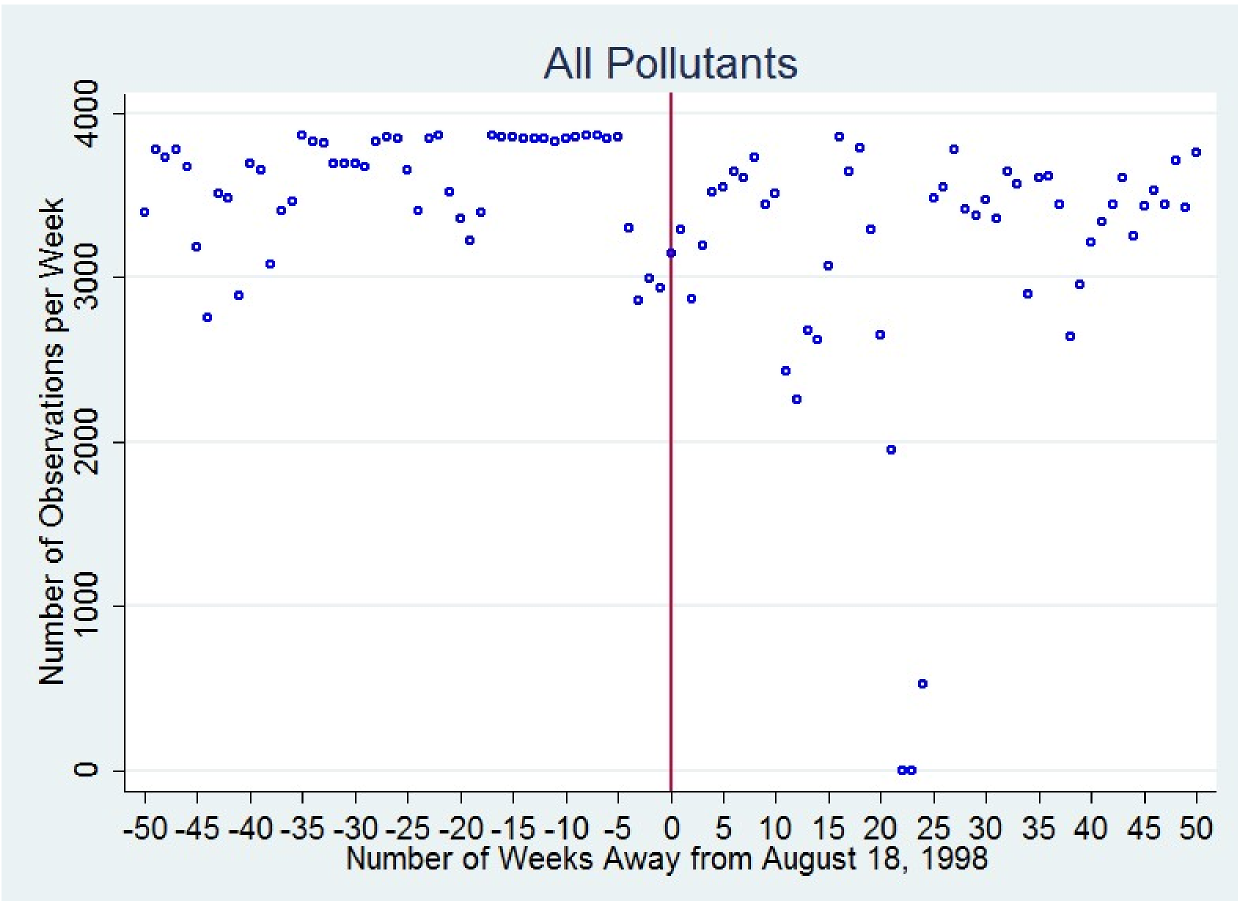
Notes: The two sets of vertical red lines indicate the restricted hours during the first driving restriction, which are the 8^{th}-9^{th} and 18^{th}-20^{th} hours of the day. The blue residuals and fitted line are for observations before the first driving restriction. The green residuals and fitted line are for observations after the first driving restriction (but before the second driving restriction).



Notes: The two sets of vertical red lines indicate the restricted hours during the first driving restriction, which are the 8^{th}-9^{th} and 18^{th}-20^{th} hours of the day. The blue residuals and fitted line are for observations before the first driving restriction. The green residuals and fitted line are for observations after the first driving restriction (but before the second driving restriction).

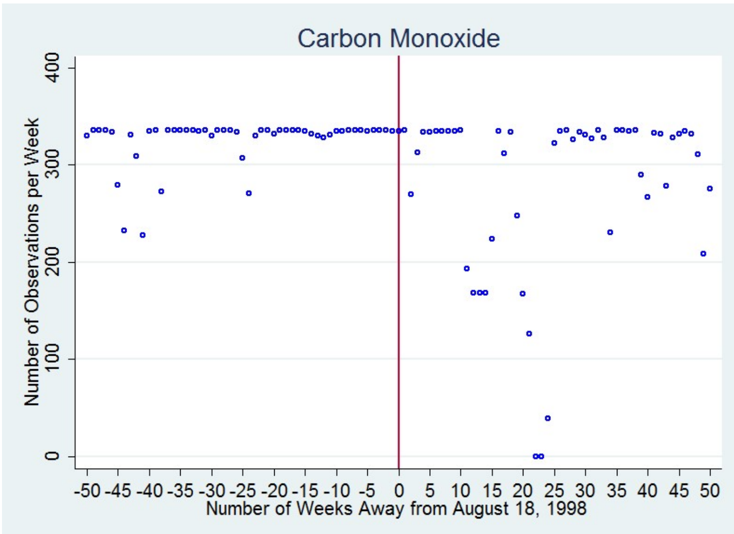
Appendix D

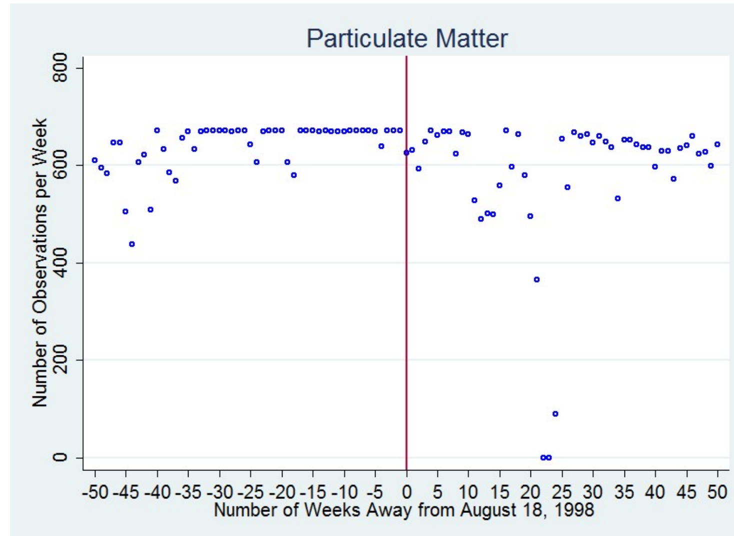
Figure D1. Number of Observations Per Week Around the Implementation of the First Version of *Pico y Placa*, All Pollutants



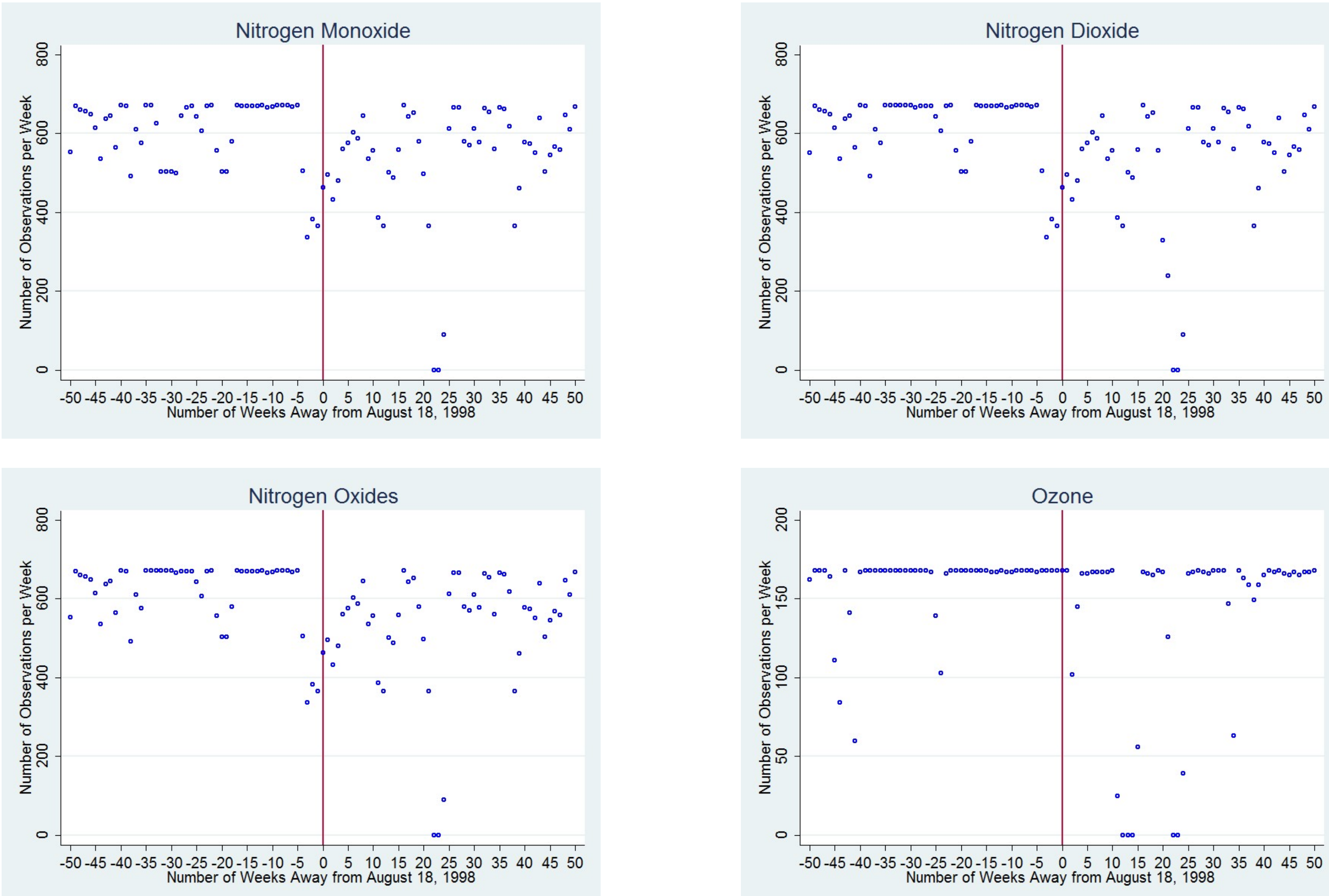
Note: The first version of the driving restriction was implemented on August 18, 1998.

Figure D2. Number of Observations Per Week Around the Implementation of the First Version of *Pico y Placa*, By Pollutant

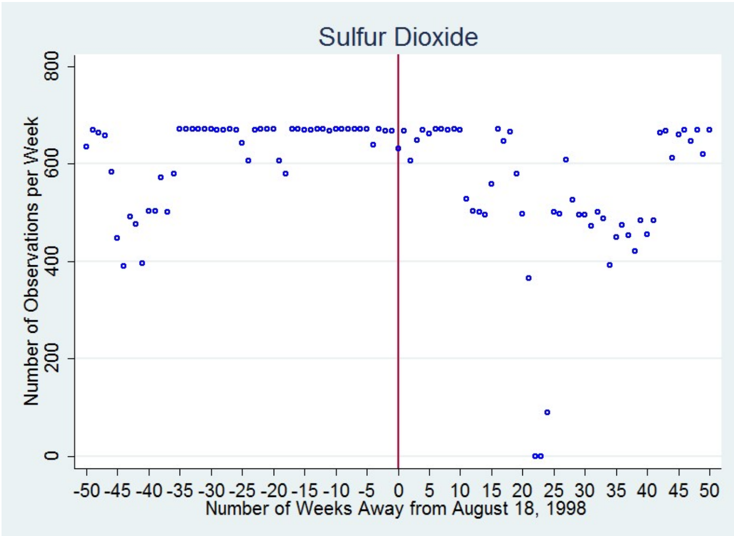




Note: The first version of the driving restriction was implemented on August 18, 1998.



Note: The first version of the driving restriction was implemented on August 18, 1998.



Note: The first version of the driving restriction was implemented on August 18, 1998.

Table D1. The Effects of Pico y Placa on Hourly Weather Measurements in Bogotá, 1997-2009

	Dependent variable is log hourly weather measurement for:		
	Temperature	Relative Humidity	Wind Speed
Restriction-1	-0.023	-0.132	-0.149
	(0.024)	(0.050)	(0.122)
Restriction-2	0.002	-0.015	-0.238
	(0.033)	(0.105)	(0.166)
Restriction-3	0.098	0.175	-0.202
	(0.037)	(0.108)	(0.158)
Restriction-4	0.056	-0.026	-0.225
	(0.043)	(0.134)	(0.175)

Notes: This table reports estimates from three separate regression discontinuity specifications, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The reported coefficients correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Appendix E

Table E1. Placebo Test of Table 4: The Effects of *Pico y Placa* on Hourly Pollution Levels in Bogotá

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Placebo Before Restriction-1	-0.905	-0.484	0.337	0.682	0.368	1.284	0.362
	(0.844)	(0.461)	(0.947)	(0.513)	(0.524)	(1.107)	(0.598)
Placebo Before Restriction-2	-0.335	0.034	0.022	-0.764	-0.012	-0.194	-0.148
	(0.215)	(0.045)	(0.144)	(1.857)	(0.319)	(0.599)	(0.100)
Placebo Before Restriction-3	0.057	-0.102	-0.453	-0.112	-0.299	0.091	0.178
	(0.272)	(0.072)	(0.436)	(0.208)	(0.301)	(0.142)	(0.160)
Placebo Before Restriction-4	0.130	-0.122	-0.127	0.243	-0.027	0.045	0.344
	(0.161)	(0.088)	(0.164)	(0.107)	(0.093)	(0.213)	(0.286)

Notes: This table reports estimates from 28 separate regression discontinuity specifications, one for each pollutant-placebo restriction date, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The 7 Placebo Before Restriction-1 regressions use a placebo restriction date of April 21, 1998 and use data from before the first driving restriction only (i.e., from August 1, 1997 to August 17, 1998). The 7 Placebo Before Restriction-2 regressions use a placebo restriction date of October 19, 1999 and use data from after the first driving restriction but before the second restriction only (i.e., from August 19, 1998 to August 28, 2001). The 7 Placebo Before Restriction-3 regressions use a placebo restriction date of July 15, 2003 and use data from after the second driving restriction but before the third restriction only (i.e., from August 30, 2001 to June 14, 2004). The 7 Placebo Before Restriction-4 regressions use a placebo restriction date of June 19, 2007 and use data from after the third driving restriction but before the fourth restriction only (i.e., from June 16, 2004 to February 5, 2009). The reported coefficients correspond to indicator variables that equal to one for every hour during the time periods of the respective placebo versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table E2. Placebo Test of Table 5: The Effects of the First Version of *Pico y Placa* on Hourly Pollution Levels in Bogotá by Time of Day

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restricted hours	-0.598	-0.778	0.498	0.977	0.700	0.649	0.910
	(0.690)	(0.586)	(0.807)	(0.530)	(0.544)	(0.746)	(0.534)
The two hours before and the two hours after restricted hours	-0.670	-0.170	0.170	1.135	0.648	0.338	0.571
	(0.755)	(0.610)	(0.880)	(0.546)	(0.481)	(1.063)	(0.475)

Notes: This table reports estimates from 14 separate regression discontinuity specifications, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The first specification (restricted hours) for each pollutant includes observations from the 8^{th}-9^{th} and 18^{th}-20^{th} hours in the sample period. The second specification (the two hours before and the two hours after restricted hours) for each pollutant includes observations from the 6^{th}-7^{th}, 10^{th}-11^{th}, 16^{th}-17^{th}, and 21^{st}-22^{nd} hours in the sample period. These 14 Placebo Before Restriction-1 regressions use a placebo restriction date of April 21, 1998 and use data from before the first driving restriction only (i.e., from August 1, 1997 to August 17, 1998). The reported coefficients correspond to indicator variables that equal one for every hour after the placebo driving restriction date of April 21, 1998. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table E3. Placebo Test of Table 6: The Effects of *Pico y Placa* on Daily Average Pollution Levels in Bogotá

	Dependent variable is log daily average pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Placebo Before Restriction-1	-1.002	-0.038	0.445	0.768	0.566	1.189	0.244
	(0.634)	(0.500)	(0.626)	(0.357)	(0.501)	(0.487)	(0.458)
Placebo Before Restriction-2	-0.177	0.043	0.123	-0.113	0.050	0.185	-0.142
	(0.106)	(0.043)	(0.097)	(0.070)	(0.079)	(0.200)	(0.088)
Placebo Before Restriction-3	-0.086	-0.091	-0.401	0.181	-0.091	0.033	-0.009
	(0.217)	(0.062)	(0.265)	(0.198)	(0.166)	(0.191)	(0.122)
Placebo Before Restriction-4	0.226	-0.040	0.251	0.736	0.359	-0.219	-0.087
	(0.152)	(0.060)	(0.175)	(0.281)	(0.161)	(0.131)	(0.159)

Notes: This table reports estimates from 28 separate regression discontinuity specifications, one for each pollutant-placebo restriction date, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The 7 Placebo Before Restriction-1 regressions use a placebo restriction date of April 21, 1998 and use data from before the first driving restriction only (i.e., from August 1, 1997 to August 17, 1998). The 7 Placebo Before Restriction-2 regressions use a placebo restriction date of October 19, 1999 and use data from after the first driving restriction but before the second restriction only (i.e., from August 19, 1998 to August 28, 2001). The 7 Placebo Before Restriction-3 regressions use a placebo restriction date of July 15, 2003 and use data from after the second driving restriction but before the third restriction only (i.e., from August 30, 2001 to June 14, 2004). The 7 Placebo Before Restriction-4 regressions use a placebo restriction date of June 19, 2007 and use data from after the third driving restriction but before the fourth restriction only (i.e., from June 16, 2004 to February 5, 2009). The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective placebo version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table E4. Placebo Test of Table 7: The Effects of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá

	Dependent variable is log daily maximum pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Placebo Before Restriction-1	-0.443	-0.068	-0.715	1.005	0.049	0.056	0.039
	(0.503)	(0.551)	(0.562)	(0.449)	(0.482)	(0.805)	(0.500)
Placebo Before Restriction-2	-0.028	0.050	0.187	-0.103	0.107	0.164	-0.158
	(0.107)	(0.042)	(0.144)	(0.076)	(0.106)	(0.249)	(0.063)
Placebo Before Restriction-3	0.077	-0.149	-0.200	0.328	0.015	-0.068	0.005
	(0.292)	(0.068)	(0.272)	(0.268)	(0.178)	(0.273)	(0.137)
Placebo Before Restriction-4	0.035	-0.083	0.163	0.678	0.250	-0.071	-0.090
	(0.180)	(0.068)	(0.205)	(0.266)	(0.172)	(0.136)	(0.143)

Notes: This table reports estimates from 28 separate regression discontinuity specifications, one for each pollutant-placebo restriction date, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The 7 Placebo Before Restriction-1 regressions use a placebo restriction date of April 21, 1998 and use data from before the first driving restriction only (i.e., from August 1, 1997 to August 17, 1998). The 7 Placebo Before Restriction-2 regressions use a placebo restriction date of October 19, 1999 and use data from after the first driving restriction but before the second restriction only (i.e., from August 19, 1998 to August 28, 2001). The 7 Placebo Before Restriction-3 regressions use a placebo restriction date of July 15, 2003 and use data from after the second driving restriction but before the third restriction only (i.e., from August 30, 2001 to June 14, 2004). The 7 Placebo Before Restriction-4 regressions use a placebo restriction date of June 19, 2007 and use data from after the third driving restriction but before the fourth restriction only (i.e., from June 16, 2004 to February 5, 2009). The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective placebo version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Appendix F

We also run a set of regressions allowing for adjustment over time. For these regressions, we use the following regression discontinuity design, which adapts a model developed by Gallego, Montero and Salas (2013b):

$$\begin{aligned}
\ln y_{ijt} = \\
&\left(a_1 + b_1(t - t_1)\right) A_{1t} + c_1 D_{1t}(1 - A_{1t}) + \\
&\left(a_2 + b_2(t - t_2)\right) A_{2t} + c_2 D_{2t}(1 - A_{2t}) + \\
&\left(a_3 + b_3(t - t_3)\right) A_{3t} + c_3 D_{3t}(1 - A_{3t}) + \\
&\left(a_4 + b_4(t - t_4)\right) A_{4t} + c_4 D_{4t}(1 - A_{4t}) + \\
&x_t{}'\beta_4 + \alpha_i + \varepsilon_{ijt},
\end{aligned} \quad (2)$$

where t_n is the time driving restriction *n* is implemented; A_{nt} is an indicator function that takes a value of 1 during the adjustment period for driving restriction *n*; and $\{a_n, b_n, c_n\}_n$ are parameters to be estimated. For each driving restriction *n*, a_n is the immediate impact, b_n is the adaptation trend, and c_n is the impact after adaptation. For these regressions, instead of using a polynomial in time, we use only a linear time trend. For the adjustment period A_{nt}, we use 12 months for each driving restriction, which was roughly the maximum adjustment period in Gallego, Montero and Salas (2013b). All the other regressors are the same.

Table F1 presents the results of the adjustment model using hourly data, and is the adjustment model analog to Table 4. In terms of immediate impact, the first driving restriction had no significant immediate impact on any pollutant. The other three driving restrictions all had a significant negative immediate impact on SO_2. The second driving restriction had a significant positive immediate impact on PM_{10} and the third driving restriction had a significant negative immediate impact on NO. None of the driving restrictions had any significant immediate impact on CO, NO_2, NO_x, or O_3.

In terms of adaptation trend, the third driving restriction had a significant positive adaptation trend for hourly CO, NO, and NO_x. Each of the 7 pollutants had a significant negative adaptation trend from at least one of the driving restrictions.

In terms of impact after adaption, all four versions of the driving restriction had a significant negative impact after adaptation on hourly SO_2. The second driving restriction had a significant negative impact after adaptation on hourly O_3. None of the driving restrictions had any significant impact after adaptation on hourly CO, PM_{10}, NO, NO_2, or NO_x.

Table F2 presents the results of the adjustment model of the effects of the first version of the driving restriction by time of day, and is the adjustment model analog of Table 5. During restricted hours, the first driving restriction had a significant negative immediate impact on PM_{10}; a significant negative adaptation trend for NO_2, NO_x, and SO_2; a significant negative impact after adaptation on SO_2; and no significant effect on CO, NO, or O_3. Similarly, during the two hours before and the two hours after the restricted hours, the first driving restriction had a significant negative immediate impact on PM_{10}; a significant negative adaptation trend for NO_2, NO_x, and SO_2; a significant negative impact after adaptation on SO_2; and no significant effect on CO, NO, or O_3.

Table F3 presents the results of the adjustment model using the daily average pollution levels, and is the adjustment model analog to Table 6. In terms of immediate impact, the first driving restriction had no significant immediate impact on the daily average pollution level of any pollutant. The other three driving restrictions all had a significant negative immediate impact on daily average SO_2. The second driving restriction had a significant positive immediate impact on daily average PM_{10}; both the third and fourth driving restrictions had a significant negative immediate impact on daily average O_3; and the fourth driving restriction had a significant positive immediate impact on daily average CO and a significant negative immediate impact on daily average O_3. None of the driving restrictions had any significant immediate impact on daily average NO_2 or NO_x.

In terms of adaptation trend, the third driving restriction had a significant positive adaptation trend for daily average CO, NO, and NO_2; and the fourth driving restriction had a significant positive adaptation trend for daily average O_3. Various driving restrictions had a significant negative adaptation trend for daily average CO, PM_{10}, NO, NO_2, NO_x, O_3, and SO_2.

In terms of impact after adaption, all four versions of the driving restriction had a significant negative impact after adaptation on daily average SO_2. All but the first driving restriction had a significant negative impact after adaptation on daily average O_3. The third driving restriction had a significant positive impact after adaptation on daily average PM_{10} and a significant negative impact after adaptation on daily average NO. None of the driving restrictions had any significant impact after adaptation on daily average CO, NO_2, or NO_x.

Table F4 presents the results of the adjustment model using the daily maximum pollution levels, and is the adjustment model analog to Table 7. All four driving restrictions all had a significant negative immediate impact on daily maximum SO_2; all but the first driving restriction had a significant negative immediate impact on daily maximum O_3; and the third and fourth driving restrication had a significant negative immediate impact on daily maximum NO. The second driving restrication had a significant positive immediate impact on daily maximum PM_{10}. None of the driving restrictions had any significant immediate impact on daily maximum CO, NO_2, or NO_x.

In terms of adaptation trend, the third driving restriction had a significant positive adaptation trend for daily maximum CO, PM_{10}, and NO_2. Various driving restrictions had a significant negative adaptation trend for daily maximum CO, PM_{10}, NO, NO_2, NO_x, O_3, and SO_2.

In terms of impact after adaption, all four versions of the driving restriction had a significant negative impact after adaptation on daily maximum pollution levels of both O_3 and SO_2. Both the second and third driving restriction had a significant impact after adaptation on NO, and the third driving restriction had a significant negative impact after adaptation on PM_{10}. None of the driving restrictions had any significant impact after adaptation on daily maximum CO, NO_2, or NO_x.

There are several robust results from the adjustment models in Tables E1-E4. First, the driving restrictions had a robust significant negative impact after adaptation on both O_3 and SO_2. None of the driving restrictions had any significant impact after adaptation on CO, NO_2, or NO_x. None of the driving restrictions had any significant immediate impact on CO or NO_2. During both (1) restricted hours and (2) the two hours before and the two hours after the restricted hours, the first driving restriction had a significant negative immediate impact on PM_{10}; a significant negative adaptation trend for NO_2, NO_x, and SO_2; a significant negative impact after adaptation on SO_2; and no significant effect on CO, NO, or O_3.

To examine the robustness of our results, we run placebo tests for each of our adjustment models using placebo restriction dates instead of the actual driving restriction dates as the treatment. We use the same placebo restriction dates used in the placebo tests of our regression discontinuity models in Appendix E. If we do not find significant treatment effects where there has been no treatment, then this means that our results are robust to our tests. Unfortunately, we do not pass the placebo test for any of the adjustment models in Tables F1-F4, as many of the placebo treatment effects are significant (results not shown). We therefore put less emphasis on these results.

Table F1. The Effects of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009: Adjustment Model

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Immediate impact							
Restriction-1	0.208	-0.187	0.040	0.107	0.061	-0.090	-0.106
	(0.111)	(0.071)	(0.114)	(0.076)	(0.068)	(0.081)	(0.097)
Restriction-2	0.147	0.290*	0.148	0.435	0.231	-0.080	-0.837*
	(0.202)	(0.065)	(0.159)	(0.178)	(0.125)	(0.182)	(0.144)
Restriction-3	-0.224	0.111	-0.800*	0.517	-0.229	-0.156	-1.567*
	(0.361)	(0.102)	(0.263)	(0.244)	(0.197)	(0.272)	(0.402)
Restriction-4	1.126	0.159	-0.503	0.242	-0.219	-0.152	-1.969*
	(0.522)	(0.149)	(0.384)	(0.418)	(0.313)	(0.405)	(0.391)
Adaptation trend							
Restriction-1	-0.001	0.000	0.000	-0.002*	-0.001*	0.000	-0.002*
	(0.001)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Restriction-2	0.001	0.000	-0.002*	-0.002*	-0.002*	-0.001	-0.001
	0.000	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Restriction-3	0.006*	0.001	0.004*	0.002	0.003*	-0.003*	0.002
	(0.002)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)
Restriction-4	-0.003*	-0.001*	0.000	0.001	0.001	0.002*	-0.007*
	(0.001)	(0.000)	(0.001)	(0.001)	(0.001)	0.000	(0.001)
Impact after adaptation							
Restriction-1	0.076	0.050	-0.022	-0.061	-0.043	0.066	-0.562*
	(0.153)	(0.053)	(0.099)	(0.105)	(0.082)	(0.133)	(0.114)
Restriction-2	0.532	0.166	-0.229	0.152	-0.129	-1.250*	-1.586*
	(0.274)	(0.078)	(0.227)	(0.225)	(0.176)	(0.238)	(0.195)
Restriction-3	0.650	0.240	-0.663	0.613	-0.054	-0.080	-1.959*
	(0.465)	(0.124)	(0.325)	(0.358)	(0.276)	(0.366)	(0.301)
Restriction-4	1.010	-0.002	-0.180	0.406	0.032	-0.280	-1.910*
	(0.528)	(0.148)	(0.379)	(0.408)	(0.311)	(0.392)	(0.356)

Notes: This table reports estimates from seven separate regressions, each with a time trend and station fixed effects. The unit of observation is a station-hour. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table F2. The Effects of the First Version of *Pico y Placa* on Hourly Pollution Levels in Bogotá by Time of Day, 1997-2001: Adjustment Model

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restricted hours							
Immediate impact	0.236	-0.227*	0.115	0.109	0.042	-0.182	-0.159
	(0.125)	(0.073)	(0.129)	(0.125)	(0.073)	(0.143)	(0.120)
Adaptation trend	-0.001	0.000	0.000	-0.002*	-0.001*	0.001	-0.003*
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Impact after adaptation	-0.163	-0.129	0.147	-0.280	-0.166	-0.172	-0.837*
	(0.143)	(0.102)	(0.165)	(0.159)	(0.116)	(0.178)	(0.156)
Two hours before and two hours after the restricted hours							
Immediate impact	0.265	-0.187*	0.176	0.128	0.086	-0.255	-0.097
	(0.135)	(0.067)	(0.119)	(0.120)	(0.073)	(0.130)	(0.132)
Adaptation trend	-0.001	0.000	-0.001	-0.002*	-0.001*	0.001	-0.003*
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Impact after adaptation	-0.169	-0.171	0.094	-0.230	-0.171	-0.200	-0.746*
	(0.178)	(0.084)	(0.160)	(0.155)	(0.113)	(0.176)	(0.156)

Notes: This table reports estimates from 14 separate regressions, each with a time trend and station fixed effects. The unit of observation is a station-hour. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table F3. The Effects of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009: Adjustment Model

	Dependent variable is log daily average pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Immediate impact							
Restriction-1	0.259	-0.203	0.090	0.038	0.108	-0.063	-0.173
	(0.111)	(0.079)	(0.099)	(0.079)	(0.066)	(0.097)	(0.094)
Restriction-2	0.185	0.263*	-0.058	0.360	0.175	-0.378	-0.974*
	(0.167)	(0.066)	(0.148)	(0.180)	(0.115)	(0.183)	(0.137)
Restriction-3	-0.384	0.129	-1.096*	0.234	-0.411	-0.838	-1.665*
	(0.398)	(0.101)	(0.266)	(0.241)	(0.206)	(0.320)	(0.378)
Restriction-4	1.219*	0.258	-1.134*	0.312	-0.224	-1.213*	-2.078*
	(0.416)	(0.146)	(0.391)	(0.391)	(0.269)	(0.397)	(0.373)
Adaptation trend							
Restriction-1	-0.001	0.000	-0.001	-0.001*	-0.001*	-0.001	-0.002*
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Restriction-2	0.001	0.000	-0.002*	-0.002*	-0.002*	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)
Restriction-3	0.007*	0.001	0.002*	0.003*	0.002	-0.003*	0.001
	(0.002)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.003)
Restriction-4	-0.002*	-0.001*	0.000	0.001	0.001	0.002*	-0.007*
	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)	(0.001)
Impact after adaptation							
Restriction-1	0.106	0.021	-0.172	-0.064	-0.062	-0.223	-0.675*
	(0.129)	(0.048)	(0.097)	(0.097)	(0.070)	(0.130)	(0.109)
Restriction-2	0.442	0.158	-0.577	-0.009	-0.238	-1.896*	-1.766*
	(0.239)	(0.078)	(0.213)	(0.211)	(0.153)	(0.291)	(0.184)
Restriction-3	0.798	0.346*	-1.159*	0.657	-0.053	-1.051*	-2.129*
	(0.374)	(0.120)	(0.345)	(0.339)	(0.240)	(0.360)	(0.286)
Restriction-4	1.033	0.075	-0.758	0.461	0.041	-1.371*	-2.090*
	(0.420)	(0.148)	(0.383)	(0.381)	(0.264)	(0.387)	(0.339)

Notes: This table reports estimates from seven separate regressions, each with a time trend and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels were averaged over all hours of the day for that station. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table F4: The Effects of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009: Adjustment Model

	Dependent variable is log daily maximum pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Immediate impact							
Restriction-1	0.179	-0.217	0.129	-0.038	0.122	-0.104	-0.381*
	(0.096)	(0.084)	(0.079)	(0.099)	(0.062)	(0.119)	(0.094)
Restriction-2	0.049	0.252*	0.001	0.291	0.108	-0.855*	-1.198*
	(0.128)	(0.067)	(0.147)	(0.191)	(0.124)	(0.226)	(0.129)
Restriction-3	-0.597	0.038	-0.950*	0.173	-0.436	-1.761*	-2.047*
	(0.292)	(0.100)	(0.283)	(0.244)	(0.218)	(0.352)	(0.337)
Restriction-4	0.578	0.324	-1.126*	0.268	-0.437	-2.176*	-2.407*
	(0.319)	(0.136)	(0.355)	(0.394)	(0.254)	(0.432)	(0.326)
Adaptation trend							
Restriction-1	-0.001	0.000	-0.001*	-0.001*	-0.001*	-0.001*	-0.002*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Restriction-2	0.000	0.000	-0.003*	-0.001*	-0.002*	-0.001	-0.001*
	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.001)	(0.000)
Restriction-3	0.005*	0.001*	0.002	0.003*	0.002	-0.003*	0.001
	(0.002)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)
Restriction-4	-0.002*	-0.001*	0.000	0.001	0.001	0.001	-0.005*
	(0.000)	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Impact after adaptation							
Restriction-1	0.042	-0.014	-0.220	-0.135	-0.158	-0.587*	-0.953*
	(0.094)	(0.043)	(0.086)	(0.100)	(0.067)	(0.158)	(0.105)
Restriction-2	-0.080	0.102	-0.632*	-0.079	-0.326	-2.701*	-2.112*
	(0.202)	(0.074)	(0.211)	(0.215)	(0.159)	(0.335)	(0.198)
Restriction-3	0.237	0.396*	-1.031*	0.579	-0.239	-1.948*	-2.588*
	(0.284)	(0.112)	(0.311)	(0.343)	(0.221)	(0.390)	(0.247)
Restriction-4	0.362	0.177	-0.749	0.320	-0.109	-2.573*	-2.521*
	(0.322)	(0.140)	(0.343)	(0.385)	(0.248)	(0.431)	(0.307)

Notes: This table reports estimates from seven separate regressions, each with a time trend and station fixed effects. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Appendix G

Table G1. The Effects of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log hourly pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction-1	0.544	-0.150	-0.307	0.310	0.029	0.374
	(0.224)	(0.112)	(0.128)	(0.134)	(0.094)	(0.167)
Restriction-2	0.793	0.094	-0.322	0.336	-0.001	0.338
	(0.319)	(0.137)	(0.202)	(0.259)	(0.180)	(0.264)
Restriction-3	-0.117	0.116	-0.221	0.929	0.405	0.976*
	(0.407)	(0.158)	(0.324)	(0.359)	(0.278)	(0.309)
Restriction-4	0.138	0.163	-0.245	1.109	0.453	1.348*
	(0.533)	(0.233)	(0.368)	(0.417)	(0.323)	(0.351)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log hourly SO_2 pollution is included as a control variable. The unit of observation is a station-hour. The reported coefficients correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table G2. The Effects of the First Version of *Pico y Placa* on Hourly Pollution Levels in Bogotá by Time of Day, 1997-2001: Using SO_2 as a Control

	Dependent variable is log hourly pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restricted hours	0.248	-0.033	-0.405*	0.627*	0.120	0.317
	(0.111)	(0.068)	(0.127)	(0.156)	(0.099)	(0.145)
The two hours before and the two hours after restricted hours	0.395*	0.079	-0.348	0.652*	0.168	0.291
	(0.127)	(0.050)	(0.129)	(0.155)	(0.108)	(0.110)

Notes: This table reports estimates from 12 separate regression discontinuity specifications, each with a ninth-order time trend and station fixed effects. Log hourly SO_2 pollution is included as a control variable. The unit of observation is a station-hour. The first specification (restricted hours) for each pollutant includes observations from the 8^{th}-9^{th} and 18^{th}-20^{th} hours in the sample period. The second specification (the two hours before and the two hours after restricted hours) for each pollutant includes observations from the 6^{th}-7^{th}, 10^{th}-11^{th}, 16^{th}-17^{th}, and 21^{st}-22^{nd} hours in the sample period. The reported coefficients correspond to indicator variables that equal one for every hour after the implementation of the first driving restriction on August 18, 1998. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table G3. The Effects of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log daily average pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction-1	0.457	-0.184	-0.043	0.301	0.145	0.513*
	(0.197)	(0.106)	(0.114)	(0.144)	(0.092)	(0.157)
Restriction-2	0.686	0.048	-0.018	0.371	0.174	0.453
	(0.279)	(0.130)	(0.193)	(0.270)	(0.180)	(0.257)
Restriction-3	-0.388	0.077	0.159	0.967	0.516	1.102*
	(0.357)	(0.143)	(0.282)	(0.357)	(0.273)	(0.310)
Restriction-4	-0.180	0.048	0.033	1.116	0.458	1.438*
	(0.469)	(0.206)	(0.324)	(0.414)	(0.324)	(0.351)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log daily average SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table G4. The Effects of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log daily maximum pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction-1	0.393	-0.184	0.106	0.172	0.164	0.652*
	(0.161)	(0.101)	(0.111)	(0.176)	(0.094)	(0.176)
Restriction-2	0.548	0.090	0.200	0.233	0.238	0.459
	(0.221)	(0.132)	(0.219)	(0.299)	(0.193)	(0.297)
Restriction-3	-0.276	0.055	0.476	0.933	0.641	1.178*
	(0.269)	(0.141)	(0.330)	(0.379)	(0.298)	(0.375)
Restriction-4	-0.070	-0.082	0.391	1.036	0.595	1.528*
	(0.390)	(0.202)	(0.357)	(0.439)	(0.332)	(0.405)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log daily maximum SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The reported coefficients correspond to indicator variables that equal to one for every day during the time periods of the respective version of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Appendix H

Table H1. The Effects of Different Versions of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log hourly pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.543	-0.150	-0.307	0.310	0.029	0.374
	(0.224)	(0.112)	(0.128)	(0.134)	(0.094)	(0.167)
Restriction-2	0.249	0.244*	-0.015	0.027	-0.030	-0.037
	(0.168)	(0.057)	(0.123)	(0.182)	(0.125)	(0.154)
Restriction-3	-0.661	0.266	0.086	0.619	0.377	0.601
	(0.310)	(0.110)	(0.283)	(0.320)	(0.245)	(0.266)
Restriction-4	-0.405	0.313	0.062	0.799	0.424	0.974*
	(0.450)	(0.194)	(0.337)	(0.381)	(0.292)	(0.304)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log hourly SO_2 pollution is included as a control variable. The unit of observation is a station-hour. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every hour during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H2. The Effects of Different Versions of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log daily average pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.457	-0.184	-0.043	0.301	0.145	0.512*
	(0.197)	(0.106)	(0.114)	(0.144)	(0.092)	(0.157)
Restriction-2	0.228	0.232*	0.025	0.070	0.029	-0.060
	(0.144)	(0.060)	(0.126)	(0.189)	(0.127)	(0.154)
Restriction-3	-0.845*	0.261	0.202	0.666	0.371	0.590
	(0.270)	(0.104)	(0.235)	(0.314)	(0.243)	(0.272)
Restriction-4	-0.637	0.233	0.076	0.815	0.313	0.925*
	(0.394)	(0.171)	(0.286)	(0.375)	(0.296)	(0.308)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log daily average SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H3. The Effects of Different Versions of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control

	Dependent variable is log daily maximum pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.394	-0.185	0.107	0.172	0.163	0.650*
	(0.161)	(0.101)	(0.111)	(0.176)	(0.094)	(0.176)
Restriction-2	0.156	0.274*	0.094	0.060	0.075	-0.193
	(0.112)	(0.071)	(0.157)	(0.199)	(0.142)	(0.189)
Restriction-3	-0.668*	0.239	0.370	0.761	0.477	0.526
	(0.197)	(0.106)	(0.287)	(0.324)	(0.270)	(0.345)
Restriction-4	-0.461	0.102	0.285	0.863	0.431	0.876
	(0.331)	(0.169)	(0.320)	(0.391)	(0.307)	(0.368)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. Log daily maximum SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H4. The Effects of Different Versions of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control and a 10th Order Time Trend

	Dependent variable is log hourly pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.403	-0.119	-0.275	0.146	-0.035	0.339
	(0.207)	(0.105)	(0.135)	(0.115)	(0.084)	(0.154)
Restriction-2	0.239	0.245*	-0.022	0.060	-0.011	-0.025
	(0.175)	(0.059)	(0.126)	(0.164)	(0.118)	(0.154)
Restriction-3	-0.831	0.297	0.148	0.305	0.240	0.557
	(0.316)	(0.116)	(0.288)	(0.260)	(0.225)	(0.267)
Restriction-4	-0.375	0.272	0.026	0.992	0.509	1.003*
	(0.481)	(0.188)	(0.346)	(0.375)	(0.282)	(0.313)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a tenth-order time trend and station fixed effects. Log hourly SO_2 pollution is included as a control variable. The unit of observation is a station-hour. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every hour during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H5. The Effects of Different Versions of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control and a 10^{th} Order Time Trend

	Dependent variable is log daily average pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.385	-0.181	-0.044	0.140	0.057	0.483*
	(0.173)	(0.105)	(0.114)	(0.136)	(0.076)	(0.135)
Restriction-2	0.236	0.232*	0.026	0.116	0.053	-0.054
	(0.149)	(0.060)	(0.127)	(0.172)	(0.119)	(0.155)
Restriction-3	-0.934*	0.265	0.200	0.359	0.205	0.569
	(0.269)	(0.110)	(0.232)	(0.252)	(0.221)	(0.277)
Restriction-4	-0.593	0.228	0.078	1.025*	0.420	0.942*
	(0.420)	(0.172)	(0.291)	(0.372)	(0.275)	(0.314)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a tenth-order time trend and station fixed effects. Log daily average SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H6. The Effects of Different Versions of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009: Using SO_2 as a Control and a 10^{th} Order Time Trend

	Dependent variable is log daily maximum pollution for:					
	CO	PM_{10}	NO	NO_2	NO_x	O_3
Restriction	0.323	-0.244	0.101	0.030	0.111	0.610*
	(0.131)	(0.110)	(0.107)	(0.195)	(0.091)	(0.149)
Restriction-2	0.163	0.277*	0.096	0.101	0.089	-0.185
	(0.115)	(0.066)	(0.159)	(0.184)	(0.139)	(0.190)
Restriction-3	-0.757*	0.186	0.359	0.494	0.381	0.498
	(0.195)	(0.110)	(0.282)	(0.273)	(0.260)	(0.349)
Restriction-4	-0.417	0.180	0.293	1.047	0.494	0.900
	(0.362)	(0.170)	(0.325)	(0.384)	(0.294)	(0.372)

Notes: This table reports estimates from six separate regression discontinuity specifications, one for each pollutant, each with a tenth-order time trend and station fixed effects. Log daily maximum SO_2 pollution is included as a control variable. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H7. The Effects of Different Versions of *Pico y Placa* on Hourly Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log hourly pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction-1	0.474	-0.161	0.024	0.406*	0.251	0.399	0.207
	(0.205)	(0.102)	(0.149)	(0.140)	(0.109)	(0.183)	(0.134)
Restriction-2	0.131	0.134	0.037	0.045	-0.003	0.082	-0.193
	(0.154)	(0.052)	(0.133)	(0.182)	(0.128)	(0.154)	(0.110)
Restriction-3	-0.539	0.204	0.194	0.524	0.367	0.631	0.301
	(0.250)	(0.076)	(0.234)	(0.279)	(0.220)	(0.271)	(0.316)
Restriction-4	-0.364	0.162	0.104	0.404	0.223	0.964*	0.292
	(0.317)	(0.096)	(0.287)	(0.314)	(0.258)	(0.287)	(0.436)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-hour. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every hour during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every hour during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H8. The Effects of Different Versions of *Pico y Placa* on Daily Average Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log daily average pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction	0.396	-0.209	0.167	0.346	0.302*	0.493*	0.242
	(0.180)	(0.112)	(0.140)	(0.145)	(0.107)	(0.163)	(0.112)
Restriction-2	0.109	0.119	-0.018	0.058	0.011	0.028	-0.162
	(0.132)	(0.058)	(0.146)	(0.192)	(0.140)	(0.157)	(0.100)
Restriction-3	-0.701*	0.202	0.304	0.546	0.323	0.637	0.380
	(0.255)	(0.081)	(0.251)	(0.281)	(0.234)	(0.292)	(0.308)
Restriction-4	-0.512	0.100	0.207	0.434	0.137	0.898*	0.367
	(0.309)	(0.095)	(0.300)	(0.322)	(0.274)	(0.306)	(0.412)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station, hourly pollution levels for were averaged over all hours of the day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Table H9. The Effects of Different Versions of *Pico y Placa* on Daily Maximum Pollution Levels in Bogotá, 1997-2009

	Dependent variable is log daily maximum pollution for:						
	CO	PM_{10}	NO	NO_2	NO_x	O_3	SO_2
Restriction	0.352	-0.243	0.278	0.255	0.317*	0.648*	0.159
	(0.145)	(0.119)	(0.121)	(0.173)	(0.095)	(0.173)	(0.078)
Restriction-2	0.090	0.143	0.046	0.074	0.064	-0.082	-0.096
	(0.105)	(0.068)	(0.185)	(0.198)	(0.158)	(0.190)	(0.100)
Restriction-3	-0.576	0.209	0.419	0.646	0.441	0.579	0.493
	(0.220)	(0.089)	(0.288)	(0.285)	(0.250)	(0.333)	(0.268)
Restriction-4	-0.383	0.010	0.204	0.494	0.183	0.830	0.364
	(0.268)	(0.097)	(0.323)	(0.336)	(0.285)	(0.344)	(0.333)

Notes: This table reports estimates from seven separate regression discontinuity specifications, one for each pollutant, each with a ninth-order time trend and station fixed effects. The unit of observation is a station-day; for each station-day, the maximum hourly pollution level is taken over all hours in that day for that station. The reported coefficients on "Restriction" correspond to indicator variables that equal to one for every day during the entire time period with any version of the driving restriction. The reported coefficients on "Restriction-2", "Restriction-3", and "Restriction-4" correspond to indicator variables that equal to one for every day during the time periods of the respective versions of the driving restriction. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week clusters. Significance code: * indicates significant at a 5% level after applying the Bonferroni correction to adjust for multiple hypothesis testing.

Appendix I

Figure I1 graphs the percentage of the population in Bogotá using private transportation (including private vehicles and motorcycles), public transportation (including buses and taxis), and walking or biking over the years 1998-2007. There does not appear to be any particularly noticeable trend, and unfortunately the limited number of data points available preclude us from running a rigorous regression discontinuity analysis. As seen in Figure I2, the number of private passenger cars in Bogotá has been increasing.

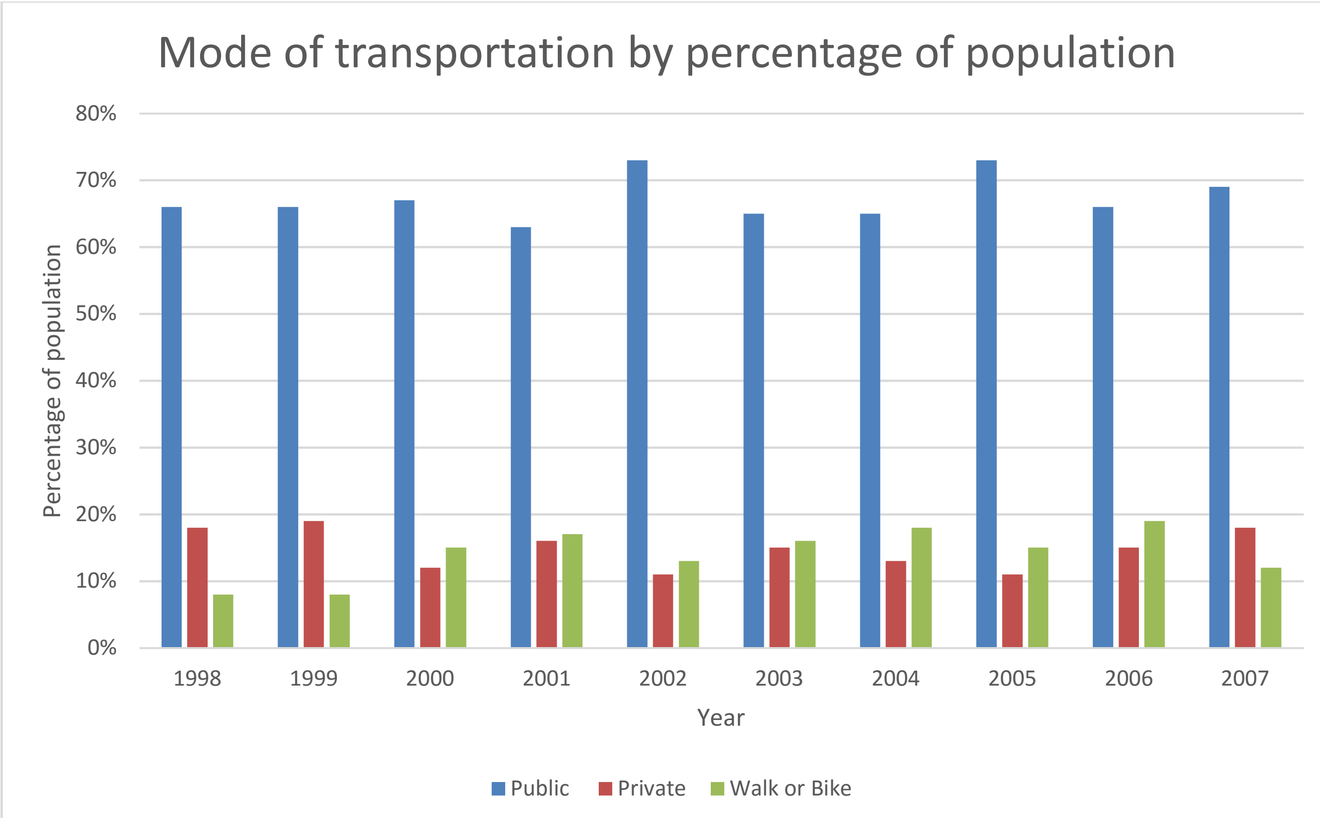
To examine the use of alternative modes of transportation, Figure I3 graphs the percentage of the population in Bogotá using buses, taxis, and motorcycles over the years 1998-2007. There appears to be somewhat of a downward trend in utilization rates for buses and an upward trend in utilization rates for taxis and motorcycles, though unfortunately the limited number of data points available preclude us from running a rigorous regression discontinuity analysis.

As seen in Figure I4, the number of motorcycles in Bogotá has been increasing rapidly. Although motorcycles may be more energy efficient than automobiles, depending on the engine motorcycles can be more polluting in terms of carbon monoxide (CO) and hydrocarbons (Chiou et al., 2009; Estupiñan et al., 2015). Although motorcycles are not currently covered by the driving restriction in Bogotá, there have been recent discussions about possibly including them in the restriction (Caracol Radio, 2016).

In terms of the types of fuel used in Bogotá, sales of gasoline in Bogotá declined from around 25,000 barrels per day to 16,000 barrels per day from 2000 to 2006 (Secretaría Distrital de Planeación, 2008). From 1996 to 2005, consumption of diesel in Bogotá increased by 296% for the taxis fleet and 126% for private cars (Secretaría Distrital de Planeación, 2008).

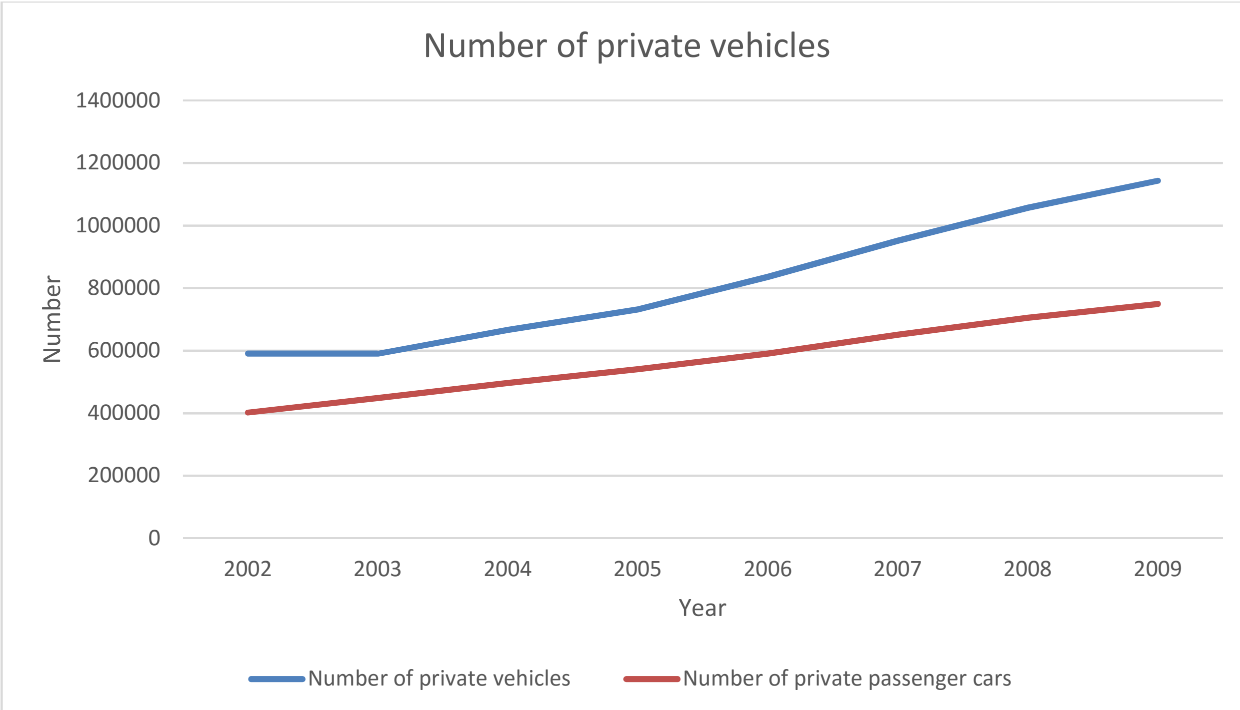
It is unlikely that many diesel vehicles in Bogotá had particle traps during our sample period, as it was not until 2015 that an environmental program was introduced by the Department of the Environment in Bogotá to install diesel particulate filters in TransMilenio and Integrated Mass Transit System (SITP) buses (Secretaría Distrital de Ambiente, 2015; Alcaldiá Mayor de Bogotá, 2014).

Figure I1. Mode of transportation in Bogotá by percentage of population



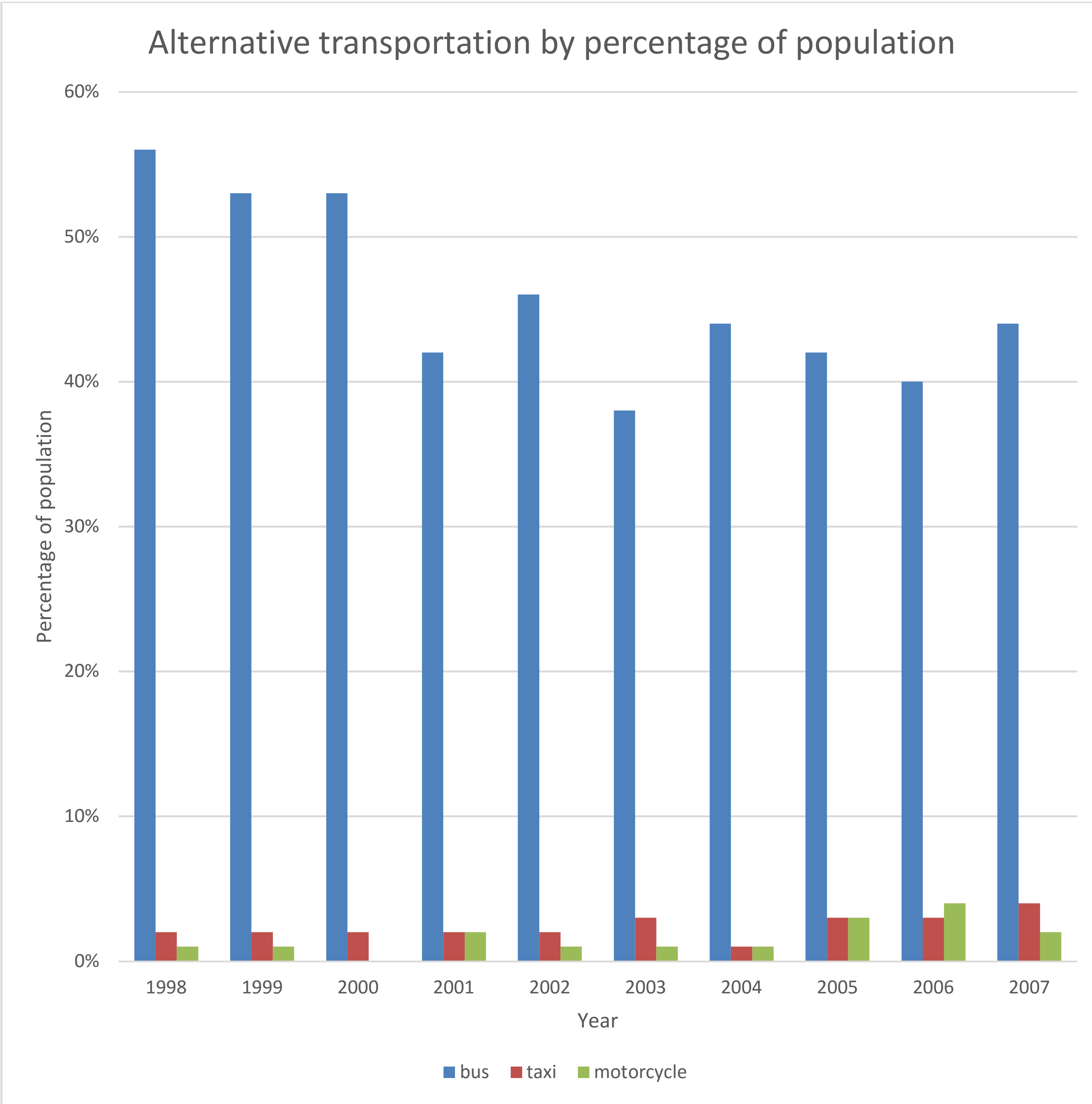
Notes: "Public" includes buses and taxis. "Private" includes private vehicles and motorcycles.
Source: Cámara de Comercio de Bogotá (2007).

Figure I2. Number of private vehicles in Bogotá



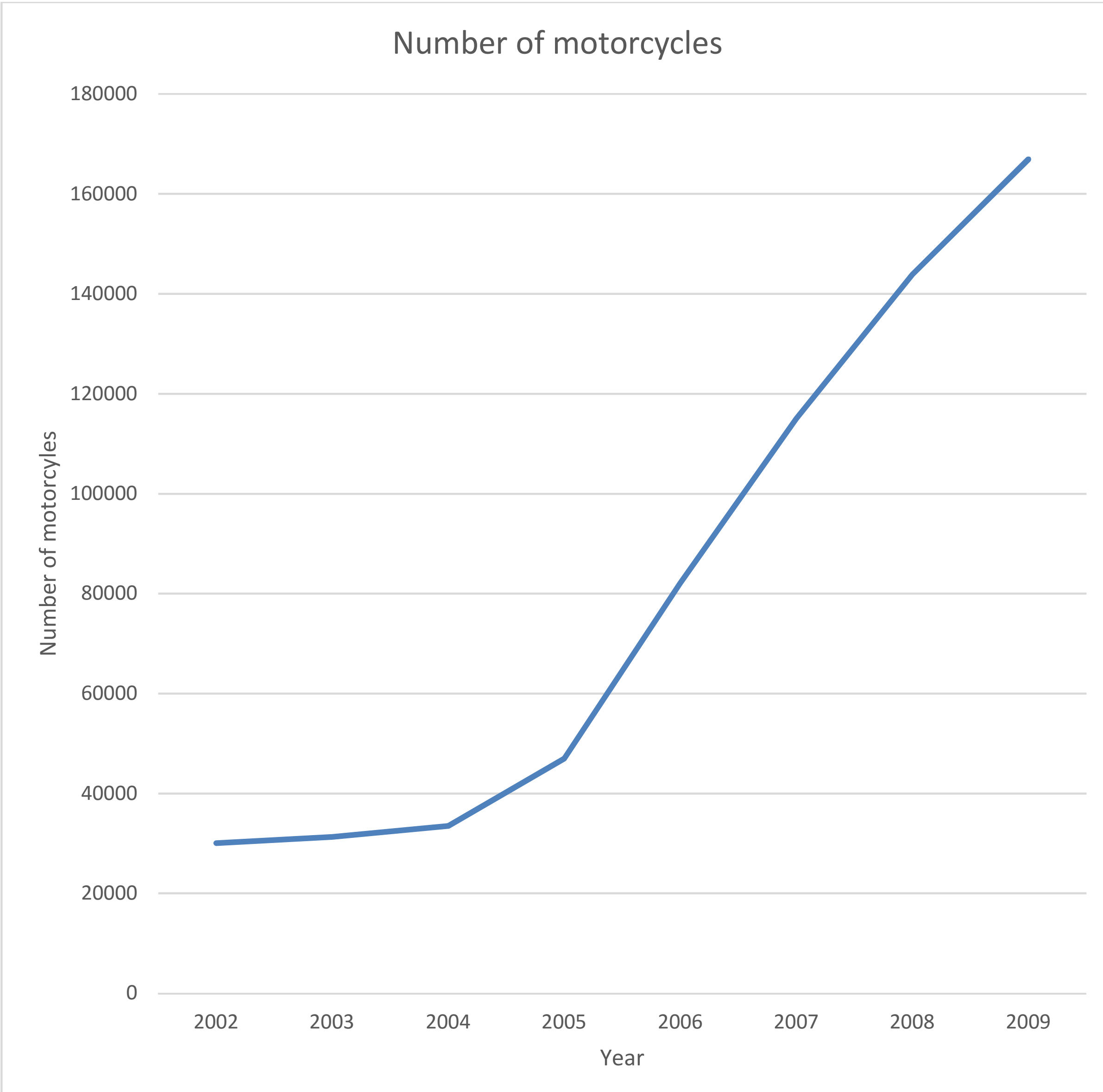
Notes: “Private vehicles” include passenger cars, pickup trucks, motorcycles, and campers.
Source: Secretaría Distrital de Movilidad (2013).

Figure I3. Mode of alternative transportation in Bogotá by percentage of population



Source: Cámara de Comercio de Bogotá (2007).

Figure I4. Number of motorcycles in Bogotá



Source: Cámara de Comercio de Bogotá (2007).