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Article

The More Stringent, the Better? Rationing Car Use in Bogotá with Moderate and Drastic Restrictions

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Abstract

Rationing car use based on license plate number has become a popular policy in several cities around the world to address traffic congestion and air pollution. This paper studies the effects of the moderate and drastic driving restrictions imposed as part of the *Pico y Placa* program on car use and air pollution in Bogotá. Using data on ambient carbon monoxide, gasoline consumption, and vehicle sales and registrations, no evidence of an improvement in air quality or a reduction in car use is found in either phase of the program. On the contrary, there is some indication that, relative to the moderate phase, gasoline consumption, vehicle ownership, and carbon monoxide in the morning peak tended to increase slightly when drastic restrictions were implemented.

JEL classification: D62, R41, Q53, Q58

Keywords: Driving restrictions, Air pollution, Car use, Policy evaluation

Rationing car use based on license plate number has become a popular policy to address congestion and air pollution in heavily populated cities,[1] as opposed to the fuel taxes and road pricing widely suggested in the literature (see Sterner and Coria 2012). Several cities around the world have implemented such driving restrictions, e.g., Mexico City, Santiago, Sao Paulo, Bogotá, Quito, Beijing, Athens, and Paris. This paper examines the effects of the *Pico y Placa* (PYP) driving restriction program on car use and air pollution in Bogotá.

The research to date has focused on assessing the overall effectiveness of these schemes; however, no study has analyzed the effects of phased-in, or progressively implemented, programs. An appealing feature of driving restrictions is that they can be introduced in progressive stages. Gradual implementation may be appropriate in response to political resistance and public opposition as such factors may impede the immediate introduction of drastic restrictions. Since the increased stringency may potentially alter

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1 For example, drivers stuck on the most congested highway in the United States waste time and fuel equivalent to an annual cost of US$95 million (Texas A&M Transportation Institute 2011). Moreover, about 1.34 million premature deaths worldwide per year are attributable to outdoor air pollution (WHO 2011).

households' responsiveness to the program, investigating how the response varies across implementation stages and affects the effectiveness of the program is of great importance. Answering these questions is relevant for policy design and enriches the debate on the replication of phased-in programs.

To the best of my knowledge, this is the first paper on how drivers respond to a phased-in program. Bogotá introduced PYP in August 1998, restricting driving during peak hours (moderate restriction) to reduce congestion caused by light vehicles. In February 2009, the restriction was intensified, extending the program to 14 hours per day (drastic restriction) to further reduce congestion and traffic emissions. Although the government has released some reports on the program implementation (see Secretaría de Movilidad 2010), there is no reliable evidence on the effectiveness of the restrictions.

Rationing car use may have other potential benefits; apart from addressing congestion and air pollution, it might also reduce the crash risk and road and parking costs.[2] Nonetheless, studies on the effectiveness of driving restrictions yield conflicting conclusions. Eskeland and Feyzioglu (1997a), Davis (2008), and Gallego, Montero, and Salas (2013) found that the *Hoy No Circula* (HNC) program in Mexico City, which banned most drivers from using their vehicles one weekday per week, was ineffective. HNC induced many households to buy additional cars (mainly old and highly polluting ones). In contrast, Carrillo et al. (forthcoming) found that driving restrictions in Quito reduced air pollution by 11 percent. In the latter case, the uncertainty about the program's permanency may have kept households from buying a second car. Viard and Fu (2015) also report reduced air pollution after driving restrictions were introduced in Beijing. They argue that high compliance and vehicle ownership costs may explain the effectiveness of the program. However, around the time of the program implementation, other strict policies, for example, factory closures and suspension of construction projects, were imposed to cut pollution during the 2008 Olympics, and thus the improvements in air quality may not be entirely attributed to driving restrictions. Moreover, these programs are quite controversial from a cost perspective. Using a contingent valuation survey for HNC, Blackman et al. (2015) found that the regulatory costs are substantial (1 percent of drivers' annual income).

The present study fills a gap in the literature by examining the effects of switching from moderate to drastic restrictions. Although the effect of multiple changes in driving restrictions on pollution has been studied by Viard and Fu (2015), their analysis explores a complex mixture of changes in a very short period, which makes it difficult to clearly separate stringency levels.[3] The most closely related studies evaluating driving restrictions are Gallego, Montero, and Salas (2013) and Davis (2008). Unlike their studies, which offer a broad analysis of a drastic driving restriction, the present paper focuses on the effects of two stringency levels. Due to a lack of a measurement of car driving, as in Gallego, Montero, and Salas (2013), the present study uses carbon monoxide (CO) levels as a proxy for car use and measure of air quality, exploiting the strong correlation with traffic. Using hourly CO in a regression discontinuity model, the effects of moderate and drastic restrictions are estimated at different times of the day and week for a two-year symmetrical time window centered on the start of each PYP phase. Within this interval, prepolicy observations are used as a counterfactual of postimplementation observations, as in Davis (2008), allowing for a polynomial time trend to control for unobserved time-varying factors.[4] To

2 Other common arguments are that such policies are easy to monitor, target the rich and the poor equally, and potentially induce use of public transport (Eskeland and Feyzioglu 1997a).

3 The ban in Beijing was introduced on July 20, 2008, and lifted on September 20. It was adjusted and reintroduced on October 11 and again readjusted on April 11, 2009. During the development of the present research, a study by Lin, Zhang, and Umanskaya (2014) assessing driving restrictions in several cities, including Bogotá, became available. Their analysis focuses on the effectiveness of a mixture of driving restrictions (private and public transport) on several pollutants, but does not evaluate the effects of moderate and drastic bans on car sales and gasoline use. The authors argue that restrictions for other transport modes may have increased the cost of using them and did not result in a clearly improved air quality.

4 The difference-in-difference method would require the assumption of a similar CO trend in a comparable city that was not subject to the program before the policy was decreed. Because other Colombian cities differ in vehicle fleet

shed light on the households' potential behavioral response to the policy, the effects of PYP on gasoline consumption and vehicle sales and registrations are examined and compared between phases. A set of robustness checks are also conducted to assess the sensitivity of the estimates. Finally, Blackman et al.'s (2015) estimates of households' willingness to pay for being exempt from HNC are used to compute the costs imposed by PYP.

The results show that CO concentrations did not decrease in either PYP phase. Relative to the moderate phase, there is even some indication that CO slightly increased in the morning peak during the drastic restriction. This outcome is consistent with mild evidence of increased gasoline consumption and vehicle ownership, which suggests that drastic restrictions tended to generate somewhat stronger counterproductive consequences than moderate restrictions. Considering that the welfare losses are substantial, price-based mechanisms such as congestion charges, which have been shown to be effective in other cities, might be considered as an alternative instrument to reduce driving and pollution.

This paper is organized as follows: Section 1 describes PYP. The car use and pollution indicator is characterized in more detail in Section 2. Section 3 describes the data. Section 4 presents the econometric approach and Section 5 shows the results. Section 6 analyzes the effects of PYP on additional outcome variables. Section 7 provides some cost calculations. Section 8 concludes the paper.

1. The Moderate and Drastic Phases of PYP

Bogotá is Colombia's most important economic center. Its population of 7.4 million implies an immense pressure on roads and highways. Urban roads are used mainly by private vehicles—approximately 1,400,000 in number, or roughly 72 percent of Bogotá's total vehicle fleet in 2014 (Secretaría de Movilidad 2015). Due to the vehicle fleet growth in the last decade, congestion has become an important problem, resulting in progressively reduced travel speeds (Secretaría de Movilidad 2012). Moreover, private vehicles cause deterioration of air quality through annual emissions of 404,000 tons of CO, 18,200 tons of nitrogen oxides (NO_x), and 46,500 tons of hydrocarbons (SDA and Uniandes 2009).

To reduce congestion, Bogotá implemented PYP on August 18, 1998 (hereafter referred to as the "moderate phase"). The program banned the use of privately owned light vehicles[5] Monday through Friday during rush hours (7:00–9:00 a.m. and 5:30–7:30 p.m.) according to a schedule based on the last digit of the license plate number. The aim was to reduce congestion by 160,000 vehicles during those hours of the day.[6] The program applied to four different last digits per day and annually assigned different days of the week for each group of digits.[7] Weekends and holidays were excluded from the regulation. Minor adjustments were made to these moderate phase rules for private vehicles in the subsequent years.[8] In 2002, the restriction periods were increased by 30 minutes in the morning (6:30–9:00 a.m.) and moved 30 minutes earlier in the evening (5:00–7:00 p.m.). In 2004, they were further increased by 30 minutes in the morning (6:00–9:00 a.m.) and one hour in the evening (4:00–7:00 p.m.).

On February 6, 2009, the length of the restricted time per day was substantially modified (the period subsequent to this date is hereafter referred to as the "drastic phase"), while other characteristics of the

composition, development, geography, and meteorological conditions and also have been affected by other driving restriction programs, that assumption is unlikely to be met by any other city. For instance, Colombia's second largest city, Medellín, had extended restrictions to motorbikes prior to the drastic phase in Bogotá.

5 Throughout this paper, "private vehicles" will refer to regular cars (*automóviles* in Spanish), station wagons (*camionetas*), and sport utility vehicles (*camperos*).

6 PYP attempted to restrict 40 percent of about 400,000 vehicles (the existing car stock in 1998).

7 For instance, vehicles with a last license plate digit of 1, 2, 3, or 4 were restricted on Mondays; 5, 6, 7, or 8 on Tuesdays; 9, 0, 1, or 2 on Wednesdays; 3, 4, 5, or 6 on Thursdays; and 7, 8, 9, or 0 on Fridays.

8 Driving restrictions for buses were also introduced in 2001 as a strategy to control their oversupply. Additional regulations in 2006 applied for buses and trucks.

program remained unchanged. In the drastic phase, private vehicle use was restricted on weekdays 6:00 a.m. to 8:00 p.m. This regulatory action aimed to reduce pollutant emissions, congestion, and accidents. Given that Bogotá had already started a district road-building plan, the program was also justified as a mechanism to counteract future congestion.

PYP has been enforced through the imposition of fines and vehicle immobilization. Since the moderate phase of the program, the annual number of fines has decreased by, on average, 40 percent, and hence this infraction has moved from second to fifth place on the list of the most frequent traffic fines imposed by the Metropolitan Transit Police (see Secretaría de Movilidad 2010). These facts have been used by the authorities to argue drivers' progressive voluntary acceptance of and compliance with PYP.[9]

2. Selection of Car Use and Pollution Indicator

Traffic counts may be considered a direct measure of vehicle use for evaluating driving restriction programs such as PYP. However, as such data is only available for the drastic phase of PYP and then only for certain parts of the city and days of the year, it is not possible to construct a continuous time series pre- and postimplementation based on traffic counts.[10]

Thus, instead of traffic counts, CO concentration is used as a proxy for car use. CO has several advantages compared with other possible proxies (Gallego, Montero, and Salas 2013). First, CO is mainly emitted by traffic (85–98 percent of total CO emissions in Bogotá in 2001 and 2007) and mainly by gasoline-powered vehicles (Derwent et al. 1995). In Bogotá, almost the entire light vehicle fleet is gasoline operated (99 percent in 1998 and 96 percent in 2009); privately owned vehicles account for 90 percent of the CO emissions of this fleet (SDA and Uniandes 2009). Second, CO is an inert tracer that reaches the highest levels during rush hours, when traffic demand is also the greatest (see Boddy et al. 2005; Comrie and Diem 1999). Third, CO is also less chemically reactive in the atmosphere than pollutants such as particulate matter (PM_{10}) and NO_x (see Body et al. 2005; Comrie and Diem 1999). Fourth, continuous series of hourly CO levels are available across the city. Fifth, CO can be used as a direct measure of air quality.[11]

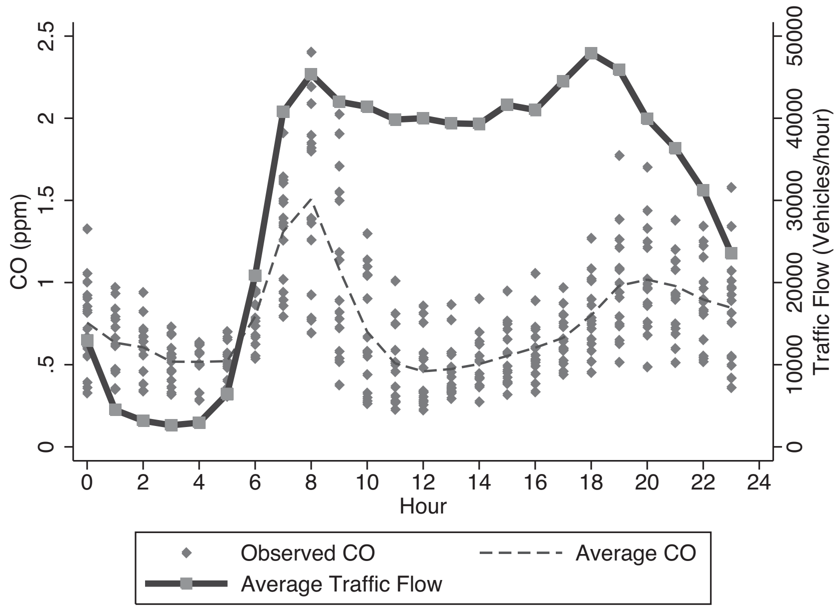
To illustrate, figure 1 depicts the diurnal pattern between CO concentration and traffic flow in the first quarter of 2010. The graph shows a close correlation between these variables, with the highest CO levels at peak traffic hours. When interpreting this relationship, it is important to consider that CO also depends on the vehicle pollution intensity, which is determined by the car fleet composition and emissions control technology (three-way catalysts (TWCs)). Therefore, given that used and old cars have higher emission rates than new ones, CO concentrations do not necessarily represent the total number of vehicles on the road. But certainly the observed rapid and sharp response of CO levels to traffic emissions enables monitoring of changes in car use. Considering that meteorological variables such as wind speed, temperature,

9 The decline in fines may have other potential explanations as well, e.g., weak monitoring or drivers gradually learning how to circumvent the policy. Yet several years into PYP, weak monitoring appears unlikely since the police had reasonably improved their control procedures. Paying bribes to police officers is also unlikely since a driver may have to pay several bribes in a single trip, making it very costly.

10 See Gallego, Montero, and Salas (2013) for a brief discussion on the use of traffic counts to evaluate car use. Certainly, vehicle speed is also an alternative measure to analyze congestion. However, there is no comprehensive data in Bogotá to conduct a reliable PYP assessment using car speeds. Constructing a vehicle speed database would be relevant for policy-making given that congestion is such that Bogotá is considered the second worst metropolitan area to drive in according to Waze (2015).

11 Although CO concentrations tend to be, on average, below the air quality standard, compliance with the standard does not imply complete protection for all people or that other traffic pollutants are not emitted. The vehicular activity, identified through CO levels, may be associated with volatile organic compounds (VOCs) and carbon dioxide (CO_2) (see EPA 2010).

Figure 1. CO Concentrations and Traffic Flow



Source: CO data from RMCAB and traffic flow from the Transport Agency of Bogotá for the first quarter of 2010. Author's calculations.

relative humidity, temperature inversion,[12] and rainfall can also alter CO concentrations (see Boddy et al. 2005; Maffeis 1999), these factors and their nonlinearities need to be accounted for in the analysis.

3. Data

This study uses historical CO and meteorological data to assess the effect of PYP on CO during two-year symmetrical time intervals centered on the start of each phase (August 18, 1997, through August 17, 1999, and February 7, 2008, through February 5, 2010); see table 1 for descriptive statistics. Allowing the analysis to span two years for each phase ensures accounting for seasonal variation and lessens the effect of possible confounding factors on CO levels (see Davis 2008). The first time window is used to evaluate the effect of moderate restrictions (pre-PYP versus moderate phase), and the second to assess the effect of drastic restrictions (moderate versus drastic phase).

Data on hourly CO levels and meteorological variables were taken from the Air Quality Monitoring Network of Bogotá (RMCAB). The RMCAB is a system of continuous and automatic monitoring of air quality dating back to August 1997[13] that measures ambient concentrations of CO, NO_x, nitrogen monoxide (NO), nitrogen dioxide (NO_2), PM_{10}, sulfur dioxide (SO_2), and ozone (O_3), as well as meteorological variables such as wind speed, wind direction,[14] relative humidity, superficial

12 A temperature inversion occurs when a warm air layer moves over a cooler air mass near the earth's surface—the opposite of normal conditions. Hence, motor vehicle emissions are trapped near ground level. Omitting this effect potentially introduces a bias when using CO as a proxy for car use. To the best of my knowledge, this is the first paper assessing driving restrictions that includes this factor.

13 At present, the RMCAB consists of 15 point stations and a mobile station. Equipment is in compliance with the US Environmental Protection Agency's regulations (Secretaría de Ambiente 2015).

14 To allow for meaningful interpretations, this reading was converted from azimuth bearings to a set of dummy variables corresponding to the eight-point compass international convention.

Table 1. Descriptive Statistics

Variable	Observations	Mean	Standard deviation	Minimum	Maximum
Data to analyze the moderate restriction: August 18, 1997–August 17, 1999					
Carbon monoxide (ppm)	17,027	3.11	1.53	0.1	11.7
Wind speed (m/s)	17,037	1.29	0.91	0	6.1
Temperature (°C)	17,013	12.88	3.73	2.4	23.4
Relative humidity (%)	15,131	72.69	12.78	16	97
Rainfall (mm)	17,014	0.10	0.65	0	22
Wind direction (degrees)	17,037	187.40	57.70	3.7	357
Temperature inversion	15,127	0.24	0.43	0	1
Data to analyze the drastic restriction: February 7, 2008–February 5, 2010					
Carbon monoxide (ppm)	17,503	0.84	0.47	0.1	6.1
Wind speed (m/s)	17,511	2.33	1.15	0.4	6.5
Temperature (°C)	17,511	14.30	2.86	4.3	23.1
Relative humidity (%)	17,473	67.46	13.74	13.0	90.9
Rainfall (mm)	17,511	0.10	0.55	0	19.9
Wind direction (degrees)	17,511	189.65	78.19	6.5	356.5
Temperature inversion	16,846	0.24	0.43	0	1

Source: Data from RMCAB for 1997-1999 and 2008-2010. Author's calculations.
Notes: Detailed statistics on wind direction converted to dummy variables representing the eight-point compass are omitted to save space.

temperature,[15] and rainfall. Monitoring stations with CO data for more than 75 percent of all possible hourly observations for the period of interest were selected,[16] yielding a total of four monitoring stations for each PYP phase.[17] The hourly CO reporting of the selected stations ranges from 78 percent to 91 percent for the moderate phase and from 80 percent to 95 percent for the drastic phase. The hourly meteorological reporting varies from 86 percent to 97 percent and from 92 percent to 100 percent, respectively.

4. Econometric Approach

The effect of PYP on CO levels is analyzed using the following model:

$$y_t = \alpha + \beta PYP_t + f(t) + \boldsymbol{X}_t^{'}\omega + \boldsymbol{Z}_t^{'}\theta + \mathrm{D}_t^{'}\eta + \epsilon_t \tag{1}$$

where y_t is hourly CO concentration in logs at period t and PYP is an indicator variable equal to one after August 1998 during the moderate phase of PYP and zero otherwise, or equal to one after February 2009 for the drastic phase and zero otherwise. $\boldsymbol{X}_t$ represents any of the meteorological variables described in the previous section in a polynomial form at time t and their corresponding lags, except temperature inversion and wind direction, which are dummies and are included in $\boldsymbol{Z}_t$. $\boldsymbol{D}_t$ denotes seasonal dummies for month of the year, day of the week, hour of the day, and interactions between weekends and hour of

15 Temperature at different heights was used to define temperature inversion. Thus, temperature inversion is an indicator variable that takes the value of one under these episodes, and zero otherwise.

16 This proportion is considered satisfactory in the field of environmental science (EPA 2010). Over time, new RMCAB stations have been installed and others eliminated. These changes cause some monitoring points to have low data representation and make it impossible to use the same stations for the moderate and drastic phases and for constructing a continuous data series for 1997–2010.

17 These stations are Sagrado Corazón, Carvajal, Olaya, and Cazucá for the moderate phase of PYP, and IDRD, Las Ferias, Puente Aranda, and Fontibón for the drastic phase.

the day. $f(t)$ is a flexible polynomial time trend and ϵ_t is the error term. CO and meteorological variables are considered at the mean city level. β reflects the average effect of PYP on mean CO concentrations.

The estimation is conducted within the framework of regression discontinuity (RD) design, allowing for a polynomial time trend to control for unobserved time-varying factors that may influence CO and make the policy effect estimates less informative. The underlying assumption of RD is that unobserved factors influencing CO levels change smoothly at the date of PYP implementation (see Hahn, Todd, and Van der Klaauw 2001). The time trend may capture unobservable time-varying variables such as changes in vehicle age, TWC, engine size, adjustments in vehicle fleet composition, and other possible economic trends. Therefore, the prepolicy observations serve as a counterfactual of the postimplementation ones.

Note that vehicles become older over time and that the efficiency of their emission control technology usually deteriorates with age. Thus, since PYP may have affected the vehicle fleet composition, i.e., may have changed the ratio of old/new cars, CO emissions may also have been affected through this channel. However, these changes typically occur gradually and should not be a concern for identification. Another possible threat to the validity of the estimates is that the households may have reacted to the announcement of the upcoming driving restriction program by buying additional vehicles and, as a result, increasing their driving and emissions before PYP implementation. I believe this effect is minor since, although households were informed about the policy in advance, they had little time to adjust. Each phase was announced in media only a few weeks ex ante. The moderate restriction was officially issued by decree almost 30 days in advance (July 15, 1998), but nothing was said about whether the program would be permanent. Then, four days before implementation, a decree added clarifications regarding exempt vehicles. Thus, given the uncertainty about the program's permanency, most households probably waited to buy a second car. As for the drastic restriction, the program was formally announced by decree one day in advance (February 5, 2009), that is, with even shorter notice than for the moderate phase.[18]

Equation (1) is estimated for the two-year symmetrical time windows (1997–1999 and 2008–2010).[19] First, the impact of PYP on CO is analyzed for the series containing hours of the day (hereafter, "all hours") when traffic is most active (5:00 a.m.–9:00 p.m.). Although the moderate restrictions applied only to peak hours, this overall model provides insights into whether the program affected the average CO levels during the day. Second, to evaluate the effects of the program in restricted and nonrestricted periods, equation (1) is estimated for time subsamples: morning peak, evening peak, off-peak, and weekends.[20] Note that PYP might have affected driving not only in the restricted periods, as it might have displaced trips to unrestricted hours. All models include weather variables as a quadratic polynomial and their first lag. Standard errors are estimated taking serial correlation into account.[21]

18 It is also reasonable to believe that people prefer to make decisions based on official messages, since it is not unusual that policy projects are abandoned due to public or political opposition.

19 CO and meteorological variables were found to be stationary according to the augmented Dickey Fuller (ADF) test. Hence, the models were estimated with the variables in levels.

20 Restricting the sample to time intervals was initially suggested by Davis (2008). For the moderate phase, the sample is restricted to 7:00 a.m.–9:00 a.m. (morning peak), 5:00 p.m.–8:00 p.m. (evening peak), and 10:00 a.m.–5:00 p.m. (off-peak) during working days. For the drastic phase, the sample is restricted to 6:00 a.m.–9:00 a.m. (morning peak), 4:00 p.m.–7:00 p.m. (evening peak), and 10:00 a.m.–4:00 p.m. (off-peak) during working days. For weekends, the subsample includes the time slot 7:00 a.m.–11:00 a.m. for both the moderate and drastic phase. Indicator variables representing interactions between weekends and hour of the day are excluded in the subsample models.

21 Based on the autocorrelation function, in most cases residuals are serially correlated between three days and one week. In very few cases, correlation exceeds one week, e.g., the "all hours" model, although the magnitude and statistical significance of the autocorrelation coefficients decrease remarkably after that period. Therefore, to account for serial correlation, standard errors, in parentheses, are robust to heteroscedasticity and arbitrary correlation within one-week clusters.

5. Results

This section presents and discusses the estimation results of equation (2). Additional robustness checks were also performed to analyze the stability of the results.

Main Results

Table 2 presents PYP estimates for different time-interval subsamples in the moderate and drastic phases using a fifth-order polynomial time trend.[22] The results indicate that PYP did not lead to reduced CO concentrations in either phase of the program for any of the subsamples. Three out of five PYP coefficients for the moderate phase are negative but statistically insignificant. For the drastic phase, all β coefficients are positive, though the PYP estimate is statistically different from zero at the 10 percent significance level only for the morning peak model. In this case, PYP appears to have increased CO by 13 percent, but the estimate is less precise. Figure 2 plots, for each phase and all subsamples, the average weekly residuals from equation (1), excluding PYP, along a fifth-order polynomial time trend and PYP. The RD graphs show that the fifth-order polynomial tends to satisfactorily represent the evolution of the time trend. Moreover, the observed discontinuities at the policy date are consistent with the obtained PYP estimates.

Table 2. Effect of Moderate and Drastic Restrictions on CO Concentration

	All hours (1)	Morning peak (2)	Evening peak (3)	Off- peak (4)	Weekends (5)
(a) Moderate phase					
PYP (moderate)	−0.008	−0.037	−0.052	0.006	0.062
	(0.066)	(0.066)	(0.076)	(0.089)	(0.130)
Observations	9,999	825	1,249	2,875	707
R^2	0.654	0.637	0.600	0.483	0.735
(b) Drastic phase					
PYP (drastic)	0.180	0.131*	0.154	0.167	0.067
	(0.147)	(0.077)	(0.164)	(0.199)	(0.092)
Observations	10,873	1,418	1,404	2,805	780
R^2	0.708	0.607	0.680	0.593	0.730
p value of hyp. testing:	0.121	0.046**	0.124	0.228	0.487
$H_0: \beta_{drastic} - \beta_{moderate} \leq 0$					
$H_1: \beta_{drastic} - \beta_{moderate} > 0$					

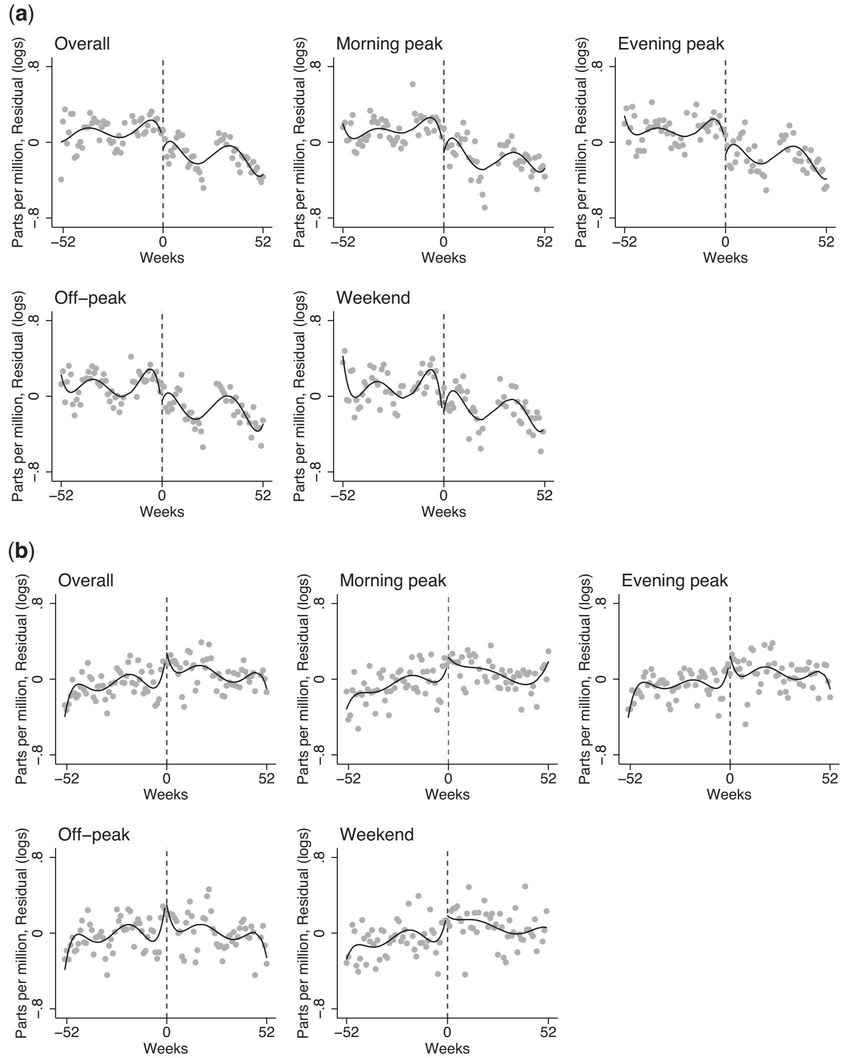
Source: Data from RMCAB. Author's calculations.

Notes: This table shows PYP estimates from five regressions for the moderate restriction (panel (a)) and five regressions for the drastic restriction (panel (b)). The dependent variable is carbon monoxide (CO) in logs. PYP (moderate) is an indicator variable equal to one after August 18, 1998, and zero otherwise. PYP (drastic) is an indicator variable equal to one after February 6, 2009, and zero otherwise. All specifications are fitted along a polynomial time trend of degree five and include meteorological variables, indicator variables for month of the year, day of the week, and hour of the day. Interactions between weekends and hour of the day are added only in the "all hours" model. Standard errors, in parentheses, are robust to heteroscedasticity and arbitrary correlation within one-week clusters. Estimates marked
*$p < 0.10$,
**$p < 0.05$,
***$p < 0.01$.

Intertemporal substitution is also analyzed as in Davis (2008). When comparing the PYP effect between time-interval subsamples of the moderate phase, the effect for off-peak and weekends relative to the evening peak is positive and statistically significant at the 5 percent level. Similarly, relative to the morning peak, the effect for weekends is positive, but the estimate is less precise. In the case of the drastic phase, all

22 Meteorological variable coefficients for the "all hours" model are shown in table S.1 of the supplementary online appendix. Most of these coefficients have the expected signs and are statistically significant. As regards the effect of temperature inversion, in both PYP phases, CO levels were 8 percent higher under these episodes than under normal conditions.

Figure 2. Mean Weekly CO Residuals. (a) two-year window to analyze the moderate restriction: August 18, 1997–August 17, 1999. (b) two-year window to analyze the drastic restriction: February 7, 2008–February 5, 2010



Source: Data from RMCAB. Author's calculations.

the relative effects between time-interval subsamples were statistically insignificant, except the effect for weekends with respect to off-peak, which was also positive. These findings are in line with intertemporal substitution toward the unrestricted driving periods of each PYP phase. As Davis (2008) suggests, it is likely that this inclination to substitute may have occurred also across weekdays, which explains why there is not an absolute decrease in pollutants. Additionally, hypothesis testing was conducted to compare the size of the PYP effects between phases. I was only able to reject the null hypothesis that the drastic-phase impact was lower than or equal to the moderate-phase effect at the 5 percent significance level for the morning peak (see the bottom of table 2). This provides some indication that air quality tended to slightly deteriorate in the period of high travel demand during the drastic restriction relative to the moderate phase. Drivers may also potentially have increased car use. This conjecture is explored in detail in the Transport Costs section. Analyzing the households' behavioral adaptation is relevant as it may explain the lack of evidence of reduced CO in both phases.

Robustness Checks

A potential concern when estimating equation (1) is that the model does not explicitly include explanatory variables that are strongly related to car use. To address this issue, two specifications were included: one accounting for gasoline price and another for the real exchange rate. Furthermore, two additional specifications deal with the possible confounding effect related to the emissions contribution from industrial sources: one pertains to the industrial production index, and the other adds SO_2 as a covariate.[23] Also, the estimations control for a few environmental regulations. A regulation introduced in 1998 established emission standards for new vehicles. Thus, one regression includes a technology indicator variable equal to one from January 1998 and zero otherwise. A similar regulation of emission standards for new vehicles went into effect in 2009; hence, a specification adds a technology indicator variable equal to one from January 2009 and zero otherwise.[24] Because roadwork was intensified during the drastic phase, a regression adding a variable with the annual total roadwork investments is estimated. The sensitivity of the estimates to the time trend and weather polynomial order is also evaluated. Time trend polynomials of sixth and seventh orders and weather quartics (as in Davis 2008) are tested. Due to the concern of collinearity among meteorological variables, which may make the estimates less precise, the model is also estimated replacing the weather covariates with their corresponding principal components. All models in this section address serial correlation.

The PYP coefficients of the moderate and drastic phases for all time slots are shown in tables 3 and 4, respectively. The results for both phases across all specifications remain largely unchanged. There is no evidence of a reduction in CO in any model or phase. As for the moderate phase, none of the coefficients is statistically significant at conventional levels. Regarding the drastic phase, four of the estimations show a positive PYP impact on CO, though the estimates are less precise, as in the main RD results. Finally, to provide a broader evaluation of PYP, equation (1) is also estimated using other pollutants (NO_x, PM_{10}, and SO_2) as outcome variables. Given that these pollutants, unlike CO, are emitted from more varied sources, the estimations are conducted using only data from stations mainly influenced by traffic emissions (table S.2 in the supplementary online appendix). All models show that PYP did not reduce any of those pollutants.

6. Additional Evidence

This analysis aims to shed light on why PYP did not reduce CO by evaluating the effect of PYP on other outcome variables associated with car use: gasoline consumption, vehicle registrations, and vehicle sales.

The Effect of PYP on Gasoline Consumption

When analyzing gasoline consumption, it is important to distinguish the PYP effect from the impact of gasoline prices, as this provides insights about the relative effectiveness of market and nonmarket policies. This analysis utilizes data (January 1996–September 2010) on monthly gasoline consumption (regular and premium) obtained from the Finance Agency of Bogotá, gasoline prices published by Ecopetrol,[25]

23 Gasoline price, real exchange rate, and the industrial production index are in the form of first monthly differences because they are nonstationary in levels. SO_2 is included in lagged form since the use of lags tends to lessen the effect of possible endogeneity.

24 These technology dummies are not included in the original model due to uncertainties regarding whether these regulations were enforced.

25 Monthly prices from 1999 to 2010 were obtained from http://www.ecopetrol.com.co/precios.htm. Information from the digital news archive *El Tiempo* (www.eltiempo.com) was used to fill some gaps in the series. The prices taken from the news corresponded to official prices and matched perfectly the prices for which information from Ecopetrol was also available.

Table 3. Effect of Moderate Restriction on CO Concentration: Robustness Checks

	All hours (1)	Morning peak (2)	Evening peak (3)	Off-peak (4)	Weekends (5)
(a) Specifications with economic variables					
With gasoline prices	−0.017	−0.040	−0.057	0.006	0.051
	(0.057)	(0.065)	(0.068)	(0.074)	(0.117)
With real exchange rate	−0.034	−0.016	−0.100	−0.031	0.051
	(0.069)	(0.072)	(0.087)	(0.100)	(0.133)
(b) Specifications with other controls					
With industrial prod. index	−0.033	−0.057	−0.085	−0.034	0.043
	(0.068)	(0.071)	(0.081)	(0.101)	(0.131)
With SO_2	−0.028	−0.023	−0.075	−0.016	0.032
	(0.067)	(0.066)	(0.075)	(0.095)	(0.129)
With technology regulation	−0.008	−0.037	−0.052	0.007	0.063
	(0.065)	(0.067)	(0.076)	(0.086)	(0.128)
(c) Alternative polynomial orders					
6th-order polynomial	−0.015	−0.026	−0.047	0.018	0.031
	(0.053)	(0.063)	(0.073)	(0.062)	(0.105)
7th-order polynomial	−0.022	−0.059	−0.129	0.027	0.057
	(0.059)	(0.074)	(0.087)	(0.063)	(0.117)
Weather quartics	−0.005	−0.008	−0.052	−0.000	0.086
	(0.065)	(0.064)	(0.075)	(0.088)	(0.129)
(d) Specifications with orthogonal regressors					
With principal components	0.020	0.002	−0.032	0.019	0.064
	(0.069)	(0.070)	(0.077)	(0.089)	(0.128)

Source: Data from RMCAB. Author's calculations.
Notes: This table shows PYP estimates from 45 regressions for the moderate phase. Each estimate reports the PYP coefficient of an alternative specification. The dependent variable is carbon monoxide (CO) in logs. All specifications are fitted along a polynomial time trend of degree five (except for the first two models in panel (c)) and include meteorological variables and indicator variables for month of the year, day of the week, and hour of the day. Interactions between weekends and hour of the day are added only in the "all hours" model. Standard errors, in parentheses, are robust to heteroscedasticity and arbitrary correlation within one-week clusters.

and GDP and total population figures reported by the National Department of Statistics (DANE). The consumption equation is as follows:

$$C_t = \alpha + \pi_1 PYP1_1 + \pi_2 PYP2_t + f(t) + \lambda_1 P_t + \lambda_2 M_t + D_t' \eta + \epsilon_t \quad (2)$$

where C_t is the total gasoline consumption per capita in logs at time t, PYP1 is an indicator variable equal to one from August 1998 to January 2009 and zero otherwise, and PYP2 is an indicator variable equal to one after February 2009 and zero otherwise. P_t is the gasoline price and M_t is the GDP per capita, both in logs at time t. Furthermore, $f(t)$ is a polynomial time trend, $\mathbf{D}_t$ is a group of month-of-year dummies, and ϵ_t is the error term. π_1 and π_2 measure the effect of PYP on consumption. This specification is closely related to the work by Eskeland and Feyzioglu (1997a) for HNC in Mexico City, although the estimation here includes a polynomial time trend to control for unobservables over time. Classical ADF tests indicate that consumption, prices, and GDP are integrated of order one, and the Bayesian information criterion (BIC) suggests that it is sufficient to consider a linear polynomial to adequately describe the underlying trend. The Engle and Granger test applied to the residuals in equation (2) supports that the series are cointegrated; hence, expression (2) provides the long-run elasticities. An error correction model (ECM) is also estimated to explore the short-run relationship. Panel (a) in table 5 shows the results of three alternative specifications of the consumption equation. Column (1) presents the estimates of equation (2) without controlling for seasonality, column (2) adds month-of-year dummies, and column (3) provides the estimates of equation (2) by dynamic ordinary least squares (DOLS). The DOLS estimator has been shown to have better small sample properties than other alternative estimators when estimating cointegration

Table 4. Effect of Drastic Restriction on CO Concentration: Robustness Checks

	All hours (1)	Morning peak (2)	Evening peak (3)	Off-peak (4)	Weekends (5)
(a) Specifications with economic variables					
With gasoline prices	0.128	0.046	0.088	0.106	0.052
	(0.117)	(0.066)	(0.129)	(0.172)	(0.094)
With real exchange rate	0.095	0.136	0.092	0.051	0.054
	(0.099)	(0.090)	(0.125)	(0.133)	(0.099)
(b) Specifications with other controls					
With industrial prod. index	0.173	0.127	0.147	0.158	0.057
	(0.152)	(0.080)	(0.170)	(0.202)	(0.092)
With SO_2	0.168	0.066	0.158	0.159	−0.038
	(0.145)	(0.071)	(0.159)	(0.195)	(0.090)
With technology regulation	0.182	0.128*	0.153	0.171	0.061
	(0.148)	(0.076)	(0.164)	(0.200)	(0.095)
With roadwork investment	0.184	0.130*	0.156	0.174	0.063
	(0.150)	(0.076)	(0.165)	(0.203)	(0.095)
(c) Alternative polynomial orders					
6th-order polynomial	0.152	0.110*	0.128	0.134	0.081
	(0.114)	(0.065)	(0.126)	(0.157)	(0.093)
7th-order polynomial	0.100	0.039	0.058	0.041	0.118
	(0.112)	(0.082)	(0.125)	(0.149)	(0.103)
Weather quartics	0.168	0.120*	0.135	0.152	0.025
	(0.143)	(0.072)	(0.171)	(0.201)	(0.098)
(d) Specifications with orthogonal regressors					
With principal components	0.168	0.072	0.142	0.211	0.049
	(0.140)	(0.084)	(0.166)	(0.167)	(0.125)

Source: Data from RMCAB. Author's calculations.
Notes: This table shows PYP estimates from 50 regressions for the drastic phase. Each estimate reports the PYP coefficient of an alternative specification. The dependent variable is carbon monoxide (CO) in logs. All specifications are fitted along a polynomial time trend of degree five (except for the first two models in panel (c)) and include meteorological variables and indicator variables for month of the year, day of the week, and hour of the day. Interactions between weekends and hour of the day are added only in the "all hours" model. Standard errors, in parentheses, are robust to heteroscedasticity and arbitrary correlation within one-week clusters. Estimates marked
$^{*}p < 0.10$.

relationships (Stock and Watson 1993) such as demand equations.[26] Standard errors in all regressions are estimated taking serial correlation into account.

Across specifications there is no evidence of a decrease in gasoline consumption as a result of PYP during the moderate phase. In contrast, the estimates of the effect of the drastic phase were shown to be positive and statistically different from zero at the 5 percent and 10 percent significance levels in the specifications without seasonal controls and DOLS, respectively. The long-run PYP effect on gasoline consumption during the drastic phase was around 10 percent, though its standard error in one of the regressions tends to be large. Across the three specifications, the estimates are precise enough that, relative to the moderate phase, the PYP effect on gasoline consumption in the drastic phase is positive and statistically significant at the 5 percent level, consistent with an increase in driving for drastic restrictions and the slight CO increase in the morning peak. This finding is also in line with Eskeland and Feyzioglu (1997a), who found that HNC increased car use.

26 It consists of adding lags and leads of the first differences of price and GDP to the model. The DOLS estimator also deals with the concern of potential simultaneity bias among regressors.

Table 5. Effect of Moderate and Drastic Restrictions on Gasoline Consumption

	(1)	(2)	(3)
(a) Long-run equation			
PYP (moderate)	0.005	0.008	0.010
	(0.037)	(0.058)	(0.047)
PYP (drastic)	0.101**	0.093	0.108*
	(0.046)	(0.075)	(0.065)
Log(price)	−0.153	−0.178	−0.122
	(0.140)	(0.143)	(0.140)
Log(GDP per capita)	0.634***	0.650**	0.734**
	(0.093)	(0.301)	(0.286)
Month-of-year dummies	No	Yes	Yes
Lags and leads of first diff. of log(price) and log(GDP per capita)	No	No	Yes
Observations	177	177	176
R^2	0.959	0.973	0.977
(b) Error correction model			
PYP (moderate)	0.002	0.004	0.005
	(0.013)	(0.011)	(0.011)
PYP (drastic)	0.012	0.008	0.009
	(0.022)	(0.019)	(0.019)
First diff. of log(price)	−0.271*	−0.432***	−0.622***
	(0.153)	(0.134)	(0.128)
First diff. of log(GDP per capita)	0.766***	0.505*	0.481*
	(0.076)	(0.263)	(0.263)
$Residual_{t-1}$	−0.310***	−0.278***	−0.274***
	(0.085)	(0.073)	(0.075)
Observations	176	176	176
R^2	0.652	0.813	0.811

Source: Data from Finance Agency of Bogotá, Ecopetrol and DANE. Author's calculations.

Notes: This table shows estimates from three regressions of the long-run equation of gasoline consumption (panel (a)) and three regressions of the associated error correction models (panel (b)) for the period between January 1996 and September 2010. PYP (moderate) is an indicator variable equal to one from August 1998 to January 2009 and zero otherwise. PYP (drastic) is an indicator variable equal to one after February 2009 and zero otherwise. (a) The dependent variable is gasoline consumption per capita in logs. Regressions in columns: (1) excludes month-of-year dummies, (2) adds month-of-year dummies, and (3) corresponds to the DOLS model. All regressions are fitted along a linear time trend. To account for serial correlation, standard errors, in parentheses, are estimated using Newey-West with a four-month lag. (b) The dependent variable is the first difference of gasoline consumption per capita in logs. Columns (1), (2), and (3) correspond to the ECM for regressions in columns (1), (2), and (3) of (a), respectively. $Residual_{t-1}$ is the first lag of the residual estimated from the long-run equation. To account for serial correlation, the ECM in (1)–(3) includes the first lag of the dependent variable, whereas the ECM in (1) also adds the second and 11th lags. Standard errors reported in parentheses. Estimates marked

* $p < 0.10$,

** $p < 0.05$,

*** $p < 0.01$.

The long-run price elasticities oscillate between –0.12 and –0.18, though they are statistically insignificant. The long-run income elasticities vary from 0.63 to 0.73 and are statistically different from zero at conventional significance levels. These values are in the range of the elasticities reported by Dahl (2012)—between –0.04 and –0.69 for price and between 0.23 and 2.06 for income—using studies from 124 countries varying in scope and methodology.

In contrast, the estimates of the ECM analysis show that neither the moderate nor the drastic phase of PYP led to short-run reductions in gasoline consumption for any of the specifications (panel (b) in table 5). This result is supported by the lack of evidence of reduced CO across all time-interval subsamples in both phases of the program and by the magnitude of the monthly rate of adjustment of gasoline consumption toward the long-run equilibrium—for example, between 27 percent and 31 percent of the adjustments happen in the first month. As regards the elasticities, the price elasticity estimates show a higher response of the gasoline demand to pricing in the short run than in the long run. Eskeland and Feyzioglu (1997b), who studied the gasoline demand in Mexico, found results in the same direction.

Considering that gasoline consumption is responsive to prices in the short run and that the monthly gasoline demand in Bogotá decreased from 42 to 24 million gallons from 1996 to 2008, it seems reasonable that gasoline prices were responsible for some fraction of that decline right after a price increase. Thus, in some way, prices rather than PYP have tended to discourage driving. However, the fact that the elasticities are small limits the use of taxes as an effective tool to substantially reduce consumption. Taxes are also considered a blunt instrument as they disregard where and at what time of the day the driving occurs. In contrast, congestion tolls, which have been shown to be effective in dealing with congestion and pollution (see Börjesson et al. 2012; Coria et al. 2015) and more efficient than gasoline taxes (Parry 2002), can be spatially and temporally differentiated, charging driving on the most congested roads and during peak hours. Clearly congestion charges would be an alternative mechanism to achieve the goals that did not occur with PYP.

The Effect of PYP on Vehicle Registrations and Vehicle Sales

The lack of evidence of a decrease in CO levels in both PYP phases might be explained by an expansion in the vehicle stock or in the number of trips made. One way to analyze this type of behavioral response is to evaluate possible increases in the number of registered vehicles and sales of new cars due to the program. Data on monthly vehicle registrations (January 1997–November 2010) from the Transport Agency of Bogotá, and on new vehicle sales (July 2000–September 2011) from Econometria S.A., are used to evaluate this effect. The model for vehicle registrations can be represented as:

$$V_t = \alpha + \omega_1 PYP1_t + \omega_2 PYP2_t + f(t) + \mathrm{V}'_{t-j}\varphi + \mathrm{D}'_t\eta + u_t, \tag{3}$$

where V_t is vehicle registrations in logs at period t, $\mathbf{V}_{t-j}$ is a set of lags of the dependent variable, u_t is the error term, and other variables are as described above[27]. ω_1 and ω_2 measure the effect of PYP on vehicle registrations. Classical ADF tests indicate nonstationarity of the registered regular cars and private vehicles. Hence, the dependent variable is the first difference of monthly vehicle registrations. Using BIC, the identified model includes the first, second, and 12th autoregressive lags, as well as a quadratic time trend. Adding lags of the dependent variable also accounts for serial correlation.

Equation (3) is estimated for regular cars and all private vehicle registrations, controlling for seasonal variation (table 6, panel (a), see columns (1) and (2)). In both specifications, the PYP effects for the moderate phase are positive but statistically insignificant. Interestingly, the PYP estimates for the drastic phase, besides being positive, are statistically different from zero at the 5 percent and 10 percent significance levels for regular and all private vehicle registrations models, respectively. The size of the long-run estimates for this phase is around 10 percent, though this estimate is less precise for the specification that includes all private vehicles. Relative to the moderate restriction, the long-run PYP effect was positive and statistically significant at the 10 percent level in both specifications. This provides mild evidence of an increase in vehicle registrations during the drastic restriction, which is also consistent with no decrease in CO and the slight indication of increased CO for the morning peak in the same phase. The estimates are in between the vehicle stock increases reported by Davis (2008) for HNC in Mexico City (19 percent) and Gallego, Montero, and Salas (2013) for TS in Santiago (8 percent). As a robustness check, the effect of the program on load vehicle (truck) registrations is tested using a similar model. These vehicles were not restricted by the program, and one might expect that PYP did not affect load vehicle registrations (see column (3) in panel (a) of table 6). Indeed, neither the moderate nor the drastic phase of the program influenced the number of truck registrations.

27 Due to lack of data, the model does not control for vehicle registration fees.

Table 6. Effect of Moderate and Drastic Restrictions on Vehicle Registrations and Sales

	Regular cars	Private vehicles	Load vehicles
	(1)	(2)	(3)
(a) Vehicle registrations			
PYP (moderate)	0.057	0.061	−0.262
	(0.080)	(0.075)	(0.292)
PYP (drastic)	0.184**	0.168*	0.065
	(0.092)	(0.086)	(0.330)
Long-run PYP (moderate)	0.034	0.036	−0.139
	(0.048)	(0.045)	(0.154)
Long-run PYP (drastic)	0.111**	0.100*	0.035
	(0.055)	(0.051)	(0.175)
Observations	154	154	154
R^2	0.73	0.77	0.37

	Bogotá OLS	Bogotá OLS	Bogotá 2SLS	Other cities OLS	Other cities OLS	Other cities 2SLS
	(1)	(2)	(3)	(4)	(5)	(6)
(b) Vehicle sales (regular cars)						
PYP (drastic)	0.096*	0.143***	0.166*	0.029	0.025	0.091
	(0.050)	(0.051)	(0.094)	(0.061)	(0.064)	(0.123)
GDP growth rate	0.000			0.009		
	(0.006)			(0.007)		
Price index		−0.726**	−1.068		0.311	−0.752
		(0.295)	(1.293)		(0.371)	(1.735)
Long-run PYP (drastic)	0.055*	0.081***	0.093*	0.022	0.019	0.069
	(0.028)	(0.029)	(0.051)	(0.045)	(0.048)	(0.094)
Observations	132	132	132	132	132	132
R^2	0.50	0.53	0.52	0.42	0.41	0.37

Source: Data from Transport Agency of Bogotá and Econometria S.A. Author's calculations.

Notes: Panel (a) shows PYP estimates from three regressions for the period 1997–2010. The dependent variable is the first difference of monthly vehicle registrations in logs. "Regular cars" includes only regular cars. "Private vehicles" includes regular cars, station wagons, and sport utility vehicles. "Load vehicles" are trucks. PYP (moderate) is an indicator variable equal to one from August 1998 to January 2009 and zero otherwise. PYP (drastic) is an indicator variable equal to one after February 2009 and zero otherwise. All regressions are fitted along a quadratic time trend. To account for serial correlation, all specifications include the first, second, and 12th lag of the dependent variable. Panel (b) shows PYP estimates from six regressions for the period July 2000–September 2011. The dependent variable is the first difference of monthly vehicle sales (regular cars) in logs. Columns (1)–(3) are specifications using data for Bogotá, while columns (4)–(6) employ data from other cities without restrictions. All regressions are fitted along a quadratic time trend. To account for serial correlation, all specifications include the first and second lags of the dependent variable. Standard errors in parentheses. Estimates marked

*$p < 0.10$,

**$p < 0.05$,

***$p < 0.01$.

Vehicle ownership does not seem to have been affected by the moderate ban. One potential explanation for this is that households may not have been inclined to own additional vehicles because they could still drive without restrictions during off-peak hours. During the moderate phase, households did not have prior experience with the program and hence a precautionary attitude may have been to wait until the mayor announced PYP as a permanent policy and explore other adaptation mechanisms before increasing their car stock. For example, in this phase there was some evidence of intertemporal substitution between restricted and unrestricted hours, indicating that some households reallocated trips. Regarding enforcement, although it has been considered satisfactory, there are indications of weak monitoring in the moderate phase. According to Acevedo (1998), there were too few police officers involved in the PYP enforcement (1,050 in total, of whom only 150 were motor officers), which may have affected compliance.[28] Also, drivers may have found routes where the probability of being caught in violation was very low. A newspaper reported that drivers were choosing secondary roads to avoid police controls and that some police officers had to focus on tasks unrelated to PYP enforcement, reducing the coverage in several areas (Nullvalue 1998).

Additionally, the following model is used to evaluate the effect of PYP on new sales:

$$S_t = \alpha + \rho PYP2_t + f(t) + S'_{t-j}\mu + \lambda R_t + D'_t\eta + \epsilon_t, \tag{4}$$

where S_t is monthly new regular car sales in logs at time t, S_{t-j} is a set of lags of the dependent variable, R_t is GDP growth rate in logs at time t, ϵ_t is the error term, and other variables are as above. ρ is the effect of PYP on new regular car sales in the drastic phase. The data span from July 2000 to September 2011, and, due to the lack of pre-2000 sales data, the moderate phase cannot be assessed. The GDP growth rate is included in the estimations as vehicle sales may be affected by the economy's performance. The variables exhibit nonstationarity and seasonality and appear not to be cointegrated under the Engel and Granger test. Thus, the variables are in first differences. BIC indicates that it is sufficient to include two autoregressive terms and a quadratic time trend. The added lags of the dependent variable also account for serial correlation.

Panel (b) of table 6 shows the estimates of equation (4) including GDP growth rate, adding a vehicle price index, and conducting two-stage least squares (2SLS) (see columns (1), (2), and (3), respectively). Although vehicle prices were not available, a price index was created using the ratio of the total monetary value of sales in the country to the total number of new regular car sales.[29] A possible concern when constructing the price index is that it might be endogenous as sales in Bogotá represent almost 50 percent of the total sales in Colombia. To address this issue, 2SLS is estimated by instrumenting the price index with the real exchange rate.[30] Across the three specifications, the short- and long-run effects of PYP2 were positive and statistically significant at the 10 percent level. The long-run estimates range from 5.5 percent to 9.3 percent, though two out of three of these estimates are less precise. This mild evidence of a growth rate increase in regular car sales relative to the moderate restriction is compatible with the results for vehicle registrations. As a robustness check, equation (4) is run for regular car sales in other Colombian cities. Since some cities had already implemented driving restrictions, sales in those cities had probably also increased as a consequence; hence, the simultaneous effect of other restrictions may yield misleading estimates. Therefore, the model is run for the aggregated regular car sales excluding those cities. Columns (4), (5), and (6) of panel (b) in table 6 present the results. The short- and long-run coefficients of PYP in those estimations are statistically insignificant, supporting the fact that the changes should have occurred in Bogotá at the time the program was implemented.

Official statistics indicate that although the number of households in Bogotá increased from 2008 to 2010, the fraction owning a car remained constant (22 percent).[31] The number of new households owning a car in 2010 was only 20 percent of the total new car sales in that year, suggesting that some households that already owned a car may have acquired a new vehicle. This is consistent with the results from other studies for HNC, where the households' strategy was to acquire a second or third car (see Eskeland and Feyzioglu 1997a; Davis 2008; Gallego, Montero, and Salas 2013). Another question that arises is how in

28 Enforcement was mainly in the hands of the motor officers (*caza – infractores*), who patrolled the major city corridors. The other 900 police officers standing in the roads could only marginally support the motor officers' work as their main job was to focus on bottlenecks in traffic. When a driver was caught in violation by any of these officers, the driver was stopped and directed to a secondary road to receive the fine. According to the Metropolitan Police's organizational structure, the police functions are separated; hence police officers not tasked with improving transit were not involved in PYP enforcement.

29 Information on these variables and GDP growth was obtained from DANE.

30 The first-stage equation indicates that the instrument is relevant at the 5 percent significance level.

31 Data accessed from DANE. Encuesta Nacional de Calidad de Vida 2008 and 2010.

practice a household can avoid the restriction by buying a new car. Not surprisingly, drivers can easily find the license plate number of their choice in the market. Car dealers buy a group of license plate numbers, which are pre-allocated by the Transport Agency of Bogotá. Although car dealers are not allowed to choose the plate numbers systematically, customers are able to choose, implying an opportunity to avoid PYP.

Furthermore, relative to the moderate phase, it is unlikely that the slight indication of increased vehicle sales in the drastic phase alone explains the increase in gasoline consumption and CO levels during the morning peak. New cars generally have a TWC, removing a large fraction of CO emissions. Thus, the effect of the new vehicles on CO might be limited, unless accompanied by an increase in the number of trips. On the one hand, gasoline consumption in the drastic phase appears to have increased, indicating that households with either new or used vehicles tended to increase their vehicle use. A second car usually brings additional use; this not only substitutes the restricted trips but also expands the possibility of using the entire car capacity for other purposes. On the other hand, used cars tend to be less fuel-efficient and more polluting than new ones.[32] In Bogotá, the lifetime of the TWC has already expired for some used cars, and more than 50 percent of the regular cars do not have a TWC. Thus, the use of old cars may have contributed to the lack of decline in CO for a given total stock of cars.

7. Transport Costs

Here I provide some calculations of the transport costs imposed by PYP. As Davis (2008) indicates, one might consider a model that takes into account people's transportation choice set to analyze the costs induced by suboptimal choices due to driving restrictions. In that model, individuals derive utility from air quality, a nonpolluting composite consumption good, and transportation goods. Under the assumption that the marginal utility of the composite good is constant, the social costs imposed by the program would be equal to the willingness to pay (WTP) to avoid the restriction (see Davis 2008). WTP values are not available for Bogotá, but recently, Blackman et al. (2015) used contingent valuation to obtain the WTP for being exempt from HNC in Mexico. Analogous to the benefit transfer approach, I used Blackman et al.'s WTP values to estimate the driving restriction costs of the drastic PYP phase. Costs are not computed for the moderate phase as Blackman et al.'s estimates were obtained in 2013 when HNC had been in force for many years—that is, WTP is conditional on households' past adaptation investments. This setting is much closer to the drastic phase as households already had some experience facing restrictions.

Blackman et al. (2015) found that the median annual WTP for an exemption from HNC was equivalent to US$103 per vehicle. This value reflects the households' costs associated with changes in travel behavior and vehicle ownership that result from limiting the transportation choice set due to HNC.[33] It is an unconditional measure of the cost of being exempt from the policy, that is, it takes respondents with positive and zero WTP into account. To estimate the PYP costs, I divide this value by the annual number of restricted days in Mexico (64) and then multiply by the ratio of GDP per capita based on purchasing power parity between Colombia and Mexico (0.78).[34] This yields a daily PYP cost of US$1.26 (COP$2,432) at 2013 prices. The annual figure, that is, the daily value multiplied by the number of days that the restriction applied in Bogotá (104), is US$131.25 (COP$252,905) per vehicle per year, or roughly 2 percent of the income per capita. Considering that the vehicle fleet after the implementation of the drastic phase was around 1 million cars, the total annual cost in Bogotá reaches US$131.25 million (COP$0.253 billion).

32 Basic statistics reported by Secretaría de Movilidad (2009) show that used vehicle sales increased four times more in the first month of the drastic phase than in the same month in the preceding year.

33 Blackman et al. (2015) provided examples of those changes: reducing or rescheduling driving, increasing travel by other modes, and buying a second car, among other household decisions.

34 Data accessed from http://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD.

This cost is about 15 percent of the total governmental budget of the Transport Agency in Bogotá in 2013.[35] Although these costs are only an approximate measure, the exercise suggests that PYP imposed considerable costs on drivers.

It is worth pointing out that these welfare losses are lower bound costs since other effects, for example, enforcement costs and impacts on commerce and labor, are not considered in the present analysis. These issues are outside the scope of this study but may increase the overall costs of the program.

8. Summary and Conclusions

Driving restrictions have been used in several cities around the world to deal with traffic congestion and air pollution. This study contrasts previous studies evaluating programs implemented in a drastic fashion by assessing the effects of shifting the regulation from moderate to drastic restrictions on car use and air quality. Neither moderate nor drastic restrictions in Bogotá were shown to be effective in improving air quality. Rather, it appears that the most stringent phase of the program may have induced more driving. Relative to moderate restrictions, the drastic phase tended to slightly increase gasoline consumption, vehicle stock, and CO concentrations in the morning peak. Households seem to be responsive to drastic restrictions, finding alternative ways to avoid the ban. These programs, besides being ineffective, were inefficient as they affected many households by increasing their commuting costs. This study questions the rationale for extending the program to other cities or making it more stringent.

Other instruments with the same aims as the PYP program need to be explored. Road tolls have effectively been used in other cities to ration the scarce road infrastructure and deal with pollution externalities. The charged fees depend on the time of day and are higher during congestion-prone times. Remarkably, evidence for Stockholm shows that the fee elasticity of car use is greater in the long run, implying that the effect of the fee does not vanish over time (Börjesson et al. 2012). In addition, the collected fee revenues may be used to finance infrastructure. Moreover, given that driving is associated with other pollutants, the decrease in vehicle traffic has other positive effects, including a reduced climate impact. Bogotá might benefit from the lessons learned from these instruments. A simulation study would be useful to quantify the impact of congestion charges in Bogotá on traffic and air quality.

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