# The Effect of Driving Restrictions on Air Quality in Mexico City

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In 1989, the government of Mexico City introduced a program, *Hoy No Circula*, that bans most drivers from using their vehicles one weekday per week on the basis of the last digit of the vehicle's license plate. This article measures the effect of the driving restrictions on air quality using high-frequency measures from monitoring stations. Across pollutants and specifications there is no evidence that the restrictions have improved air quality. Evidence from additional sources indicates that the restrictions led to an increase in the total number of vehicles in circulation as well as a change in composition toward high-emissions vehicles.

## I. Introduction

Whereas U.S. cities have seen dramatic improvements in air quality over the last three decades,[1] Mexico City has been considerably less successful. Levels of major air pollutants in Mexico City routinely exceed maximum exposure limits established by the World Health Organization (WHO). For example, the WHO (2005) has warned that 8-hour average ozone levels exceeding 100 micrograms per cubic meter threaten hu-

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[1] According to the U.S. Environmental Protection Agency (EPA 2003), between 1970 and 2002, emissions of nitrogen dioxide, ozone, sulfur dioxide, particulate matter, carbon monoxide, and lead in the United States decreased by an average of 48 percent.

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man health. During the period 1986–2005, this guideline was exceeded in Mexico City for 92 percent of all days.

A large literature documents the social cost of air pollution (e.g., Dockery et al. 1993; Pope et al. 1995; Chay and Greenstone 2005). Airborne pollutants have been linked to respiratory infections, chronic respiratory illness, and aggravation of existing cardiovascular disease. Some of the most convincing evidence of health effects comes from studies that have examined infant mortality. Chay and Greenstone (2003) and Currie and Neidell (2005) find significant effects of air pollution on infant mortality using variation in air pollution during the 1981–82 recession and in California during the 1990s, respectively. The total social cost of air pollution is likely even larger because of the changes in behavior undertaken to reduce exposure (Neidell 2007). In Mexico City such changes in behavior are widespread. For example, most residents of Mexico City avoid outdoor activity during periods of low air quality.

Record levels of ozone and other airborne pollutants led the Mexico City government on November 20, 1989, to introduce a program, *Hoy No Circula* (HNC), which bans most drivers from using their vehicles one weekday per week on the basis of the last digit of the vehicle's license plate. For example, vehicles with a license plate ending in 5 or 6 may not be used on Mondays. The restrictions are in place during weekdays between 5:00 a.m. and 10:00 p.m. and affect the vast majority of residential and commercial vehicles. Taxis, buses, police cars, ambulances, fire trucks, commercial vehicles operating with liquid propane gas, and commercial vehicles transporting perishable goods are exempt.[2] The restrictions apply to the entire Mexico City metropolitan area, hereafter "Mexico City," which includes Mexico City and municipalities in neighboring states. When imposed in 1989, the restrictions applied to 2.3 million vehicles, or 460,000 vehicles per day.

Compliance with the program is near universal. Since the first day the restrictions were implemented they have been enforced vigorously by the city police.[3] One of the advantages of basing the restrictions on license plates is that vehicles violating the ban are easy to spot. Mexican

[2] See Gobierno del Distrito Federal, Secretaría del Medio Ambiente (2004*a*) for a detailed history of the program. Modifications to the program in 1997 and 2004 have made certain additional low-emissions vehicles exempt from the restrictions and removed exemptions for some taxis and buses.

[3] In the days immediately following the implementation of HNC the media coverage focused on the large number of vehicles being impounded, the amount of money generated by fines, and the capacity of Mexico City facilities to handle additional impounded vehicles. Articles from *La Jornada* include "Ocho mil vehículos detenidos en la primera jornada de Hoy No Circula" (November 21); "Funciona el programa Hoy No Circula, asegura Camacho Solís" (November 22); "489 autos, al corralón por circular con engomado verde" (November 24); and "Espera recaudar el DDF, 710 mil millones en una semana" (November 26).

law stipulates that vehicles that violate the ban are to be impounded for 48 hours and their owners are to pay a fine equivalent to US$200.[4] Often these penalties can be avoided by paying a bribe to the police officers involved, though bribes are expensive and the large police presence in Mexico City means that one may need to pay many bribes in order to complete a short trip. In practice, these costs are large enough to have convinced most drivers to leave their automobiles at home on the days they are banned from driving.

This article measures the effect of HNC on air quality using hourly air pollution records from monitoring stations. Pollution levels are compared before and after the restrictions for five major pollutants, with levels in previous years acting as a comparison group to control for seasonal variation. The analysis controls for possible confounding factors by restricting the sample to a relatively narrow time window around the implementation of HNC and by using a regression discontinuity design. Across pollutants and specifications there is no evidence that the program has improved air quality. There is evidence that weekend and late night air pollution increased relative to weekdays, consistent with intertemporal substitution toward hours when HNC is not in place. However, there is no evidence of an absolute improvement in air quality during any period of the week for any pollutant.

Driving restrictions have been studied in the past (Levinson and Shetty 1992; Goddard 1997; Molina and Molina 2002), but this is one of the first attempts to provide empirical evidence. One exception is the study by Eskeland and Feyzioglu (1997), who examine gasoline sales and vehicle registrations in Mexico City during the period 1984–93. This article revisits the evidence on gasoline sales and vehicle registrations using a regression discontinuity specification to control for omitted time-varying factors and a number of additional refinements. Similar methods are then applied to examine bus ridership, subway ridership, taxi registrations, and advertised prices for used taxis and transit vans. While it was hoped that the program would cause drivers to substitute to low-emissions forms of transportation, there is no evidence of a decrease in gasoline sales or an increase in public transportation use. Instead, the evidence indicates that HNC led to an increase in the total number of vehicles in circulation as well as a change in the composition of vehicles toward high-emissions vehicles.

This analysis is relevant to current environmental policy in Mexico City. Air quality remains a severe problem in Mexico City, with ozone levels exceeding WHO standards for 79 percent of all days in 2005. HNC remains in place, and there is currently a high-profile discussion about whether or not to expand the HNC restrictions to include Saturdays.

[4] Dollar values throughout the article have been deflated to reflect year 2006 prices.

Some see HNC as the central component of Mexico City's strategy for addressing air pollution, whereas others would like to phase out HNC and replace it with other forms of pollution control. Reliable estimates of the effect of HNC on air pollution are necessary for evaluating these alternatives.

More generally, the analysis has implications for air quality and transportation policies throughout the urban developing world. According to the World Bank (2003, 168), the 10 cities with the highest average levels of airborne particulates are all in the developing world. Trends in population and vehicle growth in these urban areas threaten to exacerbate these problems.[5] Driving restrictions are one of the tools available to policy makers as they confront this growing problem. Indeed, since HNC was implemented, similar programs have been implemented such as *pico y placa* in Bogota, *restricción vehicular* in Santiago, and *rodízio* in São Paolo. In total, over 50 million people live in cities with driving restrictions based on license plates. Driving restrictions may seem like a sensible alternative because they are relatively inexpensive to enforce and require substantially smaller public investment than some alternative policies. However, it is important to have reliable empirical estimates of the impact of these policies and the substitution patterns that they induce in order to evaluate their cost-effectiveness.

## II. Measuring Air Quality in Mexico City

Air quality in Mexico City is recorded by the Automated Environmental Monitoring Network maintained by the city environmental agency. Established in 1986, the network consists of monitoring stations distributed throughout Mexico City.[6] The network reports hourly measures of carbon monoxide, nitrogen dioxide, ozone, nitrogen oxides, and sulfur dioxide. These measures are widely used in scientific publications and are reported to the public in the form of the Metropolitan Air Quality Index.

Figure 1 plots average daily pollution levels during the period 1986–2005. Average daily pollution levels were constructed by averaging over

[5] Between 2000 and 2030 the number of people living in cities in less developed countries is forecast to increase by 1.96 billion. This represents 97 percent of the projected global population increase during this period. See UN Population Division (2004) for more information.

[6] Station locations in the network (Red Automática de Monitoreo Ambiental) were determined by Mexico City's Environmental Agency (Secretaría del Medio Ambiente) and are intended to reflect a representative sample of neighborhoods in Mexico City. The stations have been extensively tested and are certified annually by the U.S. EPA. The EPA certification includes testing of measurement procedures and comparisons against mobile EPA equipment. The stations are located away from direct emission sources, and measurements are believed to be highly accurate, particularly for ozone (within 3 percent). See Molina and Molina (2002) for more information about the accuracy of the network.

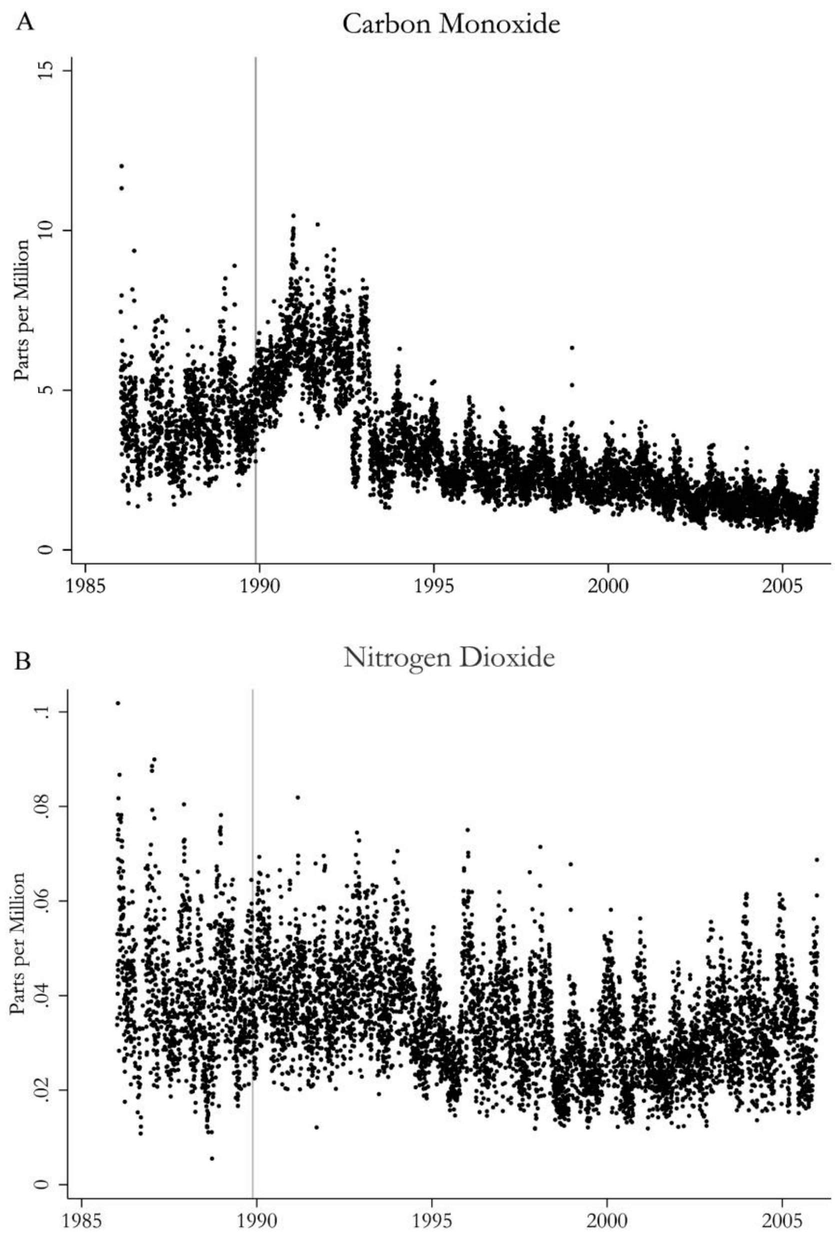
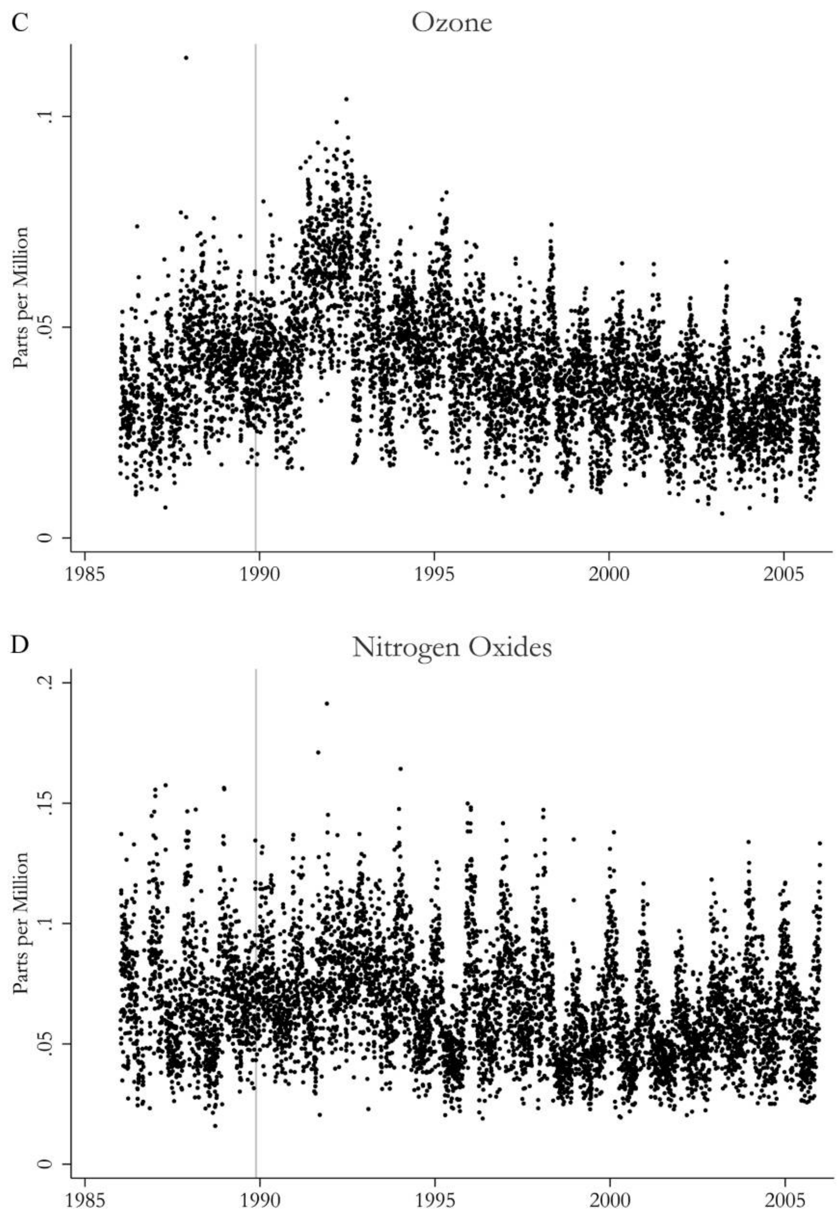



Fig. 1.—Air quality in Mexico City, 1986–2005

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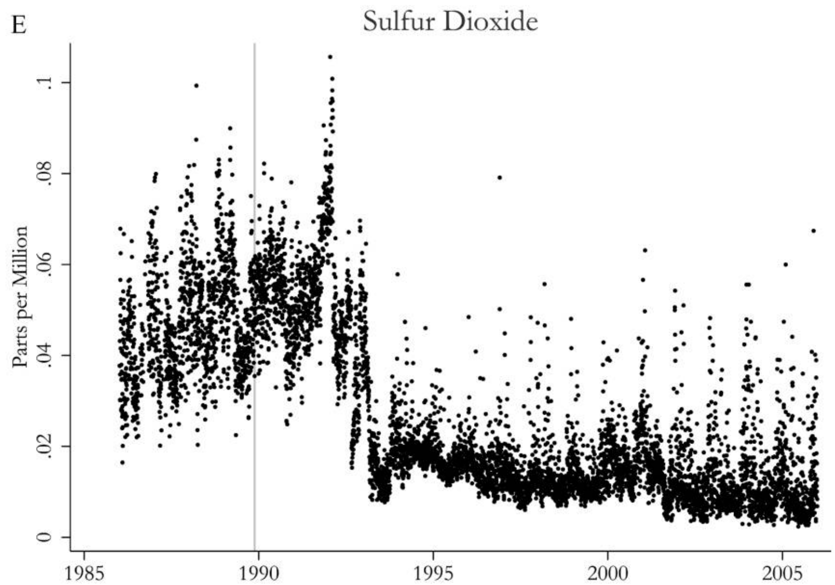



FIG. 1.—*Continued*

all hours of the day and all monitoring stations. Carbon monoxide and ozone levels increase and then decrease in the early 1990s. Levels of nitrogen dioxide and nitrogen oxides vary widely across days but exhibit no discernible long-term pattern. Sulfur dioxide levels decrease in the mid 1990s and then remain low.[7] The vertical line indicates the implementation of HNC on November 20, 1989. There is no visible decrease in air pollution that coincides with the implementation of HNC for any of the five pollutants.

The empirical analysis focuses on the period 1986–93, an 8-year window around the implementation of HNC and the largest available symmetric window. Table 1 describes pollution levels during this period, as well as temperature, humidity, and wind speed, collected by the same network used to monitor air quality. The number of monitoring stations varies across pollutants. In 1986, there were 15 stations for carbon monoxide and sulfur dioxide, nine stations for ozone, and five stations for nitrogen dioxide and nitrogen oxides. The sample is restricted to observations from stations that were operating in 1986. Although a few

[7] The decrease in sulfur dioxide during this period is widely attributed to reductions in the sulfur content of diesel fuel and heavy oil. Lacasaña, Aguilar-Garduño, and Romieu (1998) report that beginning in 1991 the use of fuel with sulfur content above 2 percent was prohibited. Their article describes annual pollution levels in Mexico City, Santiago, and São Paolo over the period 1988–95.

TABLE 1
Air Quality in Mexico City 1986–1993: Summary Statistics

| | Observations | Mean | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|---|
| Carbon monoxide | 690,644 | 4.78 | (3.41) | .100 | 50.0 |
| Nitrogen dioxide | 235,860 | .042 | (.027) | .001 | .460 |
| Ozone | 412,403 | .047 | (.044) | .001 | .500 |
| Nitrogen oxides | 227,421 | .075 | (.060) | .001 | .590 |
| Sulfur dioxide | 641,439 | .046 | (.035) | .001 | .846 |
| Temperature (Celsius) | 511,037 | 16.0 | (5.00) | .100 | 49.2 |
| Humidity | 437,449 | 48.8 | (22.8) | .050 | 102.4 |
| Wind speed (km/hour) | 233,439 | 5.91 | (3.89) | .016 | 97.4 |

Note.—Pollutant levels are reported in parts per million.

additional stations were added to the network in 1993, the sample is restricted to exclude observations from these stations to prevent compositional changes from biasing the results. No stations closed or were moved between 1986 and 1993.[8]

Figure 2 plots pollution levels across hours of the day. The figure, constructed using all observations from 1988, reveals substantial variation in pollution levels over the course of the day, with peak levels reached during the morning commute.[9] The rapid changes over the course of the day indicate that air quality in Mexico City responds quickly to changes in emissions. This is important in the empirical analysis because it means that it is possible to make inferences about changes in emissions by comparing air pollution levels within a relatively narrow time window. The average wind velocity in Mexico City reported in table 1 is 6 kilometers per hour. At this speed pollutants do not typically remain in the Mexico City atmosphere for more than 24 hours.

Vehicle emissions are overwhelmingly the primary source of air pollution in Mexico City. According to a recent emissions inventory (Gobierno del Distrito Federal, Secretaría del Medio Ambiente 2004*b*), vehicles are responsible for 99 percent of the carbon monoxide, 81 percent of the nitrogen oxides, 46 percent of the volatile organic compounds (a precursor to ozone), and 30 percent of the sulfur dioxide in the Mexico City atmosphere. Using this inventory, a report from Mexico

[8] Between 1986 and 1993, missing observations were identified using a zero, making it impossible to distinguish between missing variables and true zero measures. Fortunately, the magnitude of the bias introduced by treating all zeros as missing is likely to be small because there are few true zero measures for any pollutant. This can be verified empirically because starting in 1994 a change in procedure led missing observations to be identified using −99.99 rather than zero. Examining the histogram for each pollutant in 1994 shows that there are very few observations close to zero, and only 1.3 percent of observations are true zeros.

[9] Ozone levels follow a somewhat different pattern, peaking later in the day. Ozone levels tend to be high during the middle of the day because ozone production requires warmth and sunlight. See Seinfeld and Pandis (1998).

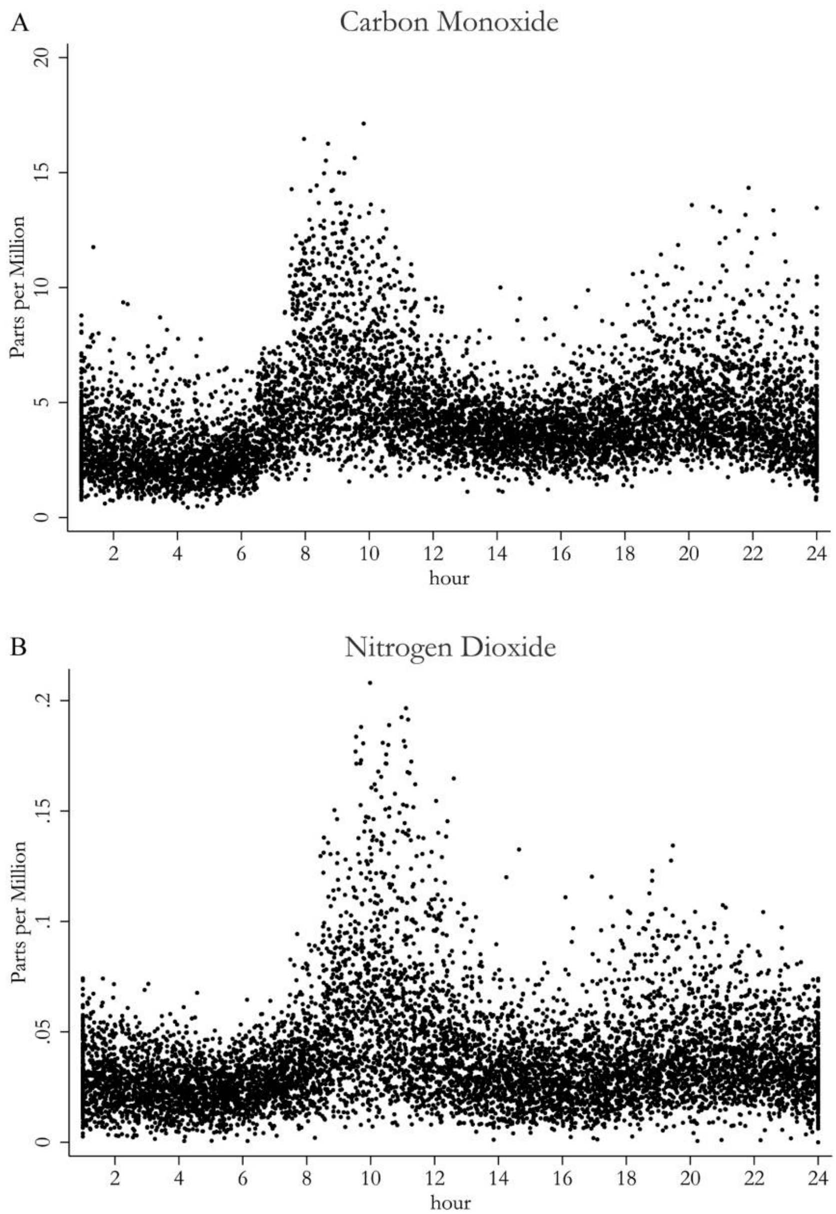
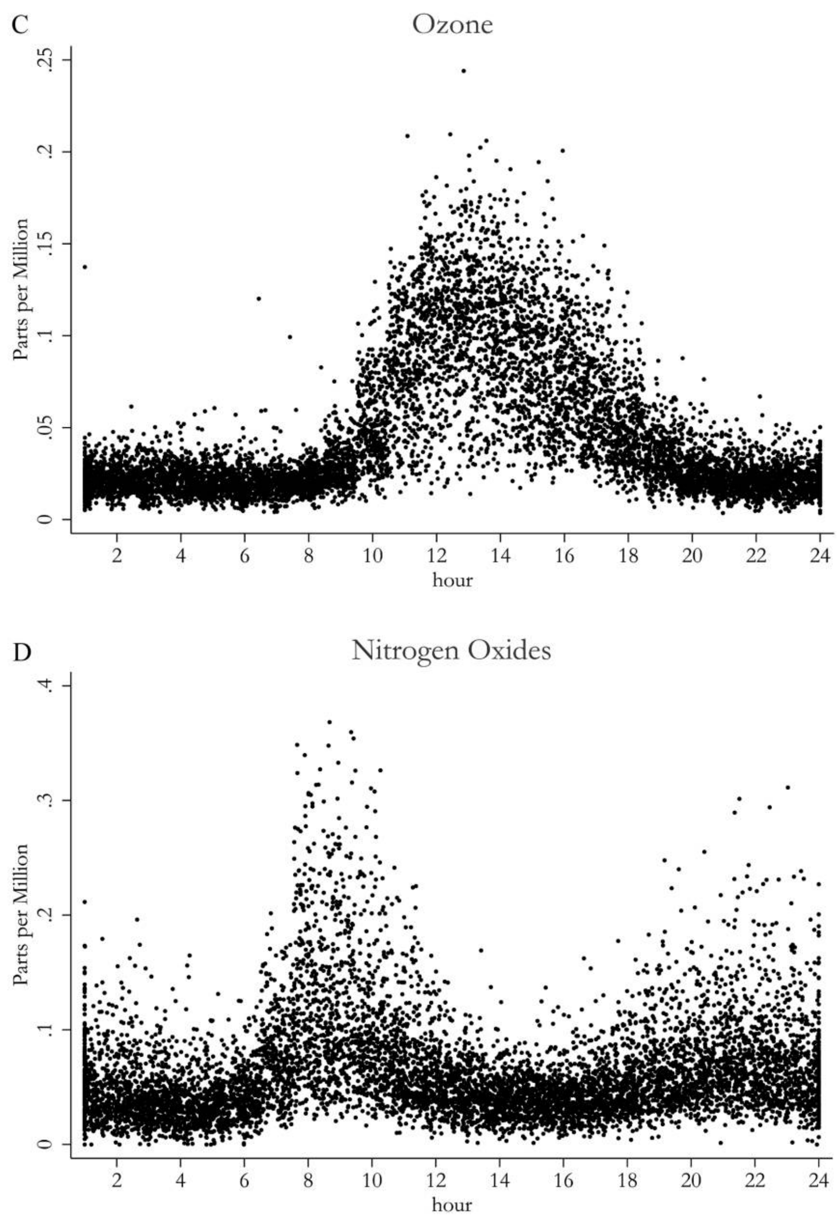



Fig. 2.—Daily pattern of air quality in Mexico City

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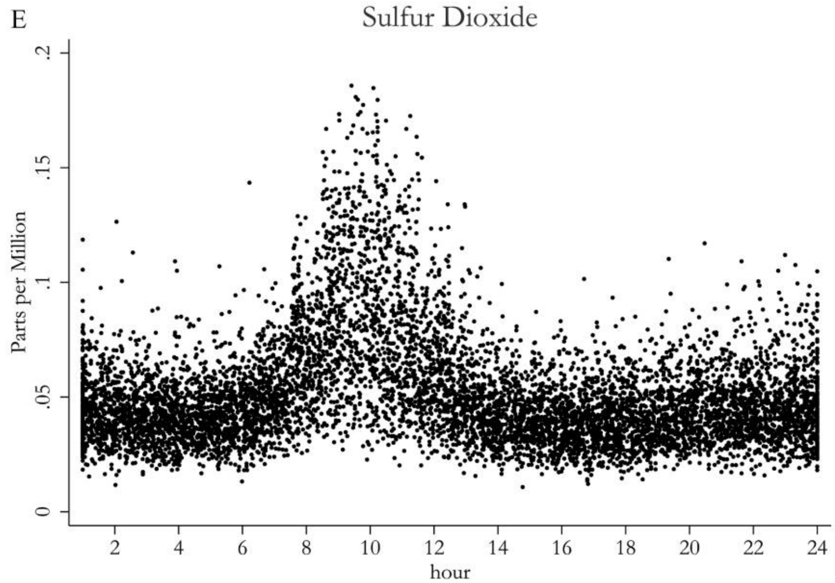



FIG. 2.—*Continued*

City's environmental agency (Gobierno del Distrito Federal, Secretaría del Medio Ambiente 2004*a*) claims that HNC has decreased monthly emissions by 30 million tons. However, this calculation assumes that HNC led to a 20 percent decrease in weekday vehicle emissions. If there have been behavioral adaptations to HNC, such as intertemporal substitution, this 20 percent assumption may not be reasonable. The following section describes the strategy used to estimate the effect of HNC on air quality empirically.

## III. The Effect of HNC on Air Quality

### A. *Empirical Strategy*

In the main specification, average hourly air pollution in logs, $y_t$, is regressed on $1(\text{HNC})$, an indicator variable for observations after the implementation of driving restrictions, and a vector of covariates $x_t$:

$$y_t = \gamma_0 + \gamma_1 1(\text{HNC}_t) + \gamma_2 x_t + u_t. \tag{1}$$

The coefficient of interest, $\gamma_1$, is the percentage effect of HNC on air pollution. The vector of covariates, $x_t$, includes indicator variables for month of the year, day of the week, and hour of the day as well as interactions between weekends and hour of the day. In addition, $x_t$

includes weather variables including current and 1-hour lags of quartics in temperature, humidity, and wind speed.[10]

Equation (1) is first estimated using ordinary least squares (OLS) for four different time windows ranging from 1986–93 to 1989–90. Windows smaller than 2 years are not considered because it becomes difficult to credibly control for seasonal variation. Limiting the sample to include observations from a relatively narrow range of dates is important because it helps disentangle the effect of HNC from the effect of other time-varying factors that influence air quality in Mexico City. For example, beginning in 1994 Mexico made a substantial change in emissions standards for new vehicles, requiring all new vehicles to meet U.S. emissions standards. This and other potential confounding factors make observations substantially after the implementation of HNC less informative about the effect of HNC on air quality. However, even within a relatively narrow time window, there are unobserved factors that are changing over time. The concern with estimating equation (1) using OLS is that these variables may cause $u$ to be correlated with time, and thus with 1(HNC), producing biased estimates of $\gamma_1$. These confounding factors can be addressed using a regression discontinuity (RD) design.[11] The RD design addresses this endogeneity by considering an arbitrarily narrow window of time around the implementation of HNC. Within this interval, the unobserved factors influencing air quality are likely to be similar so that observations before HNC provide a comparison group for observations after HNC.[12] Thus equation (1) is also estimated using

[10] It is important to control for month of the year and weather because there is a pronounced seasonal pattern to air quality. Mexico City is located in a valley surrounded by mountains that rise 1,000 meters from the valley floor. These mountain ridges exacerbate problems with air quality because they inhibit the horizontal movement of pollutants out of the city. In the summer this is less of a problem because the sun warms surface air, causing it to rise, carrying pollutants up and out of the city. In the winter, however, the sun provides less warmth, and cool surface air is trapped by warmer air above. These winter temperature inversions cause air quality to be lower during winter months. See Collins and Scott (1993) for details.

[11] An alternative approach for addressing time-varying omitted variables would be to compare Mexico City to another city. However, because of the unique geography (see the previous note), unique transportation system, and unusually large population, it is unlikely that any other city would provide a credible counterfactual.

[12] Under mild assumptions, RD yields consistent estimates of $\gamma_1$ in the presence of time-varying omitted variables. Hahn, Todd, and Van der Klaauw (2001) show that nonparametric identification of a constant treatment effect with a sharp RD design requires that the conditional mean function $E[u|t]$ is continuous at the threshold. Under this assumption there may be unobserved factors that influence air quality, but their effect cannot change discontinuously at the threshold. Without this assumption it would be impossible to distinguish changes in air quality due to HNC from changes in air quality due to other time-varying factors.

TABLE 2

Effect of HNC on Pollution Levels: Least Squares

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| 1986–93 | .310 | .089 | .280 | .173 | -.092 | .152 |
| | (.048) | (.034) | (.054) | (.033) | (.076) | (.030) |
| 1987–92 | .412 | .091 | .267 | .176 | .112 | .212 |
| | (.041) | (.036) | (.060) | (.037) | (.042) | (.027) |
| 1988–91 | .392 | .100 | .115 | .128 | .138 | .175 |
| | (.040) | (.048) | (.058) | (.045) | (.033) | (.028) |
| 1989–90 | .296 | .082 | .009 | .064 | .169 | .124 |
| | (.048) | (.038) | (.022) | (.035) | (.055) | (.026) |

Note.—This table reports estimates from 24 separate regressions. For all regressions the sample includes observations from all hours of the day and all days of the week. The dependent variable is the pollution level in logs. The reported coefficients correspond to 1(HNC), an indicator variable equal to one after November 20, 1989. CO is carbon monoxide, $NO_2$ is nitrogen dioxide, $O_3$ is ozone, $NO_X$ is nitrogen oxides, and $SO_2$ is sulfur dioxide. Specifications include weather covariates and indicator variables for month of the year, day of the week, and hour of the day, as well as interactions between weekends and hour of the day. The $R^2$'s for 1986–93 are .50, .49, .72, .51, .23, and .96. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups.

a highly flexible polynomial time trend. In all specifications the variance matrix is estimated taking into account serial correlation.[13]

### B. *The Effect of HNC on Mean Pollution Levels*

Table 2 reports OLS estimates of the effect of HNC on air pollution. For each pollutant and time window the table reports the coefficient and standard error for 1(HNC). For the 1989–90 time window, all five coefficients are positive. Taken literally, the coefficient for carbon monoxide implies that HNC is associated with a 30 percent increase in carbon monoxide levels. The other coefficients range from .01 for ozone to .17 for sulfur dioxide. Table 2 also reports results from a specification in which data for the five different pollutants are stacked. This specification allows all parameters to vary by pollutant except for the parameter for the HNC indicator. Consequently, the coefficient for the indicator variable gives the average impact of HNC across pollutants. In the 1989–90 window the coefficient in the stacked specification is .12. The OLS estimates provide no evidence that HNC has improved air quality. Except for sulfur dioxide in the 1986–93 window, all HNC coefficients are positive, and a null hypothesis of a 10 percent decrease can be rejected at the 1 percent significance level.

[13] Standard diagnostic tests were used to assess the magnitude of serial correlation. In the OLS specification, the autocorrelation coefficients are statistically significant for between 2 and 12 weeks, though in all cases the size and significance of the autocorrelation coefficients have decreased substantially after 5 weeks. In the RD specification with a seventh-order polynomial time trend, the autocorrelation coefficients are significant for between 2 and 5 weeks. Accordingly, variance matrices are estimated allowing for arbitrary correlation within 5-week clusters. Newey-West standard errors with a 5-week lag are reported as an alternative specification.

TABLE 3
EFFECT OF HNC ON POLLUTION LEVELS: REGRESSION DISCONTINUITY

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| Seventh-order polynomial time trend | .048 | −.020 | −.042 | −.029 | .224 | .037 |
| | (.100) | (.142) | (.104) | (.110) | (.109) | (.075) |
| Eighth-order polynomial time trend | .049 | −.055 | −.015 | −.062 | .206 | .028 |
| | (.098) | (.142) | (.101) | (.109) | (.104) | (.073) |
| Ninth-order polynomial time trend | .008 | −.058 | .053 | .001 | .207 | .009 |
| | (.092) | (.164) | (.104) | (.135) | (.121) | (.125) |

NOTE.—This table reports estimates from 18 separate regressions. All results are for 1986–93 and include observations from all hours of the day and all days of the week. The dependent variable is the pollution level in logs. The reported coefficients correspond to 1(HNC), an indicator variable equal to one after November 20, 1989. CO is carbon monoxide, $NO_2$ is nitrogen dioxide, $O_3$ is ozone, $NO_X$ is nitrogen oxides, and $SO_2$ is sulfur dioxide. Specifications include weather covariates and indicator variables for month of the year, day of the week, and hour of the day, as well as interactions between weekends and hour of the day. The $R^2$'s for the specification with a seventh-order polynomial are .66, .51, .79, .53, .68, and .97. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups.

Table 3 reports the RD estimates for seventh-, eighth-, and ninth-order polynomial time trends. With a seventh-order polynomial the effect of HNC on average pollution levels is .04, with coefficients for the individual pollutants ranging from −.04 to .23. Across specifications of the time trend there is no evidence that HNC improved air quality. Figure 3 plots residuals from estimating equation (1) without 1(HNC), along with a seventh-order polynomial time trend and HNC intercept. Carbon monoxide levels increase during 1990 and then decrease in 1992 and 1993. Ozone levels increase in 1991 and decrease in 1992 and 1993. Sulfur dioxide levels decrease substantially in 1992 and 1993. The seventh-order polynomial seems to adequately describe the underlying time trend, while maintaining a reasonable degree of smoothness. The discontinuities indicated in figure 3 are consistent with the estimates reported in table 3. Thus, neither the OLS nor the RD specifications provide evidence of a reduction in mean pollution levels for any pollutant.

### C. *Pollution Levels by Time of Day and Week*

Driving restrictions potentially affect pollution levels during all hours of the week. The HNC restrictions are in place weekdays between 5:00 a.m. and 10:00 p.m. Thus the direct effect of the policy will be experienced during these hours. In addition, HNC may affect air pollution levels during other hours of the week if the program causes drivers to substitute displaced trips with increased travel during these other periods. This subsection examines this possibility by estimating equation (1) for different subsamples by time of day and week.

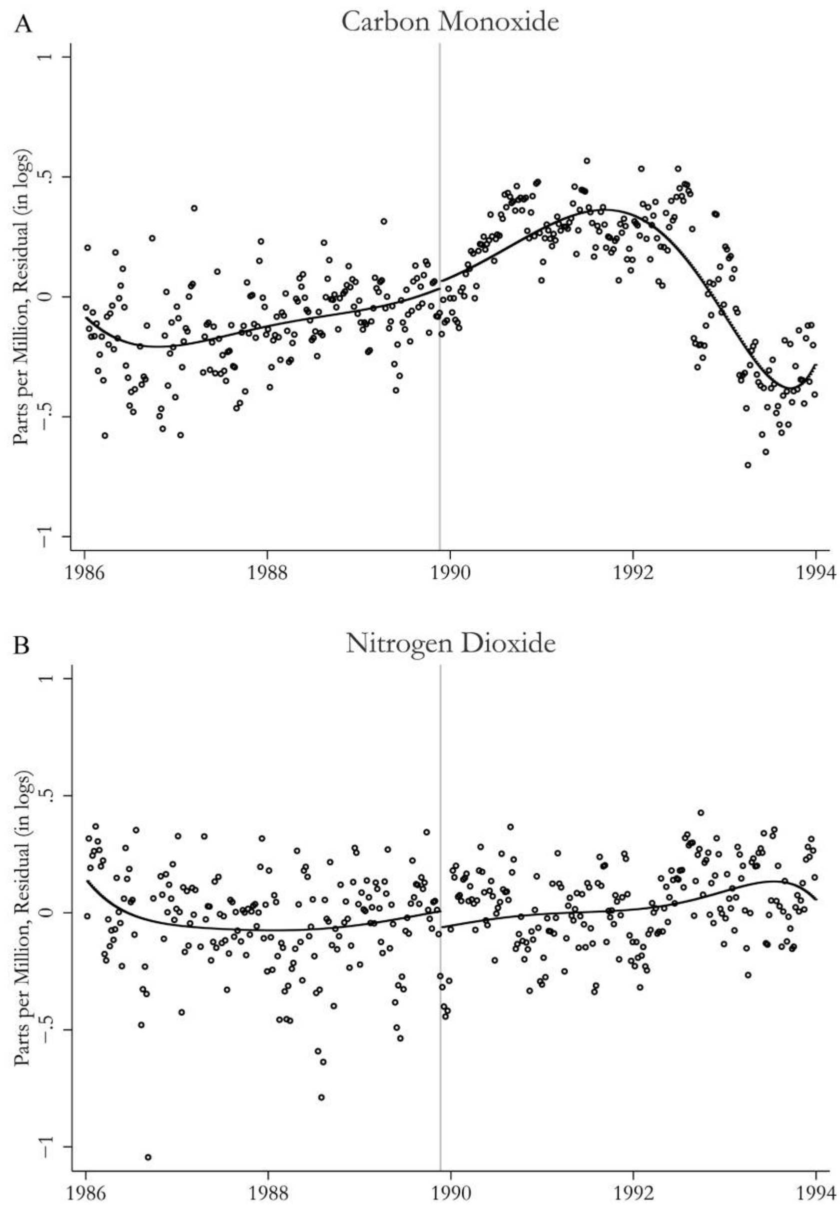
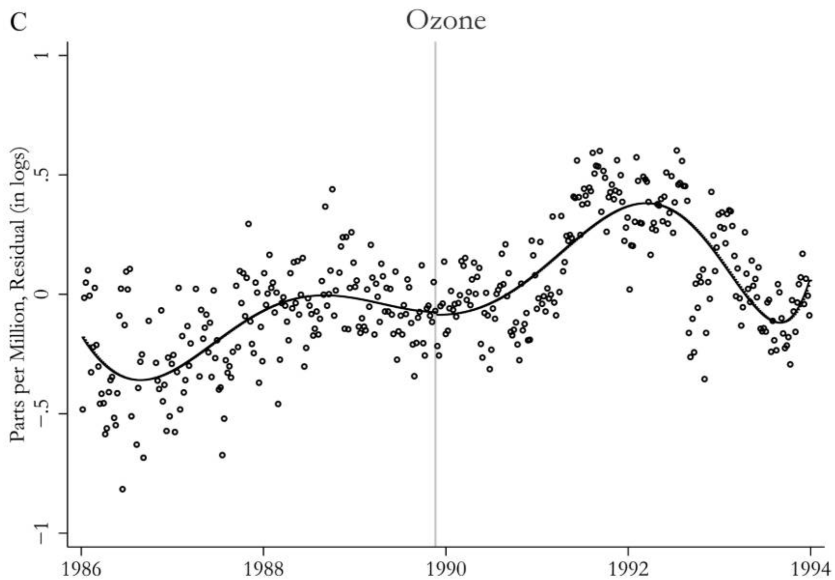
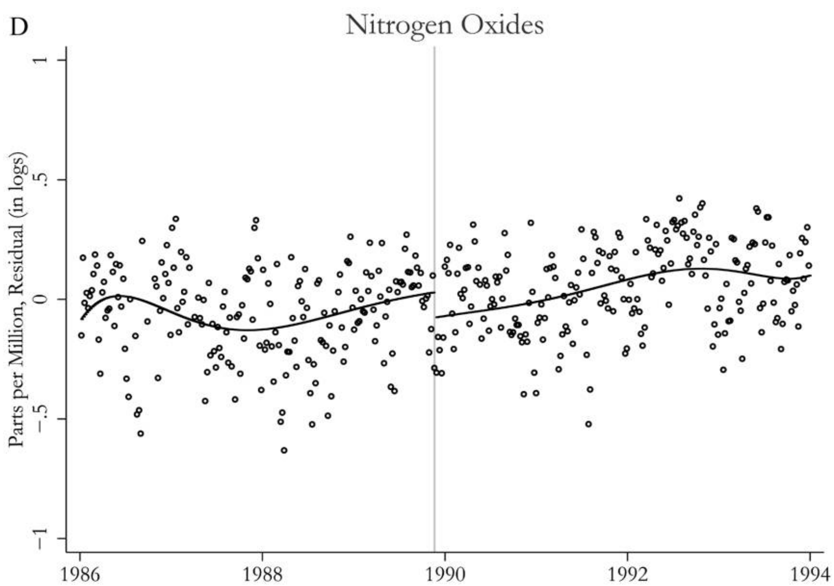



Fig. 3.—Mean weekly pollution level, polynomial time trend

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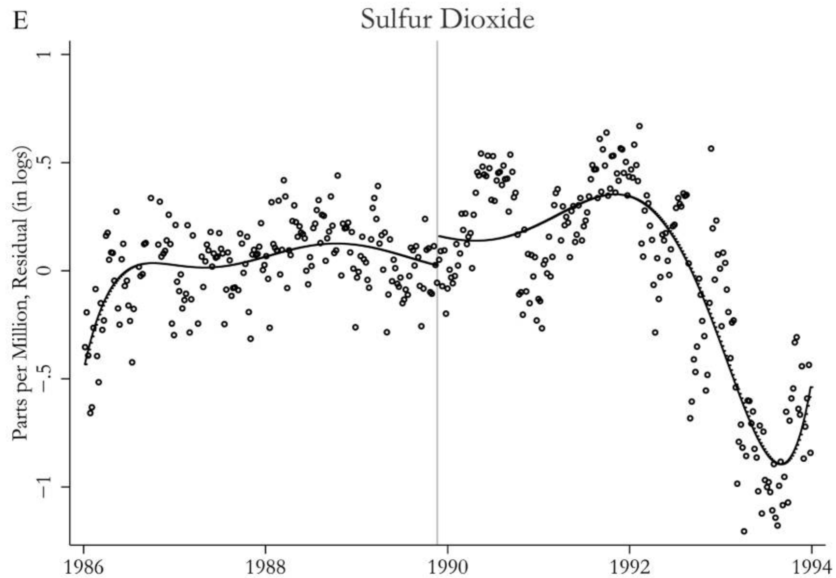


FIG. 3.—*Continued*

Table 4 reports OLS estimates of the effect of HNC on pollution levels for peak weekdays (5:00 a.m.–10:00 p.m.), nonpeak weekdays (10:00 p.m.–5:00 a.m.), and weekends (all hours). All specifications restrict the sample to include observations from 1989 and 1990 and include indicators for month of the year, day of the week, and hour of the day, as well as weather covariates. The OLS results provide no evidence of an improvement in air quality for any period of the week for any pollutant.

TABLE 4
EFFECT OF HNC ON POLLUTION LEVELS BY TIME OF DAY AND WEEK: LEAST SQUARES, 1989–1990

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| Weekdays 5:00 a.m.–10:00 p.m. | .214 | .054 | .041 | .030 | .169 | .098 |
| | (.037) | (.041) | (.020) | (.034) | (.053) | (.026) |
| Weekdays 10:00 p.m.–5:00 a.m. | .369 | .037 | −.052 | .032 | .117 | .098 |
| | (.062) | (.041) | (.030) | (.045) | (.055) | (.029) |
| Weekends | .335 | .136 | .024 | .113 | .186 | .156 |
| | (.054) | (.033) | (.024) | (.042) | (.057) | (.020) |

NOTE.—This table reports estimates from 18 separate regressions. The dependent variable is the pollution level in logs. The reported coefficients correspond to 1(HNC), an indicator variable equal to one after November 20, 1989. CO is carbon monoxide, $NO_2$ is nitrogen dioxide, $O_3$ is ozone, $NO_X$ is nitrogen oxides, and $SO_2$ is sulfur dioxide. Specifications include weather covariates and indicator variables for month of the year, day of the week, and hour of the day. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups.

TABLE 5
Effect of HNC on Pollution Levels by Time of Day and Week: Regression Discontinuity

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| Weekdays 5:00 a.m.–10:00 p.m. | −.008 | −.085 | −.030 | −.090 | .220 | −.005 |
| | (.084) | (.138) | (.090) | (.099) | (.111) | (.076) |
| Weekdays 10:00 p.m.–5:00 a.m. | .127 | −.010 | −.150 | .030 | .209 | .032 |
| | (.136) | (.152) | (.157) | (.131) | (.111) | (.081) |
| Weekends | .084 | .079 | .016 | .032 | .240 | .082 |
| | (.101) | (.156) | (.103) | (.132) | (.115) | (.077) |

Note.—This table reports estimates from 18 separate regressions. All results are for 1986–93. The dependent variable is the pollution level in logs. The reported coefficients correspond to 1(HNC), an indicator variable equal to one after November 20, 1989. CO is carbon monoxide, $NO_2$ is nitrogen dioxide, $O_3$ is ozone, $NO_X$ is nitrogen oxides, and $SO_2$ is sulfur dioxide. All estimates are from an RD specification with a seventh-order polynomial time trend, weather covariates, and indicator variables for month of the year, day of the week, and hour of the day. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups.

Of the 24 estimates, 23 are positive.[14] In addition, the estimates for weekend pollution levels tend to be higher than the estimates for weekday pollution levels, providing evidence that HNC has increased driving during weekends. Relative to peak weekdays, the effect for weekends is positive and statistically significant at the 2 percent level for two out of the five pollutants and in the stacked specification.

Table 5 reports RD estimates for peak weekdays, nonpeak weekdays, and weekends for the 1986–93 sample. In addition to all covariates included in the OLS specification, the RD specification includes a seventh-order polynomial time trend. Again there is no evidence of improvements in air quality. Most coefficients are close to zero, and no coefficients are negative and statistically significant. The weekday estimates are negative for four out of the five pollutants but not statistically significant. Estimates for nonpeak weekdays and weekends tend to be positive, consistent with intertemporal substitution toward nighttime and weekend driving. Relative to peak weekdays, the effect for nonpeak weekdays and weekends is positive and statistically significant at the 1 percent level for four out of the five pollutants and in the stacked specification, consistent with substitution toward hours when the driving restrictions are not in place.[15]

[14] The one exception is ozone during nonpeak weekday hours. Ozone formation requires warmth and sunlight for formation, so nighttime ozone levels tend to be very low and percentage changes are not economically significant. See Sillman (2003) for a complete description.

[15] This discussion of intertemporal substitution is relevant to an extensive literature that looks at congestion pricing. See Vickery (1963, 1969), Arnott, de Palma, and Lindsey (1993), and Arnott and Kraus (1998). Vickery (1969) describes a model in which the marginal social cost of driving is higher during peak periods because of congestion externalities. Drivers are assumed to have a preferred time to complete a trip and to incur

Thus in both the OLS and RD specifications there is no evidence of an improvement in air quality during any period of the week for any pollutant. In addition, both specifications provide evidence of a relative increase in air pollution during hours of the week when the restrictions are not in place. If drivers are substituting to weekends and nonpeak weekdays, it would seem reasonable to believe that they are also substituting across days of the week, providing a potential explanation for the lack of evidence of absolute improvements in air quality during peak periods.

### D. *The Effect of HNC on Extreme Concentrations*

The WHO establishes maximum exposure limits for airborne pollutants based on the idea that pollution levels above a certain level are dangerous to human health. If there are nonlinearities in the relationship between pollution and health, then in evaluating the potential benefits of HNC it is important to assess the impact not only on mean pollution levels but also on maximum pollution levels. This subsection describes estimates from two alternative specifications of equation (1). In the first specification, the dependent variable is maximum daily air pollution. In the second specification, the dependent variable is an indicator variable for days in which pollution levels exceed WHO standards.

Figure 4 plots maximum daily air pollution in Mexico City over the period 1986–93 for all five pollutants along with a seventh-order polynomial in time with an intercept for observations after HNC was implemented. The daily maximum pollution level was constructed by averaging across monitoring stations for each hour and then taking the maximum for each day. There is no visible decrease in daily maximum pollution levels when HNC is implemented. In fact, all five intercepts are positive. Table 6 reports estimated coefficients and standard errors from a full specification with seventh-order polynomial time trend, weather covariates, and indicator variables for month of the year and day of the week. For all five individual pollutants and for the stacked specification, the HNC intercept is positive or close to zero.

Table 6 also reports estimates from a specification in which the dependent variable is an indicator variable for days in which pollution levels exceed WHO standards.[16] Coefficients are derived from a linear

schedule delay costs if they arrive at a different time. In this context the social optimum is the set of trips that minimizes the sum of schedule delay costs and travel time costs. When there is high congestion as there is in Mexico City, large welfare gains are realized by moving trips away from peak driving periods.

[16] WHO (2005) establishes air quality guidelines in parts per million of 8.7 for carbon monoxide (8 hours), .106 for nitrogen dioxide (1 hour), .061 for ozone (8 hours), and .048 for sulfur dioxide (24 hours). Because the WHO does not publish a guideline for nitrogen oxides, the nitrogen dioxide guideline is used instead, adjusted for density.

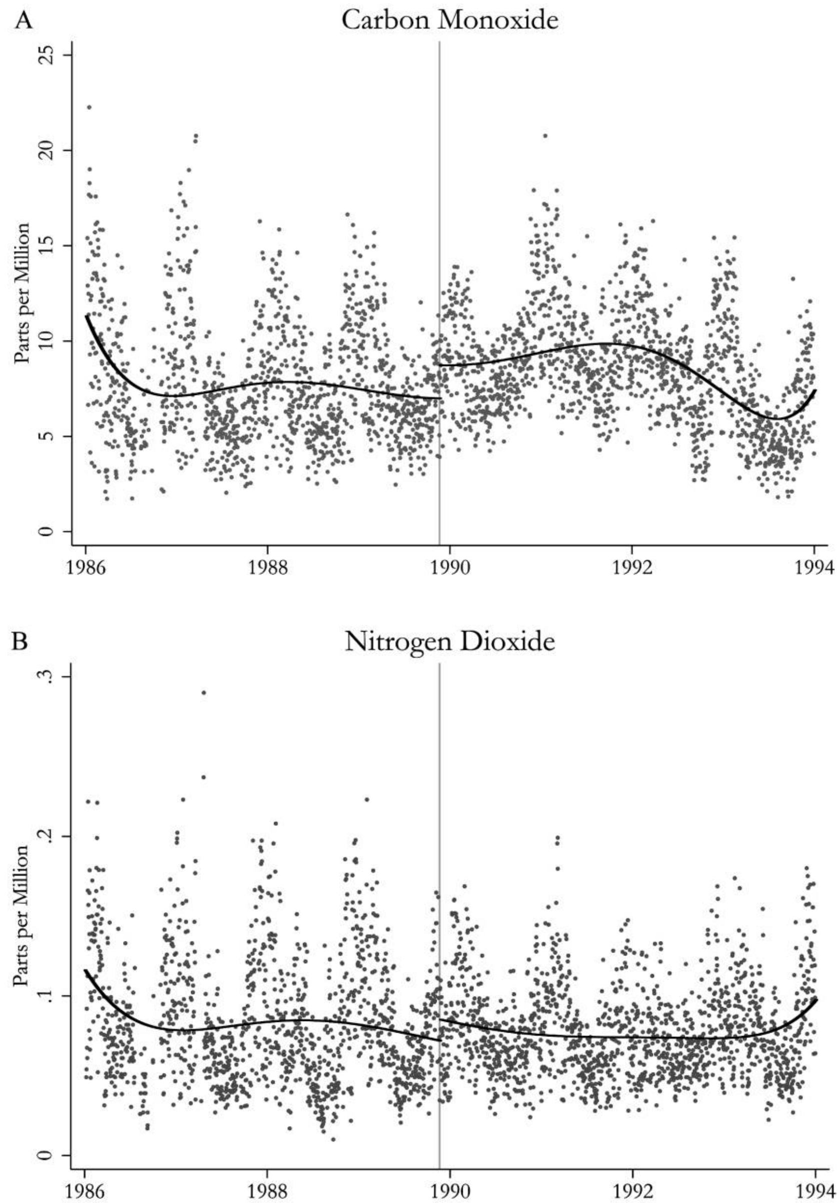


FIG. 4.—Maximum daily pollution level, 1986–93

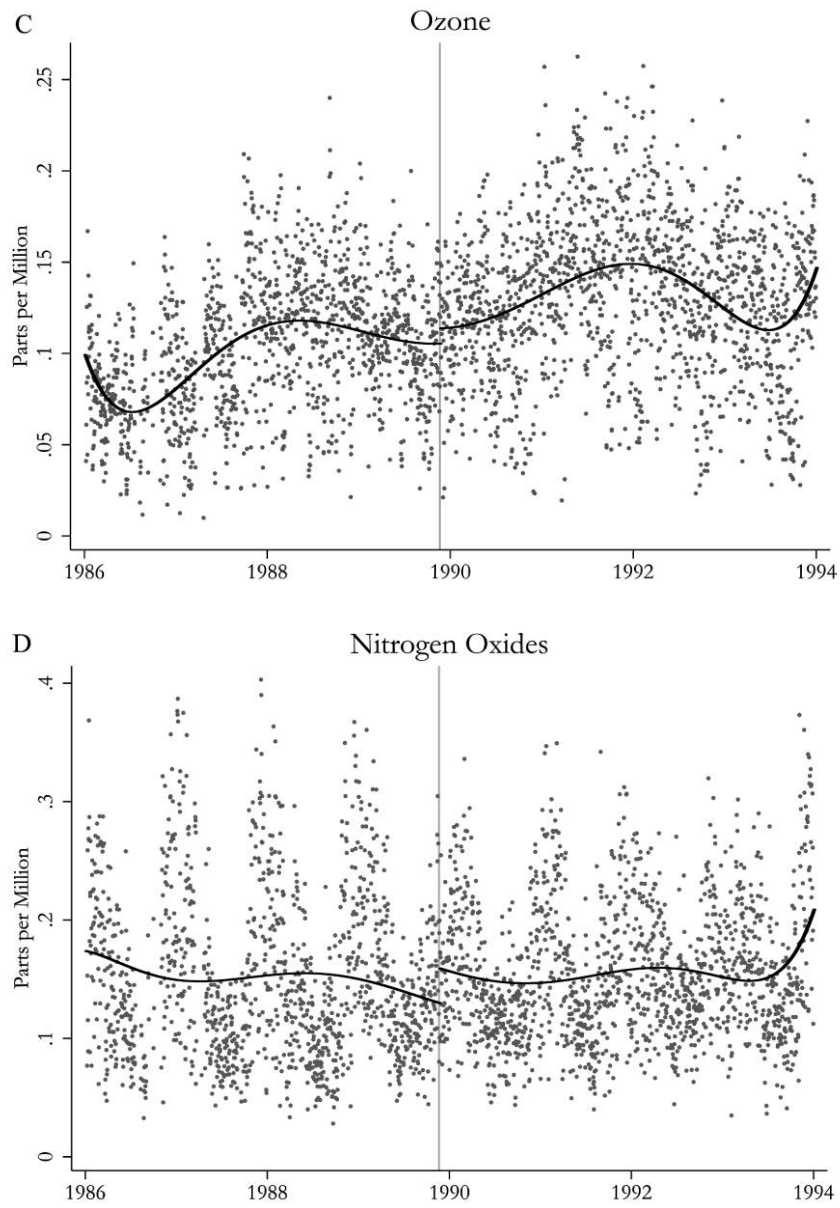


Fig. 4.—*Continued*

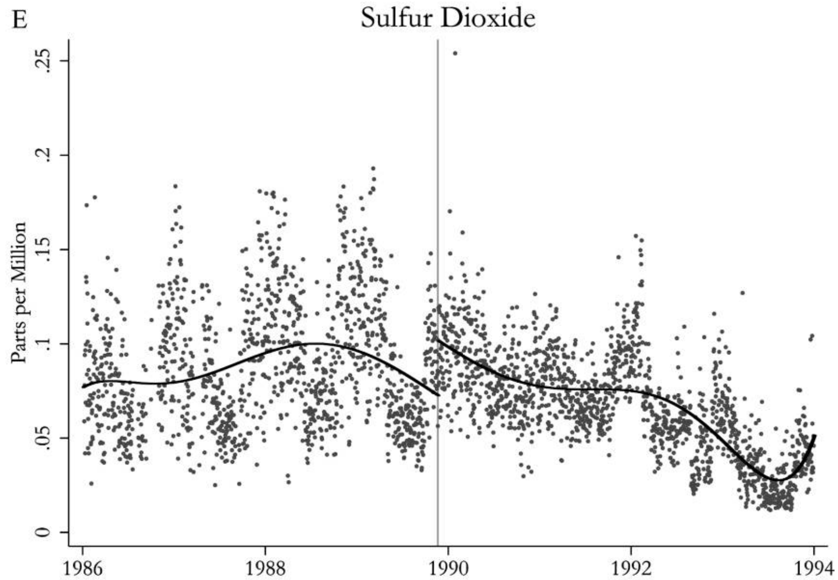


Fig. 4.—*Continued*

TABLE 6
Effect of HNC on Extreme Pollution Levels:
Regression Discontinuity Evidence

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| Daily maximum | .014 | −.004 | .082 | −.035 | .025 | .061 |
| | (.067) | (.160) | (.097) | (.088) | (.117) | (.086) |
| 1(exceeds WHO standard) | .121 | −.051 | −.052 | −.008 | .372 | .077 |
| | (.054) | (.056) | (.057) | (.047) | (.105) | (.042) |

Note.—This table reports estimates from 12 separate regressions. All specifications are for 1986–93 and include observations from all hours of the day and all days of the week. In the first row the dependent variable is daily maximum pollution level in logs. In the second row the dependent variable is an indicator variable for days in which pollution levels exceed WHO standards. The reported coefficients correspond to 1(HNC), an indicator variable equal to one after November 20, 1989. Both specifications include a polynomial time trend, weather covariates, and indicator variables for month of the year, day of the week, and hour of the day, as well as interactions between weekends and hour of the day. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups. WHO standards were exceeded for 9.3 percent, 19.7 percent, 74 percent, 37 percent, and 55 percent of all days, respectively.

probability model with a quadratic time trend. When higher-order polynomials are used, they tend to perform poorly, behaving erratically at boundaries and increasing and decreasing dramatically to fit individual observations. Again, this specification provides no evidence that HNC improved air quality. The coefficients for individual pollutants are either positive or small and negative. With the stacked specification and separately for carbon monoxide and sulfur dioxide, a null hypothesis of a 5-percentage-point decrease in the proportion of observations exceed-

TABLE 7
EFFECT OF HNC ON POLLUTION LEVELS: ALTERNATIVE SPECIFICATIONS

| | CO | $NO_2$ | $O_3$ | $NO_X$ | $SO_2$ | Stacked |
|---|---|---|---|---|---|---|
| 1. Fixed-effect estimates | .074 | .022 | −.027 | −.145 | .212 | .071 |
| | (.091) | (.129) | (.086) | (.085) | (.120) | (.076) |
| 2. High reporting stations only | −.024 | .038 | .008 | .017 | .262 | .061 |
| | (.120) | (.204) | (.101) | (.182) | (.111) | (.088) |
| 3. Excluding weather covariates | .076 | −.048 | −.112 | −.050 | .241 | .021 |
| | (.090) | (.133) | (.097) | (.107) | (.103) | (.067) |
| 4. Including gasoline prices | .056 | −.028 | −.039 | −.036 | .222 | .035 |
| | (.097) | (.138) | (.104) | (.105) | (.109) | (.075) |
| 5. Excluding outliers | .056 | −.020 | −.039 | −.028 | .213 | .037 |
| | (.010) | (.142) | (.106) | (.110) | (.105) | (.073) |
| 6. Newey-West standard errors | .078 | −.036 | .004 | −.086 | .191 | .030 |
| | (.088) | (.138) | (.072) | (.096) | (.112) | (.047) |
| 7. Complete set of interactions | .048 | −.020 | −.042 | −.029 | .224 | .037 |
| | (.100) | (.143) | (.104) | (.111) | (.109) | (.075) |

NOTE.—This table reports estimates from 42 separate regressions. All specifications are for 1986–93 and include observations from all hours of the day and all days of the week. All estimates are from an RD specification with a seventh-order polynomial time trend, weather covariates, and indicator variables for month of the year, day of the week, and hour of the day, as well as interactions between weekends and hour of the day. The stacked specification allows all parameters except for the HNC indicator to vary across pollutants. Except for row 6, standard errors, in parentheses, are robust to heteroskedasticity and arbitrary correlation within 5-week groups. High reporting stations are stations that, for a particular pollutant, report over 70 percent of hourly observations.

ing WHO standards can be rejected at the 1 percent significance level. Overall the evidence from extreme pollution levels is consistent with the results for mean pollution levels, providing no evidence that HNC led to an improvement in air quality.

### E. *Alternative Specifications*

Table 7 reports estimates for alternative specifications. All estimates are derived from an RD specification with a seventh-order polynomial time trend, weather covariates, and indicator variables for month of the year, day of the week, hour of the day, and interactions between weekends and hour of the day. Overall, the results are consistent with the results presented above.

One potential concern with the estimates is changes in the operation of monitoring stations. Figure 5 plots percentage reporting by week for the period 1988–91, averaged across monitoring stations and pollutants. Percentage reporting is reasonably consistent, though there does appear to be a mild increase in percentage reporting near the time that HNC was implemented. Any change in the operating of monitoring stations is a potential concern because a change in reporting patterns that is

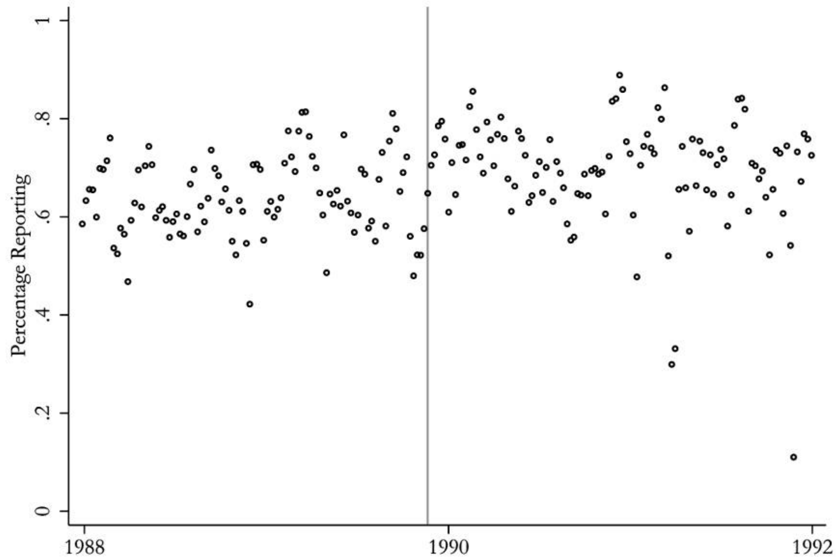


FIG. 5.—Hourly reporting by air quality monitoring stations, 1988–91. Source: Secretaría del Medio Ambiente, Red Automático de Monitoreo Ambiental, 2006.

correlated with pollution levels will cause the estimates to be biased.[17] Table 7 reports estimates from two alternative specifications used to address this concern. First, row 1 reports estimates from a fixed-effects specification in which the unit of observation is average weekly air pollution by station. Controlling for time-invariant station heterogeneity prevents disproportionate changes in reporting levels at stations with particular pollution characteristics from biasing the results. Second, row 2 reports estimates from a specification in which the sample is restricted to include observations from stations reporting at least 70 percent of hourly observations for a particular pollutant during the period 1986–93. The estimates from these specifications are consistent with the main results, suggesting that changes in reporting levels do not explain the lack of evidence of an improvement in air quality.

Row 3 reports estimates from a specification that excludes weather

[17] Gobierno del Distrito Federal, Secretaría del Medio Ambiente (2006) provides a detailed history of the network including a record of technical modifications by monitoring station since 1986. During this period there were no changes in measurement techniques at any station. Furthermore, there is no record of a change in maintenance patterns that coincides with the implementation of HNC.

covariates.[18] The estimates from this specification are similar to the main results, suggesting that the weather covariates are not driving the results. Row 4 reports estimates from a specification that includes gasoline prices.[19] Changes in gasoline prices affect driving intensity and therefore air quality. When gasoline prices are included in the regression, the coefficients for HNC are largely unchanged.

Row 5 reports estimates from a specification that excludes hourly observations that exceed three times the WHO standard. These observations with very high levels of pollution are informative because they provide information about the effectiveness of HNC. In addition, evidence from Bollinger and Chandra (2005) indicates that removing outliers can actually exacerbate measurement error or create measurement error where no measurement error existed. Nonetheless, it is reassuring that the estimates from this specification are similar to the main results.

Row 6 reports standard errors estimated following Newey and West (1987) with a 5-week lag in a specification in which the dependent variable is the daily average pollution level. The Newey-West standard errors are similar in magnitude to the standard errors reported throughout that allow for arbitrary correlation within 5-week groups.

Finally, row 7 reports estimates from a specification with a complete set of interactions between day of the week and hour of the day. Previous specifications have allowed for interactions between weekends and hour of the day, but this specification allows for different effects within weekdays and weekends. For example, Friday 9:00 p.m. is allowed to have a baseline pollution level different from that of Thursday 9:00 p.m. The results from this specification are similar to the results without the interactions, suggesting that the standard set of indicator variables used throughout does a reasonable job controlling for the predictable weekly pattern of air pollution.

[18] This specification addresses concerns about reverse causality. There is a substantial literature in the atmospheric sciences that documents elevated temperatures in urban areas. See Jauregui (1997) and Arnfield (2003) for details. Urban surfaces tend to absorb more heat than rural surfaces, so they cool more slowly at night. Air pollution is not typically studied as a cause of urban heat islands, but it could be reasonably believed to affect local weather observations by affecting the movement of heat in and out of the lower atmosphere. This could cause the weather covariates to be endogenous, potentially biasing the estimates of the effect of HNC.

[19] Gasoline prices come from INEGI, Banco de Información Económica, Sector Energético, Precios Internos de Gasolinas: PEMEX Magna (2006). Average annual gasoline prices were normalized using the Mexican consumer price index from the Mexican Central Bank, Banco de México, Indices de Precios, Índice Nacional de Precios al Consumidor (2006).

## IV. Additional Evidence

This section examines possible explanations for the lack of evidence of an improvement in air quality. Understanding the behavioral responses to HNC is important for helping to explain the air quality results as well as for assessing the extent to which the experience in Mexico City can be generalized. Overall the evidence indicates that HNC was not successful in reducing the use of high-emissions forms of transportation. When HNC was implemented, there is no evidence of a decrease in gasoline consumption or an increase in public transportation. Instead, HNC is associated with an increase in the total number of private vehicles in circulation as well as a change in composition toward high-emissions vehicles.

The section focuses on the transportation sector because of its central role in determining air quality in Mexico City. It is unlikely that the lack of evidence of an improvement in air quality can be explained by an offsetting increase in industrial activity. First, emissions in Mexico City are overwhelmingly derived from vehicles. As described earlier, this is particularly the case for carbon monoxide, for which 99 percent of emissions are derived from vehicles. Thus, a change in industrial activity would need to be very large in magnitude in order to meaningfully offset changes in the transportation sector. Second, industrial emissions in Mexico City are derived from a large number of heterogeneous facilities, so any offsetting increase in industrial activity would have needed to be a change that affected a large number of industries simultaneously. News accounts from this period have been reviewed, and there is no mention of any change in industrial activity during the period in which HNC was implemented.[20] Third, the electricity-generating sector, typically a major source of emissions, is small in Mexico City. There is virtually no electricity production within Mexico City, and electricity production in the surrounding state of Mexico increased by only 1.5 percent between 1989 and 1990 (INEGI 1994, 75).

### *A. Gasoline Sales*

Gasoline sales provide an alternative method for evaluating the effectiveness of HNC and a valuable starting point for examining the behavioral responses. Figure 6 plots monthly gasoline sales in Mexico City

[20] According to the 2004 Economic Census, there are over 45,000 businesses in Mexico City, and a recent emissions inventory tracks emissions from almost 5,000 different industrial point sources. For more information, see Gobierno del Distrito Federal, Secretaría del Medio Ambiente (2004*b*).

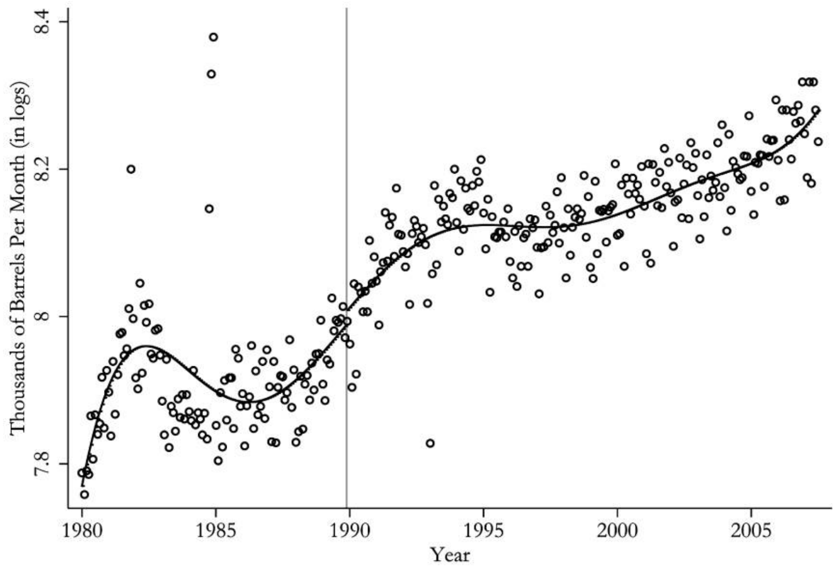


Fig. 6.—Gasoline sales in Mexico City, 1980–2007. Source: Gobierno de México, Secretaría de Energía, 2007.

from 1980 to 2007.[21] Sales include all gasoline types including leaded, unleaded, and premium. During this period gasoline sales increased by an average of 1.7 percent annually to 3.8 million barrels per month in 2007. Figure 6 also plots a ninth-order polynomial in time with an intercept at December 1989, when HNC was implemented. As reported in table 8, the coefficient on the HNC intercept is .018 (.025), indicating a small and statistically insignificant change in gasoline sales. Results are similar when indicator variables for month of the year are included to control for seasonal variation, .023 (.020). The results provide no evidence that HNC led to a decrease in gasoline sales. Moreover, the estimates are precise enough to rule out relatively small decreases in gasoline sales. For three alternative specifications of the time trend described in table 8, the null hypothesis of a 5 percent decrease can be rejected at the 1 percent level.[22] This lack of evidence of a reduction

[21] These sales records were compiled by Jorge Nuño at the Mexican Energy Ministry, Secretaría de Energía, Dirección General de Información y Estudios Energéticos, in August 2007. Measures of gasoline sales by gasoline type are not available for this period.

[22] These results are consistent with results from Eskeland and Feyzioglu (1997), who examine quarterly gasoline sales in Mexico City during the period 1984–92. Controlling for gasoline prices and outgoing international telephone calls (a proxy for income), they find no evidence of a decrease in gasoline sales. This article expands on their analysis, using an RD specification to control for time-varying factors, higher-frequency data, a longer time series, and inference based on standard errors that account for serial correlation.

TABLE 8
EFFECT OF HNC ON GASOLINE SALES IN MEXICO CITY:
REGRESSION DISCONTINUITY EVIDENCE

| | Coefficient | Standard Error |
|---|---|---|
| Eighth-order polynomial time trend | .028 | (.025) |
| Ninth-order polynomial time trend | .018 | (.025) |
| Tenth-order polynomial time trend | .013 | (.023) |

NOTE.—This table reports estimates that correspond to three separate regressions. All specifications are for 1980–2007. The dependent variable in all specifications is monthly gasoline sales in Mexico City in thousands of barrels (in logs). The reported coefficients correspond to 1(HNC), an indicator variable equal to one after the implementation of HNC. Specifications include flexible polynomial time trends as indicated. In accordance with findings from standard diagnostic tests of serial correlation, the reported standard errors are estimated following Newey and West (1987) with a 2-month lag.

in gasoline sales provides further indication that the social benefits of HNC are limited, implying that HNC did not induce drivers to substitute away from energy-intensive forms of transportation.

### B. *Public Transportation*

It was hoped that HNC would cause substitution toward low-emissions forms of transportation such as the subway and public bus system. This subsection examines evidence from ridership records, finding no evidence of an increase in either form of public transportation. These results help explain the results for air pollution and gasoline sales and motivate the examination of private vehicle adoption and taxi utilization in the following subsections.

Figure 7 plots monthly ridership for the Mexico City subway system for the period 1986–2005 as well as a fourth-order polynomial in time with an intercept at December 1989.[23] Average ridership during this period was 3.9 million trips per day. As reported in table 9, the coefficient on the HNC intercept is negative and statistically significant, $-.080$ (.014), providing no evidence of an increase in ridership. In fact, it appears that subway ridership actually decreases as HNC is implemented. One possible explanation for this apparent decrease is complementarities between subway ridership and driving. The subway operates along major routes, so it typically must be combined with other

[23] Subway ridership records are collected by the INEGI, Gobierno del Distrito Federal, Sistema de Transporte Colectivo Metro (2006). A more conventional method for describing transportation patterns would be to use evidence from origin-destination surveys. A study implemented by the INEGI in 1994 indicates that of trips in Mexico City, 64 percent are by bus, 17 percent are by private car, and 13 percent are by subway. Earlier, smaller-scale surveys were completed in 1977 and 1983, but these studies were implemented by different organizations and responses are not comparable across surveys, making it difficult to use this evidence to examine HNC. Molina and Molina (2002) provide detailed information about existing transportation surveys in Mexico City.

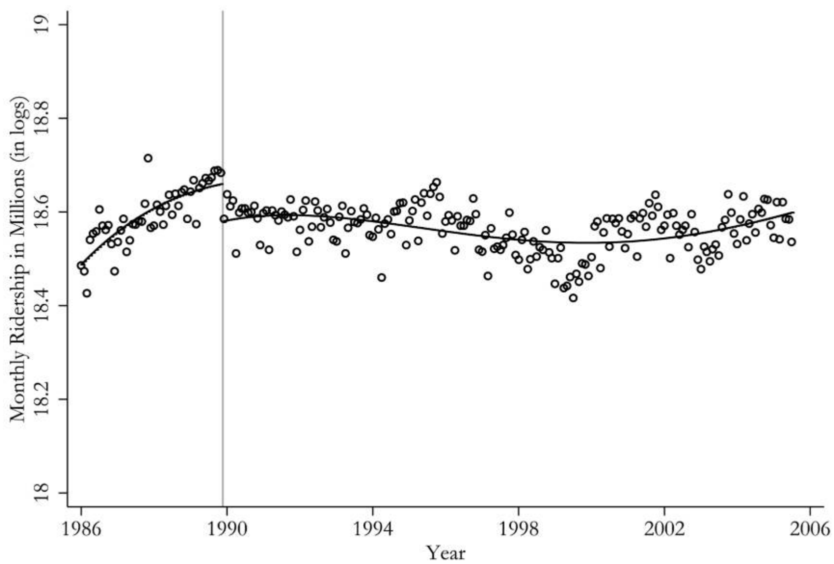


FIG. 7.—Subway ridership in Mexico City, 1986–2005. Source: INEGI, Gobierno del Distrito Federal, Sistema de Transporte Colectivo Metro, 2006.

forms of transportation, often private vehicles. When access to vehicles decreases, this may cause substitution to other forms of transportation.

Figure 8 plots ridership for the public bus system for the period 1986–90 as well as a fifth-order polynomial in time with an intercept at December 1989.[24] The period after December 1990 is excluded because the bus system was partially privatized in January 1991 under President Carlos Salinas and ridership in the public bus system fell dramatically. During the period 1986–90, average ridership was 5.7 million trips per day. The coefficient on the intercept is negative and close to zero, $-.040$ (.035), providing no evidence of a change in ridership. As reported in table 9, results for alternative specifications of the time trend are similar in magnitude.

This apparent lack of substitution toward public transportation is disappointing from the perspective of the potential social benefits of HNC because the subway and public bus system are two of the lowest-emitting forms of transportation in Mexico City. To understand this pattern it is valuable to consider the demographic characteristics of drivers. In Mexico City during this period there was one car for every eight individuals, so drivers tend to be from the middle and upper classes and have a relatively high value of time. The subway and the public bus system are

[24] Bus ridership records are collected by the INEGI, Red de Transporte de Pasajeros (2006).

TABLE 9
EFFECT OF HNC ON PUBLIC TRANSPORTATION IN MEXICO CITY:
REGRESSION DISCONTINUITY EVIDENCE

| | Coefficient | Standard Error |
|---|---|---|
| | Subway Ridership | |
| Third-order polynomial time trend | −.088 | (.015) |
| Fourth-order polynomial time trend | −.080 | (.014) |
| Fifth-order polynomial time trend | −.098 | (.020) |
| | Public Bus Ridership | |
| Fourth-order polynomial time trend | .000 | (.020) |
| Fifth-order polynomial time trend | −.040 | (.035) |
| Sixth-order polynomial time trend | .001 | (.020) |

NOTE.—This table reports estimates that correspond to six separate regressions. In rows 1–3, the dependent variable is monthly ridership in the Mexico City subway (in logs), and the sample includes 1986–2005. In rows 4–6, the dependent variable is monthly ridership in the Mexico City public bus system (in logs), and the sample includes 1986–90. Reported coefficients refer to 1(HNC), an indicator variable for the years following the implementation of HNC. Specifications include flexible polynomial time trends as indicated. In accordance with findings from standard diagnostic tests of serial correlation, the reported standard errors are estimated following Newey and West (1987) with 5-month lags for subway ridership and 12-month lags for bus ridership.

the least expensive but also in some ways the least convenient forms of transportation in Mexico City. For many residents of Mexico City the subway and public bus systems provide excellent service at an affordable price. However, the ridership evidence suggests that these forms of transportation were not the preferred form of transportation for those who were prevented from driving one day per week by HNC. It seems more likely that drivers would have substituted to other forms of private transportation, either by purchasing additional vehicles or by using taxis. Subsections *C* and *D* explore these possibilities.

### *C. Vehicle Registrations and Sales*

Levinson and Shetty (1992), Eskeland and Feyzioglu (1997), Goddard (1997), and others have pointed out that driving restrictions such as HNC create an incentive for households to acquire additional vehicles. Indeed, a driver with two vehicles can drive every day of the week as long as the last digits of the license plates are different. This subsection evaluates vehicle adoption using evidence from vehicle registrations and sales of new automobiles in Mexico City. HNC appears to be associated with increases in both the number of registered vehicles and new automobile sales. Furthermore, the increase in new automobile sales is small relative to the increase in registered vehicles, indicating that the observed increase in registered vehicles must be composed overwhelmingly of used vehicles. Because older vehicles tend to be higher-emitting and less fuel efficient, this helps explain the lack of evidence of an

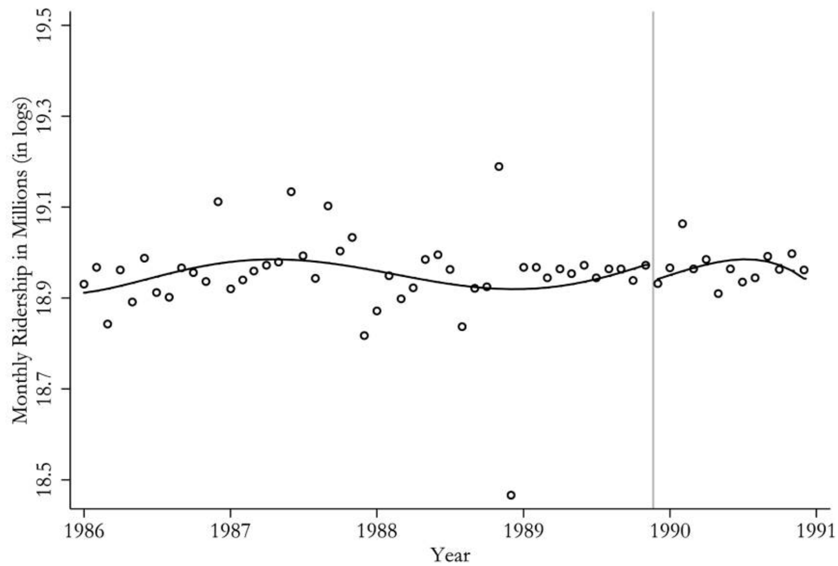


Fig. 8.—Public bus ridership in Mexico City, 1986–90. Source: INEGI, Gobierno del Distrito Federal, Red de Transporte de Pasajeros, 2006.

improvement in air quality as well as the lack of evidence of a decrease in gasoline consumption.[25]

Figure 9 plots the number of registered vehicles in Mexico City during the period 1980–2005 as well as a fifth-order polynomial in time. Table 10 reports the estimated coefficient for the HNC intercept, .189 (.076). Across specifications, the coefficient is statistically significant at the 1 percent level, providing evidence of an increase in the number of registered vehicles associated with the introduction of HNC. The coefficient implies an increase of approximately 325,000 vehicles with a ninety-fifth percentile confidence interval of 51,000–597,000 vehicles.

Figure 10 describes sales of new automobiles in Mexico City during the period 1975–2005.[26] The figure plots residuals from a regression of sales of new automobiles (in logs) on the annual growth rate for

[25] After similar driving restrictions were imposed in Santiago, Chile, some drivers responded by illegally obtaining additional license plates and using an alternate set on days in which the restrictions were in place ("Nuevos formatos para patentes y licencias de conducir," *El Mercurio*, March 3, 2000). It is unlikely that license plate fraud occurred on a wide scale in Mexico City because license plates are tightly controlled by the Department of Transportation and all vehicles must display a sticker matching the license plate affixed to the inside back window.

[26] This time series was compiled from INEGI, *La industria automotriz en México* (1981, 1986, 1991, 1997, 2000, 2005). Automobile sales were compiled rather than total vehicle sales because sales of total vehicles are not available for the entire period. In 1990, registered automobiles represented 89.4 percent of all registered vehicles in Mexico City.

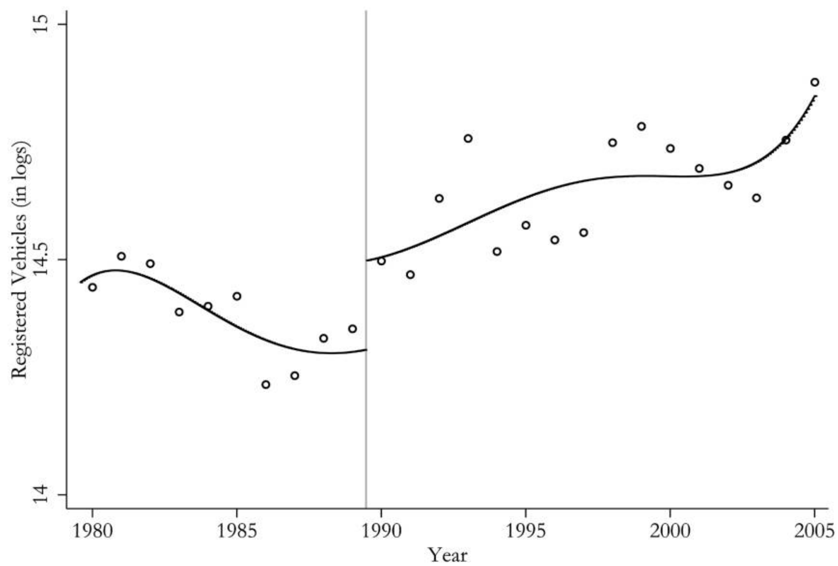


Fig. 9.—Registered vehicles in Mexico City, 1980–2005. Source: INEGI, Estadísticas de Transportes, Vehículos de Motor Registrados en Circulación, 2007.

TABLE 10
Effect of HNC on the Number of Vehicles in Mexico City: Regression Discontinuity Evidence

| | Coefficient | Standard Error |
|---|---|---|
| | Registered Vehicles | |
| Fourth-order polynomial time trend | .220 | (.085) |
| Fifth-order polynomial time trend | .189 | (.076) |
| Sixth-order polynomial time trend | .192 | (.083) |
| | Sales of New Automobiles | |
| Ninth-order polynomial time trend | .177 | (.087) |
| Tenth-order polynomial time trend | .152 | (.090) |
| Eleventh-order polynomial time trend | .149 | (.093) |

Note.—This table reports estimates that correspond to six separate regressions. In rows 1–3, the dependent variable is the number of registered vehicles by year in Mexico City (in logs), and the sample includes 1980–2005. In rows 4–6, the dependent variable is annual sales of new automobiles in Mexico City (in logs), and the sample includes 1975–2005. The table reports coefficients for 1(HNC), an indicator variable for the period after the implementation of HNC. Specifications include flexible polynomial time trends as indicated. In accordance with findings from standard diagnostic tests of serial correlation, reported standard errors are estimated following Newey and West (1987) with a 1-year lag.

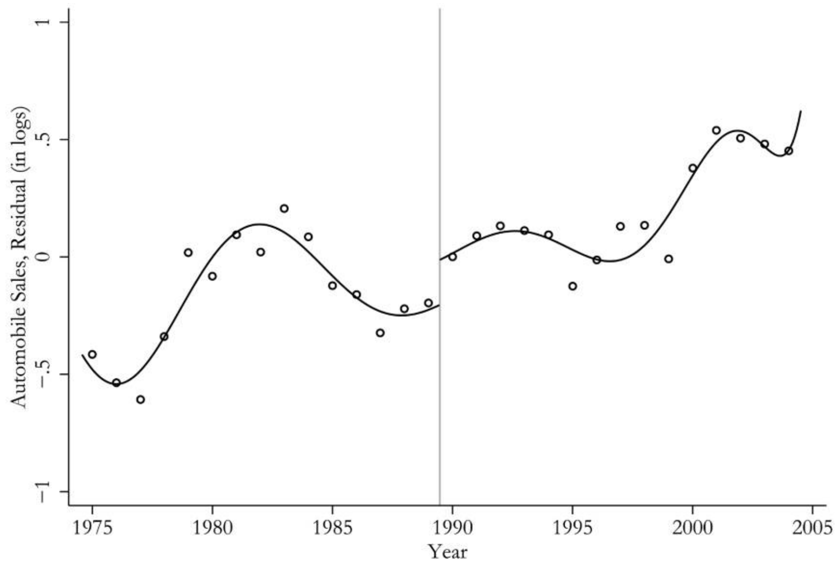


FIG. 10.—Sales of new automobiles in Mexico City, 1975–2005. Source: INEGI, *La industria automotriz en México*, 1981, 1986, 1991, 1997, 2000, and 2005.

Mexico.[27] The specification includes the growth rate and the square of the growth rate, as well as the lagged growth rate and lagged squared growth rate. Figure 10 also plots a tenth-order polynomial time trend with intercept at 1990. The estimated HNC intercept is .152 (.090), providing mild evidence ($p = .12$) of an increase in car sales. Table 10 reports estimates for alternative specifications of the time trend.

In 1990 automobile sales represented 7.5 percent of the total stock of registered vehicles in Mexico City, so a 15 percent increase in new automobile sales represents less than 2 percent of the total number of registered vehicles. Consequently, the observed increase in registered vehicles must be composed overwhelmingly of used vehicles, imported from other parts of Mexico or from the much larger U.S. market.[28] This increase in used vehicles would have had a substantial negative impact on air quality since older vehicles tend to emit more than newer vehicles because they lack emissions control equipment and because the effec-

[27] The annual growth rate of GDP comes from Alan Heston, Robert Summers, and Bettina Aten, Penn World Table version 6.2, Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, September 2006.

[28] Eskeland and Feyzioglu (1997) reach similar conclusions examining the number of registered vehicles and sales of vehicles for 1983, 1989, 1990, and 1993. This article expands on their analysis with the entire annual time series rather than just the four years, using the RD approach to control for time-varying factors and reporting standard errors for formal hypothesis testing.

tiveness of emissions control equipment decreases with vehicle age.[29] Beaton, Bishop, and Stedman (1992) report that emissions per vehicle in Mexico City during this period were unusually high, in large part because of the lack of adequate vehicle maintenance and because of the widespread practice of deliberately tuning vehicles for peak power. In addition to increasing the overall level of emissions, these factors tend to cause emission levels to further increase with vehicle age.

The evidence from vehicle registrations and automobile sales provides a compelling explanation for the lack of evidence of an improvement in air quality, particularly over the period of 1 year or multiple years. Certainly it is possible that many additional vehicles were added to the roads in the days immediately following the implementation of HNC or between the announcement of HNC on November 6 and implementation on November 20. Still, it seems more likely that there would have been an initial increase in purchases, followed by an additional, more gradual increase. Many households, for example, may have chosen to wait before purchasing an additional vehicle, or to decide not to scrap vehicles that they otherwise would have. This distinction between short-run and long-run adaptation is relevant for interpreting the air quality evidence. The impact of driving restrictions on air quality is likely to be largest immediately after implementation because the opportunities for adaptation are most limited in the short run. This makes the lack of evidence of an improvement in air quality in the RD specification particularly striking.

### D. *Substitution to Taxis*

An additional possible explanation for the lack of evidence of an improvement in air quality is the increased use of taxis. In 1989, when HNC was implemented, there were 75,000 taxis in Mexico City, or approximately one taxi for every 100 residents.[30] In comparison, New York City has approximately one taxi for every 600 residents and Beijing has

[29] Beaton et al. (1992) document the correlation between vehicle age and carbon monoxide emissions in a sample of 49,700 vehicles in four cities, finding that each additional year increases vehicle emissions by approximately 16 percent. Furthermore, using remote sensing evidence on 30,000 vehicles recorded in Mexico City in the summer of 1990, they show that in Mexico City a small number of vehicles are responsible for a substantial portion of total emissions. Of the vehicles surveyed, half of all carbon monoxide emissions are derived from 24 percent of the fleet and half of hydrocarbon emissions are derived from 14 percent of the fleet. Because the distribution of emissions per vehicle is skewed to the right, the addition of a relatively small number of so-called mega-polluters can substantially increase average emissions.

[30] According to the Mexican Census of Population, INEGI, Censo General de Población y Vivienda 1990, Mexico City had 8,200,000 residents in 1990. Taxi registrations come from INEGI, Estadísticas de Transportes, Vehículos de Motor Registrados en Circulación (2007).

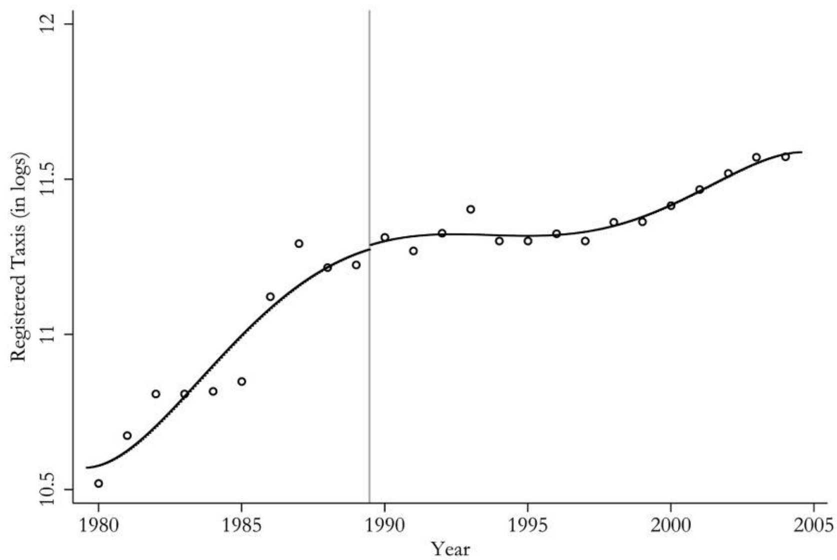


FIG. 11.—Taxis in Mexico City, 1980–2004. Source: INEGI, Estadísticas de Transportes, Vehículos de Motor Registrados en Circulación, 2007.

one taxi for every 175 residents.[31] This unusually large stock of taxis in Mexico City was well positioned to absorb any increase in demand from HNC.

Figure 11 plots the number of taxis in Mexico City during the period 1980–2004 as well as a fifth-order polynomial in time with an intercept at 1990. The coefficient on the intercept is small and not statistically significant, .013 (.059), providing no evidence of a change in the number of taxis associated with the introduction of HNC. As reported in table 11, results are similar for alternative specifications of the time trend. In order to operate as a taxi in Mexico City, one needs a taxi concession from the City Department of Transportation.[32] During the 1980s the number of taxis in Mexico City increased by 7.8 percent per year compared to less than 1 percent per year during the 1990s. This

[31] According to the New York City Taxi and Limousine Commission, there were 13,000 taxis in New York City in 2007 compared to a 2005 population of 8.0 million according to the U.S. Census Bureau, American Fact Finder. According to the official Web site of the 2008 Beijing Olympics, there are 60,000 taxis in Beijing, compared to a population of 10.7 million reported by the UN Population Division (2004).

[32] During this period, concessions could be purchased from the Department of Transportation (Secretaría de Transportes y Vialidad) for approximately $2,000 (in U.S. 2006 dollars). However, evidence from the market for used taxis described below indicates that during 1989 and 1990 the implied price of a concession in secondary markets was substantially below $2,000, consistent with little change in the number of taxis during 1989 or 1990.

TABLE 11
EFFECT OF HNC ON THE NUMBER OF TAXIS IN MEXICO CITY: REGRESSION DISCONTINUITY EVIDENCE

| | Coefficient | Standard Error |
|---|---|---|
| Fourth-order polynomial time trend | −.021 | (.075) |
| Fifth-order polynomial time trend | .013 | (.059) |
| Sixth-order polynomial time trend | −.007 | (.065) |

NOTE.—This table reports estimates that correspond to three separate regressions. All specifications include 1980–2005. In all three rows the dependent variable is the number of registered taxis by year in Mexico City (in logs). The reported coefficients correspond to 1(HNC), an indicator variable equal to one after the implementation of HNC. Specifications include flexible polynomial time trends as indicated. In accordance with findings from standard diagnostic tests of serial correlation, reported standard errors are estimated following Newey and West (1987) with a 1-year lag.

large increase in taxis during the 1980s, due in part to taxi concessions being given away as political gifts, caused the stock of taxis to be unusually large relative to international and historical standards just at the time that HNC was implemented.

This unusually large taxi fleet could have easily accommodated a substantial increase in utilization. According to a recent governmental study (Gobierno del Distrito Federal, Secretaría del Medio Ambiente 2004*b*), private vehicles in Mexico City travel approximately 36 kilometers per day.[33] With 460,000 private vehicles banned from driving each weekday, this implies that HNC displaced 16.6 million kilometers per day, or 221 kilometers per day per taxi. Although it seems unreasonable that taxis could have accommodated this entire increase in demand for trips, a substantial proportion of these trips could have easily been accommodated by an increase in the number of hours worked per day.

Any increase in taxi utilization would have likely had a negative impact on air quality because during this period taxis in Mexico City were among the highest-emitting vehicles in circulation. First, most taxis in Mexico City during this period were Volkswagen Beetles. The Beetle has always been a relatively high-emitting vehicle, leading the U.S. EPA to ban sales of new Beetles beginning in 1977. The air-cooled design makes the vehicle difficult to adapt for use with emissions-reduction equipment, and none of the Beetles during this period had catalytic converters.[34] Second, the taxi fleet in Mexico City during this period was unusually old. According to Streit and Guzmán (1996), the average age of taxis in Mexico City in 1990 was 11 years, compared to 8 years for

[33] No such measure is available for the period prior to HNC.

[34] Supporting evidence comes from Riveros, Cabrera, and Ovalle (2002), who examine emissions testing evidence from VW Beetles and other vehicles in Mexico City. They find that the median 1992 VW Beetle emits four times as much carbon monoxide as the median 1992 VW Golf or VW Jetta. This analysis is only partially relevant because by 1992 all these vehicles were equipped with catalytic converters. Nevertheless, the study provides suggestive evidence about the potential emissions characteristics of the air-cooled Beetles.

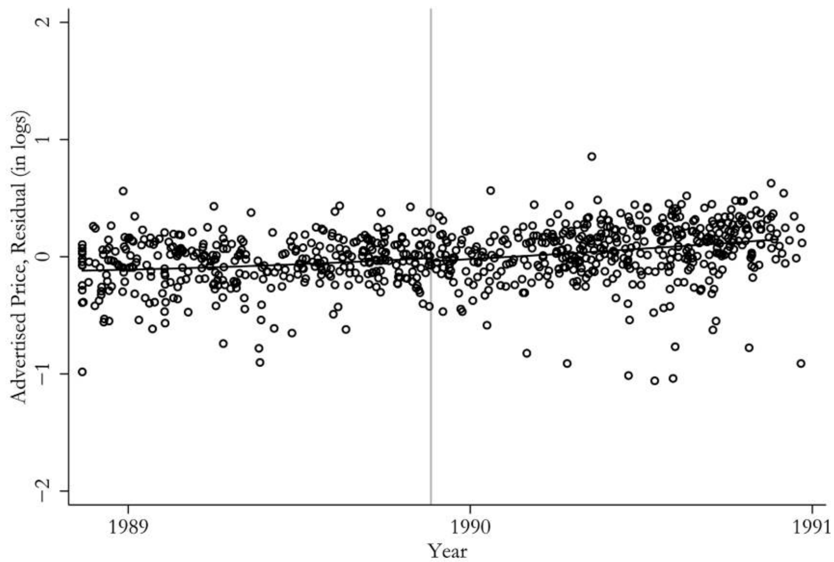


FIG. 12.—Taxi prices in Mexico City, 1988–90. Source: *El Universal*, Sunday vehicle section, November 1988–November 1990.

private cars. Moreover, because taxis tend to be used more intensively than private automobiles, their effective age was much older. Third, taxis tended to be tuned for peak power, a practice that according to Beaton et al. (1992) was common in Mexico City during this period and increases carbon monoxide emissions by as much as a factor of two. The chronically underpowered Beetle (44 horsepower) and other taxis were prime candidates for such tuning.

An increase in taxi utilization should have caused the value of a taxi concession to increase. Taxis in Mexico City are sold together with taxi license plates, and thus the concession to operate as a taxi. Figure 12 describes advertised prices for taxis in Mexico City over the period November 1988 to October 1990, as well as a third-order polynomial in time.[35] Observations are residuals from a regression of price (in logs) on a cubic in vehicle age, indicator variables for different taxi models, and interactions between a cubic in vehicle age and the model indicator

[35] Classified advertisements were compiled with generous assistance from Guillermo Cerón at the Mexican National Periodicals Library. The sample includes all taxis advertised in the Sunday edition of *El Universal*, a major Mexico City newspaper, over this 2-year period. Date of advertisement, the model of the vehicle, asking price, and vehicle age were recorded for all taxis and transit vans. In almost all cases mileage is not provided in the advertisements, so mileage is not included as a covariate. Alternatives to examining classified advertisements would have been to examine taxi ridership directly or to examine records of actual sales of taxi concessions, but neither is available.

TABLE 12
EFFECT OF HNC ON USED VEHICLE PRICES IN MEXICO CITY: REGRESSION DISCONTINUITY EVIDENCE

| | Coefficient | Standard Error |
|---|---|---|
| | Taxi Prices | |
| Second-order polynomial time trend | −.022 | (.025) |
| Third-order polynomial time trend | −.027 | (.033) |
| Fourth-order polynomial time trend | −.028 | (.033) |
| | Transit Van Prices | |
| Second-order polynomial time trend | .069 | (.062) |
| Third-order polynomial time trend | .025 | (.074) |
| Fourth-order polynomial time trend | .023 | (.074) |

NOTE.—The table reports estimates that correspond to six separate regressions. The sample includes all advertisements in the Sunday edition of *El Universal* between November 1988 and November 1990. In rows 1–3, the dependent variable is the advertised price of taxis (in logs). In rows 4–6, the dependent variable is the advertised price of transit vans (in logs). The table reports coefficients for 1(HNC), an indicator variable for the period after the implementation of HNC. Specifications include flexible polynomial time trends as indicated as well as a cubic in vehicle age, model indicator variables, and interactions between a cubic in age and the model indicator variables. Reported standard errors are robust to heteroskedasticity.

variables. The figure provides no evidence of an increase in taxi prices associated with HNC. As reported in table 12, the coefficient on the HNC indicator is −.027 (.033).[36] Still, this lack of evidence of an increase in the implicit price of a taxi concession does not rule out the possibility that taxi utilization increased. As shown above, the taxi fleet was unusually large, potentially severely diluting any capitalization effect. Furthermore, taxi fares are controlled by the Department of Transportation, did not change during this period, and were very low compared to international standards, limiting the benefits to taxi owners from any increased demand.

Similarly, figure 13 describes advertised prices for Volkswagen transit vans in Mexico City over the same period. During the 1980s in Mexico City there was a large increase in privately owned small-occupancy buses, and these vans were used extensively for this purpose. Whereas the public buses considered in Subsection *B* follow major routes and make regular stops, these smaller vehicles follow less traveled routes and allow riders to start and stop anywhere. As with taxis, these vehicles operate with concessions from the City Department of Transportation, and the number of vans in Mexico City was relatively constant during this period, ranging between 7,971 and 8,042 during the years 1988–91, so any increase in demand for utilization should be reflected in the value of a concession.[37] The estimated HNC intercept is .025 (.074), providing

[36] If individuals are forward-looking, the market should respond to the announcement of the program on November 6, 1989, rather than the implementation 2 weeks later. When this earlier date is used as the threshold, the results are very similar.

[37] Van registrations come from INEGI, Estadísticas de Transportes, Vehículos de Motor Registrados en Circulación, 2007.

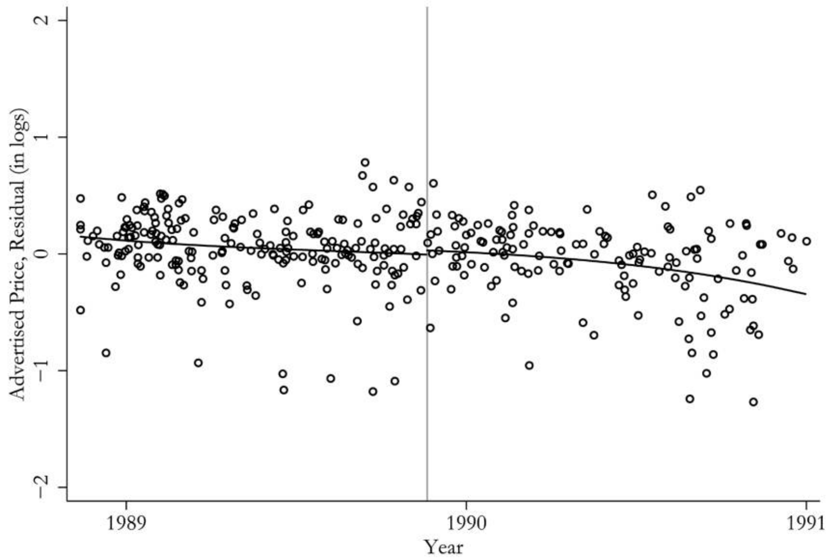


FIG. 13.—Transit van prices in Mexico City, 1988–90. Source: *El Universal*, Sunday vehicle section, November 1988–November 1990.

no evidence of a change in van prices. Table 12 reports estimates for alternative specifications of the time trend. This finding is consistent with the ridership results described in Subsection *B*, providing further evidence that HNC did not lead to an increase in public transportation.

## V. Cost-Benefit Analysis

An appealing feature of the empirical estimates in Sections III and IV is that they provide some of the information necessary to evaluate whether or not HNC passes a cost-benefit test. A large literature documents the social benefits of improved air quality. World Bank (2002) finds that the annual benefits of a 10 percent reduction in ozone and particulates (PM10) in Mexico City would be approximately $882 million (in 2006 U.S. dollars). Evidence from recent studies in the United States implies that the benefits from improved air quality could be even larger. For example, estimates from Chay and Greenstone (2003) imply that a 10 percent reduction of total suspended particulates (TSPs) would reduce the number of infant deaths in Mexico City by 800 per year.[38] From

[38] Chay and Greenstone use within-state, cross-county variation in changes in TSPs induced by the 1981–82 recession to estimate the impact of TSPs on infant mortality, finding that a 1 percent reduction in TSPs results in a 0.35 percent decline in the infant mortality rate. In calculations of the reduction in infant deaths, the birth rate and infant mortality rate for Mexico for 1990 were used from the 2006 edition of the World Bank's *World Development Indicators*.

the baseline value of a statistical life used in the World Bank study ($1.85 million), this hypothetical 10 percent reduction would imply annual benefits of $1.48 billion from reduced infant mortality alone.[39] However, although the potential benefits from improved air quality are large in magnitude, there is no evidence that these benefits were realized with HNC. Across specifications in Section III, there is no evidence of a reduction in pollution levels for any of the five criteria pollutants. Perhaps most important for human health, there is no evidence of a reduction in extreme concentrations. This lack of evidence of benefits makes it difficult to justify the program in terms of cost-effectiveness regardless of the exact magnitude of the social costs.

Driving restrictions impose social costs because they prevent drivers from using a preferred mode of transportation. As a starting point, consider a model of transportation choice in which individuals derive utility from a vector of transportation goods, a nonpolluting composite consumption good, and air quality.[40] Furthermore, suppose that air quality depends on the quantity of each transportation good consumed as well as the emissions characteristics of those goods. The market failure in such models is that individuals do not take into account the social benefits of air quality when making transportation choices. As a result, the equilibrium level of air quality is lower than the socially optimal level. The market failure is particularly severe in a case such as Mexico City because the private cost of emissions is small relative to total social costs. Driving restrictions attempt to address this market failure by imposing quantity constraints on one or more transportation goods. However, quantity restrictions do not guarantee an improvement in air quality. The effect of driving restrictions on air quality depends on the pattern of substitution across transportation goods and the emissions characteristics of these substitutes. If, for example, restrictions induce substitution toward a high-emissions alternative such as used vehicles, air quality may actually decline.

The model described above can be used to characterize the social costs from forcing drivers to make suboptimal transportation choices. In particular, if the marginal utility of the composite good is constant, then social costs are equal to total willingness to pay to avoid HNC. This willingness to pay is not directly observable. However, evidence from Section IV.*C* provides an indirect measure. The evidence from vehicle

[39] Estimates based on housing market differentials imply even larger potential benefits, incorporating both health and nonhealth benefits. Using county attainment status as an instrument for changes in TSPs to measure the effect of air quality on housing values, Chay and Greenstone (2005) find an elasticity of housing values with respect to TSP concentrations of −.20 to −.35. Even for conservative estimates of the value of the housing stock in Mexico City, these estimates imply substantially larger potential social benefits.

[40] See Baumol and Oates (1988, chap. 4) for a standard general equilibrium model of externalities.

registrations indicates that HNC led thousands of individuals to purchase additional vehicles. These purchases indicate that individuals were willing to pay the cost of an additional vehicle in order to circumvent the driving restrictions, so total increased vehicle expenditures provide a proxy for social costs. Households in the 2005 Mexican National Household Survey of Income and Expenditure (Encuesta Nacional de Ingresos y Gastos de los Hogares)[41] report spending $1,053 in vehicle expenditures annually per vehicle, including $625 in vehicle purchases, $288 in maintenance, $83 in insurance, and $57 in licenses and fees. For the increase of 325,000 vehicles indicated in Section IV.*C*. this implies annual costs of $342 million.

A number of caveats are in order. This measure may overstate social costs because vehicles provide additional benefits beyond the ability to drive 5 days per week. For example, additional vehicles allow multiple drivers to drive simultaneously. Thus, prior to HNC, some households may have already been close to the margin between adopting and not adopting an additional vehicle, and expenditure exceeds willingness to pay for these households. However, there are other households that would have been willing to pay more than the observed expenditure in order to avoid HNC. When an individual is observed adopting an additional vehicle, this reveals that his willingness to pay exceeds the required expenditure, but his reservation price may have been much higher. Moreover, this expenditure-based measure understates total social costs because it excludes costs borne by individuals who were not led to purchase additional vehicles. When HNC was implemented there were 2.3 million vehicles in Mexico City. All vehicle owners were inconvenienced by the program. Many drivers were not made worse off enough to purchase an additional vehicle, but their losses should still be considered in the cost-benefit analysis. Furthermore, this measure of social cost excludes enforcement costs. HNC is enforced using the city police force and existing patrol cars, so the program did not have an immediate direct impact on the cost of municipal crime prevention; but increased attention to HNC restrictions likely reduced enforcement of other crimes, potentially below the socially optimal level.

Thus overall the evidence indicates that the social costs of HNC are large, likely in excess of $300 million annually. With 2.3 million vehicles affected by HNC, this is $130 per vehicle annually, or $2.50 for each day each vehicle is prevented from driving. HNC is a program that substantially altered transportation choices for millions of individuals,

[41] This is a nationally representative survey. Comparable surveys from 1989 or 1990 are not available. All amounts are in 2006 U.S. dollars. Costs per vehicle in the United States are much higher. In the Bureau of Labor Statistics, Consumer Expenditure Survey, 2004, households report spending $5,439 annually per vehicle, including $3,397 in vehicle purchases, $652 in maintenance, $964 in insurance, and $426 in licenses and fees.

yet yielded no apparent improvement in air quality, making it difficult to justify on the basis of cost-effectiveness.

## VI. Conclusion

This article examines the effectiveness of Mexico City's driving restrictions. Air quality is compared before and after the restrictions were implemented using high-frequency measures of five major air pollutants from monitoring stations. Across pollutants and specifications there is no evidence that the program improved air quality. The policy has engendered a relative increase in air pollution during weekends and non-peak weekdays, but there is no evidence of an absolute improvement in air quality during any period for any pollutant. This lack of evidence of an improvement in air quality is explained by examining data from a large number of different sources. Whereas it was hoped that the driving restrictions would cause drivers to substitute to low-emissions forms of transportation, there is no evidence of increased ridership of the subway, public bus system, or private bus system. Instead, evidence from vehicle registrations and automobile sales indicates 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. This pattern explains the lack of evidence of an improvement in air quality as well as the evidence from gasoline sales. In addition, although evidence from taxi registrations and used taxi prices provides no direct evidence of substitution toward taxis, the article describes how a relatively small increase in taxi utilization could have substantially contributed to the apparent lack of effectiveness of HNC. Overall, the pattern of behavioral responses indicates that the restrictions were unsuccessful in inducing drivers to substitute away from private vehicles.

The program in Mexico City has been since emulated in São Paolo, Bogota, and Santiago. Similar programs are currently being considered for Monterrey and Beijing. Driving restrictions may seem like a reasonable approach for addressing the difficult problem of urban air pollution. However, this article illustrates the importance of conducting ex ante economic analysis of the substitution patterns likely to be induced by these policies. Although the particular experiences will differ across contexts, the overall pattern of adaptation observed in Mexico City is likely to be repeated elsewhere. Drivers everywhere have a revealed preference for fast and convenient transportation and will find ways to circumvent rationing programs of this form. Depending on the emissions characteristics of available alternatives, these changes in behavior can seriously undermine the potential benefits.

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