Driving Restrictions That Work? Quito's *Pico y Placa* Program

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Programs to reduce traffic congestion and air pollution by restricting use of motor vehicles on working days have generally not met with success, given existing studies of such programs. We conduct the first study of Quito, Ecuador's three-year-old *Pico y Placa* program and find that it has reduced ambient concentrations of carbon monoxide (CO), a pollutant primarily emitted by vehicles, by 9-11% during peak traffic hours. During an extended daytime period that encompasses hours when population exposure to air pollution is likely to be highest, CO concentrations have been reduced by approximately 6%. Given that ambient concentrations of CO generally track the spatial and temporal distributions of traffic, these reductions in pollution suggest similar reductions in vehicle flows.

Keywords: driving restrictions, traffic congestion, air pollution, difference-in-differences

JEL Classification: R41, D62, Q53, C31, C54

1. Introduction

The social costs of traffic congestion have become difficult to ignore in many cities of the world. In developing countries, the costs of most concern are not just the longer travel times experienced by drivers, but also the health effects of the air pollution generated by the growing number of vehicles on the road. These vehicles are often "dirtier" than vehicles in developed countries, because of less stringent vehicles emissions regulations or use of "dirtier" fuels. The recently released 2010 Global Burden of Diseases Study (Lim et al. 2013) places air pollution among the top ten health risks worldwide, and among the top six in the developing countries of Asia. This is the first time that air pollution has appeared among the top ten risks since the first such study was conducted in 1990.

A number of studies have linked pollutants emitted by vehicles, including carbon monoxide, particulate matter and nitrogen oxides, to a range of adverse health effects (e.g., Loomis et al. 1999, Schwartz 1999, Kunzli et al. 2000, Friedman et al. 2001, Wilhelm and Ritz 2003, Metzger et al. 2004, and Currie and Walker 2011). In the setting of this study, Quito, Ecuador, two recent papers have linked carbon monoxide and other air pollutants to higher incidence of respiratory illnesses (Estrella et al. 2005 and Harris et al. 2011).

City governments have employed a variety of approaches to reduce traffic congestion. They range from improvements in public transport, dedicated lanes for high occupancy vehicles, to the congestion pricing schemes in place in London, Stockholm, Singapore, and Milan. These approaches are expensive for governments to implement, requiring substantial capital outlays. A number of cities, primarily in Latin American and Asia, have opted for a cheaper alternative: driving restrictions that limit use of vehicles at specific times of day in either all or part of a city. The best known example is the *Hoy No Circula* (HNC) program in Mexico City, introduced in 1989 in an effort to improve air quality. Under HNC, each private vehicle is barred from operating in the Mexico City metropolitan area on one weekday between the hours of 5 am and 10 pm. The restricted weekday is determined by the last digit of the vehicle's license plate. Sao Paolo (Brazil) introduced a similar program in 1996, also prompted by concerns about air quality, while Bogota (Colombia) introduced one in 1998 to reduce traffic congestion. Other cities in Colombia subsequently followed suit. Beijing, as well as other cities in China, introduced temporary driving restrictions during the 2008 Olympic Games to reduce traffic congestion and air pollution, with Beijing subsequently imposing permanent restrictions. Santiago has used a combination of permanent and temporary driving restrictions since 1998 to reduce air pollution in autumn and winter. Athens (Greece) first introduced driving restrictions in 1979 as a temporary measure to conserve fuel during the oil crisis. The restrictions were made permanent in 1982, with the revised objectives of reducing traffic congestion and air pollution. A similar set of objectives motivated the driving restrictions that have been in place in San Jose (Costa Rica) since 2005. Jakarta (Indonesia) is scheduled to introduce driving restrictions in an effort to alleviate traffic congestion.

The most recent city to have adopted driving restrictions is Quito. The *Pico y Placa* program was introduced in May 2010 with the objective of reducing air pollution and traffic congestion in the central part of the city during peak traffic hours on weekday mornings and evenings.

The programs in the various cities differ in the types of vehicles they target, the size of the restricted zone, and the times of day during which restrictions are in effect. But they generally share common goals of reducing either traffic congestion or air pollution, or both. A handful of studies have examined the effectiveness of these programs, focusing primarily on their ability to improve air quality. This focus reflects the availability of data on air quality and a paucity of data on traffic flows. Mexico City's program has received the most attention (Eskeland and Feyzioglu 1997, Davis 2008, and Gallego et al. 2011). The programs in Santiago, Beijing and Bogota have only recently been studied (Chen et al. 2011, de Grange and Troncoso 2011, Troncoso et al. 2012, Viard and Fu 2012, and Bonilla 2013). The predominant finding of these studies is that permanent driving restrictions have not been effective. By and large, they have not reduced traffic congestion or air pollution. Where reductions have been detected, they have been short-lived, lasting a few months to less than a year (Bonilla and Gallego et al.). The sole exception is the finding by Viard and Fu that Beijing's permanent driving restrictions have resulted in a significant reduction in particulate matter pollution. Perversely, there is evidence that the programs in Mexico City and Bogota have exacerbated pollution and congestion in the longer run by inducing drivers to buy additional vehicles to circumvent the restrictions. These additional vehicles tend to be older and hence more polluting.[1]

In this paper we present the first analysis of Quito's *Pico y Placa* (PyP) program. The program is well suited to study for a number of reasons: (i) the presence of restrictions only during peak (traffic) hours; (ii) a restricted zone that is limited to the central part of the city; and (iii) the availability of a fairly long time series of hourly pollution and meteorological data for the parts of the city that are subject to restrictions as well as those that are not. These features allow us to make use of difference-in-differences (DD) and difference-in-difference-in-differences (DDD) research designs that exploit both temporal variation and spatial variation to identify the effects of the program. We use pollution levels as our outcome measure, and define our treatment group to be the set of peak (traffic) hours inside the restricted zone.[2] We define two alternative control groups: (i) off-peak hours inside the restricted zone, and (ii) peak hours outside the restricted zone. We exploit temporal variation by using a DD strategy that compares the change in pollution during peak hours inside the restricted zone to the change in pollution during off-peak hours in the same zone. Spatial variation is exploited by using a DD strategy that compares the change in pollution during peak hours inside the restricted zone to the change in pollution during the same hours outside the restricted zone. Both types of variation are exploited simultaneously with a difference-in-difference-in-differences strategy.

The studies of Mexico City's HNC program (Eskeland and Feyzioglu, Davis, and Gallego et al.) as well as Bogota's *Pico y Placa* program (Bonilla 2013) have been limited to using temporal variation given the extensive spatial coverage of the programs. Existing studies of Santiago's temporary and permanent driving restrictions have also relied solely on temporal variation. The only other studies that exploit both temporal and spatial variation are those of Beijing's program (Chen et al. and Viard and Fu). However, the spatial variation they exploit is of a different variety.

[1] A driver with two vehicles can drive on every day of the week provided the last digits on the vehicles' license plates do not restrict their use on the same day.

[2] An unusual feature of this DD strategy is that the treated units are intervals of time instead of groups of individuals or political jurisdictions. As we discuss below, this raises the possibility that the untreated units, which are also intervals of time, are in fact affected by treatment.

Chen et al. use data for other cities in China as controls, while Viard and Fu use proximity of monitoring stations to roads in an effort to separate the contribution of motor vehicles to pollution readings from the contribution of other sources. In contrast, the spatial variation we exploit stems from the narrow geographic coverage of Quito's program and the presence of multiple pollution monitoring stations inside and outside the restricted zone. Unlike Chen et al. and Viard and Fu, we are able to make use of high quality, hourly data on ambient concentrations of carbon monoxide, a pollutant that is primarily emitted by motor vehicles.[3]

The temporal variation we exploit also differs from that in existing studies. Given the limited number of hours of the day that PyP is in place, we take advantage of diurnal variation in pollution levels to identify its effects, whereas existing studies employ either inter-day variation or, more commonly, before-and-after program introduction, or program modification, variation. A final difference in our approach is that we make use of year-month, or year-week, fixed effects to control for time-varying confounding factors, as opposed to the polynomial time trends used in other studies.

We show that PyP has been successful in achieving modest, but significant, reductions in air pollution. The DD and DDD strategies yield very similar estimates of the reduction in CO concentration during peak traffic hours–between 9% and 11%. For an extended daytime period that encompasses the hours when population exposure to air pollution is likely to be highest (6 am to 8 pm on working days), CO concentrations have been reduced by approximately 6%. Though somewhat diminished, the reductions have persisted two years after the start of the program. Given that ambient concentrations of CO generally track the spatial and temporal distributions of traffic (as discussed in Section 3.2), these reductions in pollution suggest similar reductions in vehicle flows.

In the next section, we present a review of the existing literature on driving restrictions. In Section 3 we provide some more detail about the PyP program, along with background information about Quito and its air quality. Our empirical strategy is described in Section 4. In Section 5, we

[3]Because of limited reporting of air quality in Beijing, Chen et al. and Viard and Fu are forced to rely on an index of daily maximum air pollution or a remotely-sensed, indirect measure of air quality.

present and discuss our results. The final section contains some concluding observations.

2. Existing Literature

The driving restrictions program in Mexico City (HNC) has received by far the most attention. Eskeland and Feyzioglu (1997) were the first to assess its effectiveness. They examine changes in gasoline demand over time and find that demand increased after the imposition of HNC, instead of decreasing. Davis (2008), in a more detailed analysis of the program, finds no evidence that HNC has reduced gasoline consumption or that it has improved air quality. Instead he finds evidence, using a regression discontinuity design, that it has resulted in a relative increase in air pollution on weekends and during nighttime hours on weekdays (when HNC is not in effect), implying a temporal shift of driving from restricted hours to unrestricted hours. Both sets of authors present evidence that HNC has resulted in purchases of additional cars to circumvent the restriction, with a disproportionate increase in purchases of used cars. These cars are likely to be more polluting than new cars and less fuel efficient, thereby providing an explanation for the absence of improvements in air quality or reductions in gasoline consumption.

Gallego et al. (2011) also study HNC, focusing attention on changes in ambient concentrations of CO, a pollutant that is typically emitted primarily by motor vehicles. They find that HNC reduced average ambient CO concentration during peak hours by 11% in the short run, but after an 11-month adjustment period it raised the average concentration by 13%.

de Grange and Troncoso (2011) examine the permanent driving restrictions that have been in place in Santiago since 1998 in autumn and winter. The restrictions are in effect only during morning rush hours and only target vehicles without catalytic converters. They find that the permanent restrictions have had no effect on traffic flows. They also examine additional, temporary restrictions that are imposed on days designated as environmental "pre-emergencies" because of poor air quality. On these days, vehicles with and without catalytic converters are restricted. They find that these temporary restrictions do reduce traffic flows. de Grange and Troncoso argue that given the infrequent, sporadic nature of the temporary restrictions, the incentive for drivers to buy additional vehicles to circumvent the restrictions is weak. Drivers find it more cost-effective to time-shift their morning commute or take public transport. The effectiveness of Santiago's temporary restrictions is corroborated in a subsequent study by Troncoso et al. (2012), which examines their effects on air pollution. They find that the temporary restrictions reduce daily average concentrations of a number of air pollutants on weekdays but not on weekends.

Chen et al. (2011) study the air quality effects of measures imposed before, during and after the Beijing Olympic Games. Identifying the effects of the temporary driving restrictions imposed before and during the Games is difficult because they were combined with other measures to reduce air pollution. The task is further complicated by the absence of detailed air quality data. Only a daily maximum air pollution index (API) is available, with the most prominent pollutant identified if the API exceeds 50. Chen et al. supplement the API data with data on aerosol optical depth (AOD), a remotely-sensed, indirect measure of air pollution. They find that the stringent, temporary driving restrictions imposed during the Games were effective in reducing both API and AOD, but the less stringent, permanent restrictions imposed after the Games were not. Viard and Fu (2012) study the permanent post-Olympics restrictions using a longer sample than Chen et al., but rely exclusively on the API data. They find that the restrictions reduced particulate matter pollution by 7-19%.

Bonilla (2013) conducts a detailed study of Bogota's *Pico y Placa* program. For the first ten years of its existence, the program only restricted vehicles during morning and evening peak hours. In 2009, the restrictions were extended to cover 14 hours of the day. The program's history allows Bonilla to study not only the short-run and long-run effects of the restrictions, but also the effect of the increase in their stringency. Using data on ambient CO concentrations, he studies the program's effectiveness using a regression discontinuity design framework that incorporates an autoregressive distributed lag model. He finds that the program reduced CO concentrations in the first few months after its introduction in 1998, but the reductions subsequently disappeared. Similarly, the increase in program stringency in 2009 reduced CO concentrations during off-peak hours, as desired, but these reductions were sustained for less than a year. Over the long run, Bonilla finds that the increased stringency resulted in higher CO concentrations during both peak and off-peak hours. He attributes this increase to household purchases of additional vehicles to circumvent the more stringent restrictions.

In sum, existing studies indicate that permanent driving restrictions have, by and large, not been successful in reducing air pollution or traffic congestion. In the case of Mexico City and Bogota, there is evidence that the restrictions have exacerbated both problems. The sole exception is Viard and Fu's study of Beijing's permanent restrictions.

3. Background

3.1 Pico y Placa

Pico y Placa went into effect in Quito on May 3, 2010. The program is subject to review, and possible cancellation, every six months. It has been extended repeatedly and remains in effect today. It restricts access to the central part of the city during weekday peak (traffic) hours: 7:00-9:30 am and 4:00-7:30 pm. There are no restrictions on weekends or holidays. Figure 1 shows the area subject to restrictions.

PyP targets both privately-owned and government-owned light vehicles, namely, motorcycles, cars, SUVs, and pickup trucks (Agencia Publica de Noticias de Quito 2010). Taxis and other forms of public transport are exempt, as are all heavy vehicles. As is the case for programs elsewhere, the last digit of a vehicle's license plate number determines the one day of the week on which the vehicle is barred from the road. The assignment of digits to days of the week has not changed since the program's introduction.[4]

Pico y Placa was motivated by a number of objectives as reflected in the formal regulation: (i) reducing emissions of conventional mobile-source pollutants as well as emissions of greenhouse gases; (ii) reducing traffic congestion during rush hours; and (iii) reducing gasoline and diesel fuel consumption in order to lower government expenditures on subsidies to these fuels (Alcaldia Metropolitano de Quito 2010). In principle, during the hours when it is in effect, PyP reduces the number of targeted vehicles on the road by up to 20%. On a daily basis, the municipal government anticipated a 2.36% reduction in the number of vehicles on the road, and an equal reduction in vehicular emissions (Empresa Municipal de Movilidad y Obras Publicas 2010).

[4] The programs in both Bogota and Beijing alter the assignment periodically in an effort to reduce the incentive to purchase additional vehicles to circumvent the restrictions (Bonilla, and Viard and Fu).

Drivers were expected to respond to PyP by making greater use of public transportation and by increasing ride-sharing in private cars or taxis, as well as shifting the times at which they drive in the restricted zone (Empresa Municipal de Movilidad y Obras Publicas 2010). To facilitate changes in transportation habits, the municipality established a number of free parking areas on the periphery of the restricted zone at which drivers can leave their vehicles and switch to public transportation.

Compliance with the restrictions are enforced by both the metropolitan police and the national police. Sanctions for violating the restrictions are stiff. Vehicles found in violation are impounded for one day (first violation) to five days (third and subsequent violations). In addition, violators must pay fines that are linked to the government-determined minimum monthly wage. One-third of the monthly wage must be paid for the first violation (USD 97 as of 2012), half the monthly wage for the second violation, and the full monthly wage for the third and subsequent violations (USD 292 as of 2012). Available evidence suggests that enforcement of the program has been strict, with 55,000 violations punished over the first 13 months of the program's existence (Empresa Municipal de Movilidad y Obras Publicas 2011, 2012), and 40,691 violations punished in 2012 (Municipio del Distrito Metropolitano de Quito, Secretaria de Movilidad 2012).

3.2 Air Pollution

The city of Quito is situated in a valley and is part of the larger Metropolitan District of Quito (MDQ). A recent report on air quality in the MDQ indicates that mobile sources account for over 95% of carbon monoxide (CO) emissions, approximately 15% of sulfur dioxide (SO_2) emissions, and approximately 50% of both nitrogen oxides (NO_X) and particulate matter (PM) emissions (Municipio del Distrito Metropolitano de Quito, Secretaria de Ambiente 2012, p. 42).[5] These estimates are for all vehicles, including those that are not subject to PyP, such as taxis, buses, trucks and other heavy vehicles. A more detailed 2007 emissions inventory for the MDQ indicates that vehicles subject to PyP account for 57.7% of CO emissions, 4.4% of SO_2 emissions, 18.9% of NO_X emissions, 5.1% of PM10 emissions, and 6.5% of PM2.5 emissions (CORPAIRE 2009a, pp.

[5] Exact numbers are not provided because the report only presents the information in a bar chart.

22-23).[6] The 2007 emissions inventory also provides estimates of the proportion of total MDQ pollutant emissions that originate within the city boundaries: approximately 50% for CO, 37.8% for SO_2, 33% for NO_X and 18% for PM10 (CORPAIRE 2009a, pp. 30-31).[7]

The above estimates suggest that the effects of PyP on air quality are most likely to be detected by examining changes in ambient concentrations of CO. Whether changes in *ambient concentrations* of CO reflect changes in vehicular *emissions* of CO depends on how closely ambient concentrations track changes in emissions. In general, the relationship between ambient concentrations of a pollutant and vehicular emissions of the pollutant depends on a number of factors, including the chemical reactivity of the pollutant, meteorological conditions, and the topography of the area. CO is a non-reactive pollutant that dissipates relatively quickly and its ambient concentrations generally follow the spatial and temporal distributions of vehicular traffic. This is true in Quito, as well as elsewhere (CORPAIRE 2009b, p. 54; Jaffe 1968; Tiao et al. 1975; Singh et al. 1990; Morawska et al. 2002; Schmitz 2005; and Kumar et al. 2008). Gallego et al. rely on CO to evaluate the effectiveness of Mexico City's program for similar reasons, as does Bonilla in his evaluation of Bogota's program.[8] However, as Gallego et al. and Bonilla point out, ambient CO concentrations are not a perfect proxy for traffic flows. Concentrations of CO and other pollutants are influenced by the presence of atmospheric temperature inversions. These prevent vertical mixing of air masses, causing pollutants to be trapped close to the ground (National Research Council 2003, Chapter 2).[9] The presence of inversions is not closely correlated with meteorological variables that are routinely measured, such as surface temperature, wind speed, and humidity. Thus, controlling for these

[6] PM2.5 and PM10 refer to particles that are less than 2.5 micrometers and 10 micrometers in diameter, respectively.

[7] No estimate is provided for PM2.5.

[8] Another candidate pollutant is ozone, but ozone does not closely track the temporal and spatial distribution of traffic flows. Ozone is generated from a sunlight-catalyzed reaction of pollutants emitted by vehicles that takes several hours to a day. Ozone concentrations can be high even on days when traffic flows are low, given similar meteorological conditions (e.g., see Chinkin et al. 2003 and Blanchard and Tanenbaum 2006).

[9] Temperature normally decreases with height above the earth's surface. This relationship is reversed if there is a temperature inversion. Establishing the presence of an inversion requires temperature measurements at various heights above the ground. Routinely reported air temperatures only measure temperatures at 2 meters above the ground.

variables does not control for the effect of inversions. Quito is susceptible to inversions (Brachtl et al. 2009, CORPAIRE 2009b, p. 54), as are other cities in which driving restrictions have been imposed, including Mexico City (Davis 2008), Santiago (Jorquera 2002), Bogota (Bonilla 2013) and Beijing (Li et al. 2005).[10] We return to the effect of inversions in Section 3.4 below.

The 2007 inventory of emissions in the MDQ also provides estimates of greenhouse gas (GHG) emissions. PyP vehicles account for a substantial 32.9% of carbon dioxide (CO_2) emissions and 57.4% of nitrogen dioxide (NO_2) emissions (CORPAIRE 2009a, p. 22). Quito's air quality monitoring network does not measure concentrations of GHGs, as a result we cannot study changes in their concentrations. However, the reductions we find for CO should imply that emissions of these GHGs have been reduced commensurately. More generally, CO is a broad indicator of vehicle emissions and hence of exposure to these emissions. For example, CO concentrations have been found to be closely correlated with concentrations of longer-lived, toxic organic pollutants emitted by vehicles, such as benzene (National Research Council 2003, pp. 57-64).

3.3 Air Quality Monitoring

Quito's air quality and meteorological monitoring network was established in mid-2003 and is operated by CORPAIRE (Corporacion Municipal para el Mejoramiento del Aire de Quito), the municipal organization charged with improving air quality. The network consists of several sub-networks. The relevant sub-network for this study is a set of eight automated monitoring stations (RAUTO) that continuously measure concentrations of CO and other pollutants in the city and its immediate surroundings. Hourly averages are made available to the public. An obvious concern is the accuracy of the pollution measurements. A U.S. Environmental Protection Agency (2008) audit of RAUTO concluded that the monitoring system is "accurate and well-implemented." Measurements of CO were described as being of "good quality." CORPAIRE's own evaluations indicate that between 2006 and 2011 over 95% of the measurements for each pollutant satisfied standard, international criteria for being classified as valid (Municipio del Distrito Metropolitano de Quito,

[10] Only Bonilla controls for the presence of inversions by including an inversion indicator variable that is based on data on temperatures at different heights above the ground.

Secretaria de Ambiente 2012, p. 37). We encountered relatively few missing observations in the time series that we worked with.

The locations of the RAUTO stations are shown in Fig. 1. Four stations are located inside the restricted zone–Belisario, Centro, Cotocollao and El Camal. The Cotocollao station's location at the edge of the restricted zone implies that air quality measurements at this station are likely to reflect traffic flows both inside and outside the zone, making it a weak candidate for inclusion in our treatment group. We therefore restrict our treatment group stations to Belisario, Centro and El Camal. Four stations are also located outside the restricted zone, but CO is measured at only two of them–Carapungo and Guamani. These two stations constitute our control group. Note that both these stations are within a few kilometers of the restricted zone. This proximity suggests that the stations are well suited to being in a control group, but it also raises the possibility that traffic flows in the vicinity of these stations are reduced by PyP, to the extent that traffic into the restricted zone originates or passes through these areas. In addition to these negative traffic spillovers from PyP outside the restricted zone, positive spillovers are possible, that is, PyP could result in increased traffic flows outside the restricted zone. For example, individuals who previously shopped within the restricted zone might now choose to shop outside it. We find no evidence of positive spillovers, and only limited evidence of negative spillovers. Any negative spillovers would result in the effect of PyP being underestimated given our DD strategy.

A number of the RAUTO stations also monitor meteorological variables. Given the varied topography of the city and its surroundings, data on local meteorological conditions are important, since factors such as wind speed have a strong influence on the relationship between vehicle emissions and ambient pollution concentrations (e.g., see Jaffe 1968, Tiao et al. 1975, Mukherjee and Viswanathan 2001, National Research Council 2003, Chapter 2, and Ito et al. 2007). Meteorological data are collected at Belisario, Carapungo, and El Camal, but not at Centro and Guamani. For the latter two stations we use data from the closest stations–in terms of distance and geography–at which meteorological data are collected, namely, Belisario and Los Chillos.

3.4 Carbon Monoxide Concentrations

Table 1 provides summary statistics for hourly CO concentrations for our sample period of January 2008 through December 2012. To facilitate isolating the effect of PyP from the effects of other time-varying factors, we do not use data prior to 2008 in our analyses.[11] The sample period selected encompasses a four-year window centered on the introduction of PyP. Table 1 reveals that mean and median concentrations are higher at the stations inside the restricted zone, as is the variability of concentrations.

The strategy we employ to identify the effects of PyP relies on differences over time in CO concentrations across monitoring stations–those inside the restricted zone versus those outside it– as well as across hours of the day–hours subject to PyP versus hours that are not subject to it. For this identification strategy to be valid, CO concentrations must be sufficiently localized in space and in time. If this is not true, our strategy will underestimate the effects of PyP. As noted in Section 3.2, the literature on air pollution meteorology indicates that CO concentrations are localized in space and in time. Evidence specific to Quito can be found in the monitoring station data. Localization of CO concentrations in space can be verified by examining the correlation of hourly CO concentrations across stations in Table 2. The correlations range from 0.23 to 0.77. The highest correlation between a station inside the restricted zone and one outside it is 0.53 (between Carapungo and El Camal). The inverse relationship between the correlations and distance between stations is illustrated in Fig. 2. Note that some degree of spurious correlation between stations will be present simply because of the coincidence of high CO concentrations during peak (traffic) hours.

The localized nature of CO concentrations in time can be verified by examining their diurnal variation. Figure 3 illustrates this variation using data for Centro, which is representative of the other stations. Note that the CO concentration reported (and plotted) for a given hour captures the average of CO concentrations measured at that hour and at five 10-minute intervals after it. For example, the CO concentration reported for 7 am reflects the average of readings taken at 7:00,

[11] Anomalies in some of the meterological data for earlier years also influenced our decision to use data from 2008 onwards.

7:10, 7:20, 7:30, 7:40 and 7:50 am.[12] Figure 3 reveals wide swings in concentration over the course of the day, especially on weekdays, with substantial variation over spans of just one to three hours.

The weekday trace in Figure 3 shows a pronounced double hump, with a sharp early morning peak around 7 am and an evening peak about 12 hours later. The higher morning peak reflects, in part, the effect of temperature inversions. In Quito the effect of inversions is strongest in the early morning hours, between 6 and 8 am, before the sun warms the earth's surface, breaking up the inversions (Brachtl et al.). This is also borne out by a comparison of estimates of diurnal variations in mobile source *emissions* of CO (CORPAIRE 2009a, p. 33), which reflect traffic flows, and the traces in Figure 3, which show CO *concentrations*. The reported morning emissions peak typically occurs between 8 am and 9 am, about an hour later than the concentration peak, while the evening emissions peak occurs between 5 pm and 7 pm, which corresponds more closely to the evening concentration peak. The influence of inversions should not be a significant issue for our analysis given that we rely on difference-in-differences (DD) strategies to identify the effects of PyP. This is especially true of the DD strategy that relies on differences in CO concentrations between stations inside and outside the restricted zone. For the DD strategy that relies on differences in pollution between peak and off-peak hours, we test for the effect of inversions by estimating models using data for only the evening peak hours when inversions are not present.

Following practice in the existing literature on driving restrictions, we use the natural log of pollutant (CO) concentration as our measure of pollution. An advantage of using the log, rather than level, of pollutant concentration in a DD framework is that it reduces the likelihood of confounding the effects of driving restrictions with the effects of reductions over time in average vehicle emissions per mile traveled. Such reductions could arise simply because of increases in the average fuel efficiency of vehicles on the road. *Ceteris paribus*, reductions in emissions per mile traveled would increase the magnitude of differences in vehicular CO emissions, and hence in ambient CO concentrations, between locations (or periods) with high traffic flows (i.e., inside the restricted zone) and those with low traffic flows (outside the restricted zone). This is not true

[12] Personal communication with Valeria Diaz, Secretaria de Ambiente, Distrito Metropolitano de Quito, February 8, 2013.

of differences in log CO because these differences track the ratio of emissions between the two locations. This ratio would not be altered by a reduction in emissions per mile traveled alone. However, a relative or absolute reduction in vehicle flows at high-traffic-flow locations would lower the ratio, as desired.

4. Empirical Strategy

The identifying assumption underlying DD strategies is that of a common trend for the treatment and control groups in the absence of treatment. In our setting, with log CO as the dependent variable, the assumption implies that the percentage change in CO concentrations over time is the same for the two groups. To the extent that CO concentrations track vehicle flows, this is equivalent to assuming that the percentage change in vehicle flows is the same for the two groups. The treatment group in our DD strategies is peak-hours on working days inside the restricted zone, i.e., the set of hours during which PyP is in effect. There are two plausible candidates for control groups: (i) same-station pollution during non-peak hours, and (ii) same-hours pollution at stations outside the restricted zone. To help identify suitable control groups, Figure 4 displays monthly averages of the value of log CO for three different subsets of working-day hours: peak hours (7-9 am and 4-7 pm), nighttime hours (9 pm-5 am), and off-peak hours (6 am, 10 am-3 pm, 8 pm). Restricting attention for the moment to Figure 4a, which displays averages for stations inside the restricted zone, we can see that the traces exhibit an overall downward trend, especially those for Belisario and Centro. This trend, which is present despite a growing number of registered vehicles in the DMQ, can be attributed to reductions in the average emissions per mile traveled of vehicles on the road. These reductions are associated with nation-wide improvements in the average fuel efficiency of vehicles and the quantity of pollutants they emit, and with a DMQ-wide program of vehicle emissions checks introduced in 2003 (the *Revision Tecnica Vehicular*). The program has steadily expanded its coverage over time (Fundacion Natura 2009, Municipio del Distrito Metropolitano de Quito, Secretaria de Ambiente 2012, p. 13).

Examining Figure 4a more closely reveals that for each of the three stations the peak-hours trace follows a different trend than the nighttime hours trace in the pre-treatment (pre-PyP) period–the traces are not parallel. This is not altogether surprising. An implication is that including nighttime hours in the control group will likely result in the common trend assumption not holding. We therefore exclude nighttime hours from our control group. The trace for the resulting "off-peak-hours" control group is close to parallel to the peak-hours trace over the pre-treatment period. This engenders some confidence in the common-trend assumption being satisfied when off-peak hours are used as the control group. Turning to the traces for the stations outside the restricted zone in Figure 4b, we see that for each of these stations the peak-hours trace is also close to parallel to the off-peak-hours trace.[13]

To the extent that the effects of PyP can be detected in Figure 4a, the traces present mixed evidence of a change in trend after the imposition of PyP. For Centro and El Camal there is a perceptible narrowing of the gap between the peak-hours and off-peak-hours traces. But this does not appear to be true for Belisario.

A concern with the use of off-peak hours as a counterfactual is the possibility that PyP has induced traffic to shift from peak hours to off-peak hours. Davis, and deGrange and Troncoso find evidence of such traffic shifting. Traffic shifting would imply that off-peak hours are influenced by "treatment," and would result in the effect of PyP on peak-hours pollution being overestimated. To the extent that we can detect such post-treatment traffic shifting in the off-peak traces in Figure 4a, there is little evidence of it. Our formal tests for traffic shifting, described in Section 5.3 below, yield no evidence that it has been significant.

Returning to Figure 4, a comparison of the traces for peak hours across stations reveals quite a bit of variation in trends. This is true not just across stations inside and outside the restricted zone, but also across stations inside the restricted zone. We nonetheless consider a DD strategy that uses same-hours pollution at stations outside the restricted zone as the control group. We do this for two reasons: this strategy is not susceptible to the traffic shifting problem; and more importantly, it allows us to evaluate whether traffic shifting into off-peak hours has in fact occurred. As noted above, this DD strategy is susceptible to possible spillover effects from PyP. However, the

[13] The traces in Figure 4b do not exhibit the overall downward trend found in Figure 4a. In these areas the increase in vehicle flows has presumably offset the reduced average emissions per mile traveled.

negative spillovers we detect would result in the effect of PyP being underestimated.

To control for differences in trends across stations as well as differences in trends between peak and off-peak hours, we also employ a difference-in-difference-in-differences (DDD) strategy. We describe this strategy, as well as our two DD strategies, in greater detail below. With all three strategies, we focus attention on working days, i.e., we exclude weekends and holidays, given that PyP is not in effect on these days.[14] But we also examine pollution on non-working days. At first blush, non-working days provide a ready opportunity to conduct placebo tests given that PyP is not in effect on these days. However, traffic flows, and hence pollution, on non-working days could be influenced by PyP, for at least two reasons. First, PyP could induce some shift in traffic from weekdays to weekends, as Davis finds in Mexico City. Second, changes in working-day travel behavior induced by PyP could spillover to non-working days. For example, an individual who has become accustomed to taking public transportation into the city center on working days because of PyP might choose to do the same on weekends.

4.1 Difference-in-Differences Strategy with Off-Peak-Hours as Controls

For our primary DD strategy, which relies on same-station off-peak-hours pollution as the control, we start with the simplest DD specification:

$$\log CO^i_{ymdh} = \alpha^i_0 + \alpha^i_1 Peak_h * After_{ymd} + \alpha^i_2 After_{ymd} + \alpha^i_3 Peak_h + \epsilon^i_{ymdh}, \quad (1)$$

where $\log CO^i_{ymdh}$ is the log of CO concentration at hour h of day d in month m of year y at station i, $After_{ymd}$ is an indicator variable that takes on a value of 1 from the start of PyP (May 3, 2010), and ϵ^i_{ymdh} is an error term. $Peak_h$ takes on a value of 1 for the peak hours of 7, 8, and 9 am and 4, 5, 6, and 7 pm. Given that the reported hourly CO concentration is an average of readings taken at 10-minute intervals starting on the hour and ending 50 minutes after the hour, pollution readings

[14] Considerable care was taken when identifying holidays, given that holidays are often moved or extended so that they are adjacent to weekends, and verifying the suspension of PyP on holidays. The latter task was facilitated by the existence of a Pico y Placa Twitter feed (twitter.com/picoyplacauio) that provides updates on the status of PyP.

for this set of peak hours extend 20 minutes beyond the restricted period in the morning (7:00-9:30 am) and evening (4:00-7:30 pm). As part of our robustness checks, we omit data for 9 am and 7 pm from the set of peak (and off-peak) hours; pollution readings then fall short of the restricted period by 40 minutes each morning and evening.

The coefficient of interest in the above model is α_1^i. It measures the change after introduction of PyP in the mean percentage difference between peak- and off-peak-hours pollution. Its sign will be negative if PyP has reduced peak-hours pollution relative to off-peak-hours pollution.

We extend the specification in eq. (1) incrementally to control for station and hour-of-week heterogeneity, time fixed effects, and meteorological factors, culminating in our preferred specification:

$$\log CO_{ymdh}^i = \alpha_0^i + \alpha_1^i Peak_h * After_{ymd} + \delta_{dh}^i + \mu_{ym}^i + W_{ymdh}^i \theta^i + \epsilon_{ymdh}^i, \tag{2}$$

where δ_{dh}^i is a full set of day-hour fixed effects obtained by interacting day of week and time of day, μ_{ym}^i is a set of 60 year-month fixed effects, W_{ymdh}^i is a vector of weather covariates and θ^i is an associated vector of coefficients.[15]

The day-hour fixed effects (δ_{dh}^i) allow for heterogeneity in pollution levels across hours of the week, e.g., they allow for pollution at 8 am on a Wednesday to differ in a systematic manner from pollution at 5 pm on a Friday. The year-month month dummies (μ_{ym}^i) capture the effects of time-varying factors that can influence CO concentrations during both peak and off-peak hours, such as seasonality, changes in the number of registered vehicles, changes in the average emissions per mile traveled of vehicles on the road, changes in the level of economic activity, and changes in fuel prices.[16]

The vector W_{ymdh}^i includes a host of meteorological variables that can influence CO concentrations. The set of variables is based on the pollution meteorology literature and past studies of driving restrictions. They are: temperature, relative humidity, precipitation, an indicator variable

[15] The inclusion of year-month fixed effects implies that the coefficient α_2^i in eq. (1) can no longer be identified; similarly, the inclusion of day-hour fixed effects implies that α_3^i can no longer be identified.

[16] Gasoline and diesel prices are regulated in Ecuador. Over the past decade they have changed infrequently, and by only a few percent.

that takes on a value of 1 for hours in which there is precipitation, solar radiation, atmospheric pressure, and wind speed interacted with one of eight dummy variables capturing the eight principal wind directions. With the exception of the precipitation indicator and atmospheric pressure, a quartic specification is used for all variables. A linear specification is used for atmospheric pressure because it exhibits little variation over time. As a result, polynomial terms are often collinear with the linear term. In total, there are 50 meteorological covariates for each station. Summary statistics for the meteorological variables are presented in Table A-1 of the Appendix.

We conduct two different placebo tests of this DD strategy by estimating the above models for: (i) non-working days, and (ii) stations outside the restricted zone. Subject to the possibility of spillovers mentioned above, the coefficient of interest should not have a negative sign for these regressions.

4.2 Difference-in-Difference-in-Differences Strategy

To control for factors other than PyP that might affect the relationship between peak and off-peak hours CO concentrations over time we make use of a difference-in-difference-in-differences (DDD) strategy. Conceptually, the strategy computes two pooled DD estimates. The first is obtained by estimating eqs. (1)-(2) using pooled data for the three stations inside the restricted zone. In the case of eq. (1), we do not allow any of the coefficients to vary across stations. But for eq. (2) we allow all but the coefficient of interest, α_1, to vary across stations. This pooled DD estimate, which we label α_1^{IN}, captures the average effect of PyP on peak-hours pollution inside the restricted zone with off-peak hours pollution inside the zone as the control. The second pooled DD estimate, α_1^{OUT}, is obtained in the same manner but using pooled data for the two stations outside the restricted zone. The DDD estimate is given by the difference $\alpha_1^{IN} - \alpha_1^{OUT}$.[17]

[17] We compute pooled estimates to faciliate exposition. An alternative approach would be to compute the full set of six DDD estimates given three stations inside the restricted zone and two outside it. As part of our robustness tests, we compute a pooled DDD estimate that excludes Carapungo from the control group.

Formally, our first DDD estimate is obtained using the simplest DDD specification:

$$\begin{aligned}\log CO^i_{ymdh} &= \beta_0 + \beta_1 Inside^i * Peak_h * After_{ymd} + \beta_2 Peak_h * After_{ymd} \\ &\quad + \beta_3 Inside^i * After_{ymd} + \beta_4 After_{ymd} + \beta_5 Inside^i * Peak_h \\ &\quad + \beta_6 Inside^i + \beta_7 Peak_h + \epsilon^i_{ymdh},\end{aligned} \tag{3}$$

where $Inside^i$ is an indicator variable that takes on a value of 1 for stations inside the restricted zone. The coefficient of interest, β_1, is by construction equal to $\alpha_1^{IN} - \alpha_1^{OUT}$.

The specification in eq. (3) is extended incrementally to incorporate a full set of *station-specific* fixed effects and meteorological covariates:[18]

$$\begin{aligned}\log CO^i_{ymdh} &= \beta^i_0 + \beta_1 Inside^i * Peak_h * After_{ymd} + \beta_2 Peak_h * After_{ymd} \\ &\quad + \mu^i_{ym} + \delta^i_{dh} + W^i_{ymdh}\theta^i + \epsilon^i_{ymdh}.\end{aligned} \tag{4}$$

4.3 Difference-in-Differences Strategy with Outside Stations as Controls

Our final DD strategy relies on same-hours pollution at stations outside the restricted zone as the control. We start by estimating the following basic model:

$$\log CO^i_{ymdh} = \gamma_0 + \gamma_1 Inside^i * After_{ymd} + \gamma_2 After_{ymd} + \gamma_3 Inside^i + \epsilon^i_{ymdh}. \tag{5}$$

The coefficient of interest is γ_1. It captures the change induced by PyP in the mean percentage difference between pollution levels inside and outside the restricted zone. γ_1 will have a negative sign if PyP has reduced pollution inside the restricted zone.

We estimate eq. (5) by pooling data for all stations. An alternative approach would be to estimate the equation using data for a single station inside the restricted zone and a single station outside it, and repeating this for each pair of stations. We choose to pool the data for all stations

[18] The coefficient β_3 in eq. (3) is no longer identified because the interaction term $Inside^i * After_{ymd}$ is collinear with the station-specific year-month fixed effects. Similarly, β_5 is no longer identified because $Inside^i * Peak_h$ is collinear with the station-specific day-hour fixed effects.

because it allows us to incorporate a common set of year-month fixed effects in the extended specification described further below. Among other things, these fixed effects correct for seasonal factors that influence CO concentrations.[19]

We once again extend the specification in eq. (5) incrementally to control for station and hour-of-week heterogeneity, time fixed effects, and meteorological factors, culminating in our preferred specification:

$$\log CO^i_{ymdh} = \gamma^i_0 + \gamma_1 Inside^i * After_{ymd} + \delta^i_{dh} + \mu_{ym} + W^i_{ymdh}\theta^i + \epsilon^i_{ymdh}, \tag{6}$$

where γ^i_0 captures station fixed effects, δ^i_{dh} is a full set of station-specific, day-hour fixed effects, and μ_{ym} is a common set of year-month fixed effects.

To assess the effect of PyP on peak-hours pollution, we estimate the above models using data for the set of peak hours defined above. We drop 9 am and 7 pm from this set as part of our robustness tests so that pollution readings do not extend beyond the restricted hours.

To assess whether PyP has shifted traffic from peak hours to off-peak hours, we also estimate eq. (6) using data for: (i) hours between the morning and evening peaks (10 am to 3 pm), and (ii) an extended daytime period stretching from 6 am to 8 pm (which includes pollution readings taken at 8:50 pm) that encompasses our set of off-peak hours. Traffic shifting by the light-duty vehicles targeted by PyP is likely to take place within this daytime period, rather than into late-night or early-morning hours. For the first case, γ_1 would have a positive value if PyP has simply shifted traffic from peak hours to between-peak hours. For the second case, γ_1 would have a value of zero if PyP has simply shifted traffic from peak hours to off-peak hours.

We estimate all of the above models using ordinary least squares. Serial correlation as well as contemporaneous correlation in pollution across stations are accounted for by clustering (robust) standard errors at the week level, with all stations in the same cluster. The gaps introduced in our time series by estimating models for subsets of hours of the day and week prevent us from using

[19] Making the year-month fixed effects station specific would result in the coefficient of interest, γ_1, in eq. (5) not being identified, because the interaction term $Inside^i * After_{ymd}$ would be collinear with the year-month fixed effects.

Newey-West standard errors.[20]

5. Results

5.1 Difference-in-Differences with Off-Peak Hours as Controls

We first present the results obtained using our primary DD strategy, which makes use of same-station off-peak hours pollution as the control. Table 3 displays the results for stations inside the restricted zone on working days. To conserve space, only estimates of the coefficient of interest (α_1^i in eqs. (1)-(2)) are presented. A larger set of coefficient estimates is presented in the Appendix in Table A-2.

The first entry in each row is the estimate obtained using the simplest DD specification in eq. (1). The second entry is for a specification that adds day-hour fixed effects, and the third is for one that adds year-month fixed effects. The last entry is for the preferred specification in eq. (2), which includes meteorological covariates. At all three stations, the table reveal significant post-PyP reductions in peak-hours CO concentrations relative to concentrations at off-peak hours. The reductions range from 6% at Belisario to 14% at El Camal.

We subject these estimates to a number of robustness tests by modifying the preferred specification in eq. (2) or the sample used to estimate it. The results of these tests are shown in Table 4. The first column presents estimates of α_1^i when the 60 year-month fixed effects are replaced with 262 year-week fixed effects, allowing for finer control of other time-varying factors. The second column presents estimates obtained using a shorter, symmetric sample: one that extends from two years before the introduction of PyP to two years after it, i.e., from May 2008 through April 2012. The symmetric sample reduces the possibility that seasonal effects not adequately controlled for by the year-month fixed effects influence our findings. The third column presents estimates obtained when 9 am and 7 pm are omitted from the set of peak hours. Data for these two hours reflect pollution readings taken 20 minutes after the end of PyP in the morning and evening, and could, in principle,

[20] An analysis of the residuals from regressions using hourly data for all days reveals an AR1 process. Therefore, clustering at the week level should adequately account for serial correlation. Bertrand et al. (2004) find that in DD regressions, nonparametric correction for serial correlation performs well given a large number of groups, as is true here given our clustering at the week level with five years of data.

dilute estimates of the effect of PyP on peak-hour pollution.[21] A comparison of the estimates in Table 4 with the base estimates in Column 4 of Table 3 reveals no meaningful differences.

To assess the possibility that these results reflect the effects of changes other than the imposition of PyP, we conduct two placebo tests. Since PyP is not in effect on holidays and weekends, one plausible placebo test is to estimate eqs. (1)-(2) using data for non-working days. Whether non-working days are well-suited to conducting placebo tests is open to question. As noted earlier, it is possible that PyP induces some traffic to shift from working days to non-working days, which would result in higher pollution levels on non-working days. Alternatively, changes in working-day travel behavior due to PyP could carryover to weekends, resulting in lower vehicle flows and pollution. The results in Table 5 offer some evidence of this carryover effect. For the specifications omitting the meteorological covariates, the estimates imply a small, but significant reduction in peak-hours CO concentrations post-PyP on non-working days at Centro and El Camal. But for our preferred specification, only the estimate for Centro is significant. The estimated reduction at Centro is half as large as the estimate for working days in Table 3 (4.85% vs. 10.04%). The carryover at Centro could be due to the fact that it is Quito's historic colonial center. The area, including its network of narrow roads, has been preserved, and is a tourist attraction that is congested even on weekends.

The second placebo test entails estimating eqs. (1)-(2) using data for stations outside the restricted zone. Ideally, PyP would result in no change in peak-hours pollution, and traffic flows, at these stations. However, as noted above, traffic flows could be reduced to the extent that traffic into the restricted zone originates or passes in the vicinity of the stations. Table 6 offers evidence of such negative spillovers for one of the two stations, Carapungo. As seen in Figure 1, Carapungo is located within two kilometers of the restricted zone. The estimate for our preferred specification implies a 3% reduction in CO concentration at this station. In contrast, there is no evidence of a reduction at Guamani, which is farther away from the restricted zone.

As noted in Section 3.4, inversions affect CO concentrations in the early morning hours. To check whether our results are influenced by these morning inversions, we estimate eqs. (1)-(2) using

[21] Whether the estimated effect is diluted depends on, among other things, whether atmospheric concentrations of CO respond to changes in traffic flows within 20 minutes.

data for only the evening peak hours, when inversions are not present. The results are presented in Table 7. Comparing these results to those in Table 3, obtained using both morning and evening peak hours, we see fairly small differences. For the preferred specification, the two sets of estimates are similar in magnitude.

Table 8 presents the results of running the placebo test using stations outside the restricted zone with only the data for evening peak hours. The significant reduction observed in Table 6 at Carapungo is no longer present. We suspect that this difference is due to the spillover effects of PyP outside the restricted zone being more diffuse during the longer evening peak hours (morning peak hours last 2.5 hours whereas evening peak hours last 3.5 hours).

5.2 Difference-in-Difference-in-Differences

The DDD strategy is arguably the most robust of our strategies for estimating the effect of PyP on peak-hours pollution. The first two rows of Table 9 present the estimates of α_1^{IN} and α_1^{OUT} obtained by estimating eqs. (1)-(2) using pooled data for stations inside the restricted zone and outside the restricted zone, respectively. Note that the estimate of α_1^{OUT} for our preferred specification is no different than zero. The third row presents the estimates of β_1 in eqs. (3)-(4). The estimate for the preferred specification implies that PyP has resulted in a 9% reduction in peak-hours CO concentrations inside the restricted zone. Note that, as should be the case, the estimates in the third row are equal in magnitude to the difference between the corresponding estimates in the first two rows, except for discrepancies in the fourth decimal place due to rounding.

The results of robustness tests applied to our preferred specification are shown in Table 10. In addition to our usual tests, in the last column we present the estimate of β_1 obtained when Carapungo is dropped from the set of control stations, leaving only Guamani. The estimates are all negative and significant, and are similar in magnitude to the base estimate.

Table 11 presents results of a placebo test based on estimating eqs. (3)-(4) using data for weekends and holidays. The estimates of β_1 are not significant, at conventional levels, for any of the specifications.

5.3 Difference-in-Differences with Outside Stations as Controls

Our final DD strategy makes use of same-hours pollution at stations outside the restricted zone as the control. The observed reduction in pollution at Carapungo post-PyP raises questions about its inclusion as a control in this DD strategy. It is clearly not an ideal control. We chose to include it to avoid the potential pitfalls associated with relying on pollution at a single outside station as a control. We explored the effects of excluding Carapungo, leaving only Guamani as a control. We found that this did not qualitatively change the results reported below. In most cases, the estimates of the coefficient of interest were very similar in magnitude. This was true, in particular, of estimates for daytime pollution levels on working days.

Table 12 displays the results from this DD strategy for working days. The first row in the table presents estimates of γ_1 in eqs. (5)-(6) when the equations are estimated using data for peak hours. In all cases, the estimates in this row are negative and significant. They do not differ appreciably in magnitude across specifications. The estimate for our preferred specification (in Column 4) implies that PyP has reduced peak-hours CO concentrations inside the restricted zone by approximately 11% relative to concentrations outside the restricted zone. This is very close in magnitude to the average 10% reduction estimated using our primary DD strategy with off-peak hours as controls (see the last entry in the first row of Table 9).

The entries in the second row of Table 12 are obtained by estimating eqs. (5)-(6) using data for hours between the morning and evening peak hours. The objective is to assess whether PyP has shifted traffic from peak hours to between-peak hours. Estimates with a positive sign would constitute evidence of such traffic shifting. However, the estimates are either negative or not significantly different from zero. This suggests that PyP has resulted, at worst, in no change in CO concentrations between peak hours, and at best in a slight reduction, as would be consistent with PyP resulting in fewer cars being driven into the city.

The entries in the third row are obtained by estimating (5)-(6) using data for an extended daytime period stretching from 6 am to 8 pm that encompasses our off-peak hours. If PyP has simply shifted traffic from peak hours to off-peak hours within this extended daytime period, the estimates in this row would be no different than zero. However they are negative and significant, in all cases. The magnitude of the estimate for our preferred specification implies a 6% reduction in CO concentrations during the extended daytime period.

The last row of Table 12 shows the outcome of estimating eqs. (5)-(6) using data for nighttime hours stretching from 9 pm through 5 am. These are the hours excluded from our off-peak hours control group. Strikingly, the entries in the last row are all positive and significant. They imply that in the post-PyP period there has been a significant increase in nighttime traffic inside the restricted zone compared to outside it. An analysis of subsets of hours within this nighttime period (the results of which are not shown), reveals that the largest increase is observed between midnight and 3 am.[22]

At first blush, this nighttime increase in pollution might lead one to conclude that PyP has induced traffic to shift from daytime hours to nighttime hours. But this is unlikely given that PyP targets light vehicles, namely motorcycles, cars, SUVs, and pick-up trucks. It is unlikely that operators of these vehicles would choose to drive them at night because they are restricted from doing so during the day.[23] It is especially unlikely that they would choose to drive them between midnight and 3 am, which is when the largest increase is observed. How then do we explain the relative increase in nighttime pollution inside the restricted zone? An examination of the nighttime traces in Figures 4a and 4b offers an explanation. For both stations outside the restricted zone, there is a noticeable drop in nighttime pollution post PyP, a drop that is not mirrored at the stations inside the restricted zone. This post-PyP divergence in nighttime pollution between the two sets of stations could readily explain the estimated *relative* increase in nighttime pollution at stations inside the restricted zone. What cannot be determined from the traces is the reason for this post-PyP drop in nighttime pollution at the stations outside the restricted zone. There is no apparent reason to believe that it was induced by PyP. We surmise that it is due to some other factor that we have not yet identified.

[22] We initially suspected that the nightime increase was an artefact of using log CO as our measure of pollution. Given very low CO concentrations at night, even small increases in CO concentrations would translate to very large percentage increases. However, the nighttime increase is observed even if the dependent variable in our regressions is CO.

[23] A shift in the use of heavy vehicles, such as trucks, from daytime to nighttime hours would be plausible, but these vehicles are not restricted by PyP.

The estimates in Table 12 stand up to our robustness tests, the results of which are presented in Table 13. The relevant reference estimates for these tests are those in the last column of Table 12. A comparison of the two sets of estimates reveals no notable differences.

Non-working days once again provide an opportunity to conduct placebo tests. The results of these placebo tests are presented in Table 14. With one exception, the estimates for peak hours, between-peak hours, and extended daytime hours are not significantly different from zero. The sole exception is the estimate for between-peak hours in Column 3, but adding weather covariates renders the estimate insignificant. Collectively, these results indicate that PyP has not resulted in an appreciable change in daytime pollution levels on non-working days.[24]

The last row of Table 14 reveals, once again, a significant post-PyP relative increase in nighttime pollution at stations inside the restricted zone. The persistence of this nighttime effect on non-working days lends support to our belief that it is unrelated to PyP.

5.4 Were the Effects of *Pico y Placa* Short-Lived?

Two previous studies that have detected reductions in pollution from permanent driving restrictions have found the reductions to be short lived. Gallego et al. estimate an 11% reduction in peak-hours CO concentrations in the first 11 months of Mexico City's HNC program, but this is then followed by a 13% increase. In the case of Bogota's *Pico y Placa* program, Bonilla finds that it resulted in lower CO concentrations for a period of less than one year after being introduced or modified. To assess whether the average post-PYP reductions we estimate are driven by short-lived reductions after the introduction of PyP, we modify our preferred specification in eq. (2) for the DD strategy that relies on off-peak hours as controls. The modification entails adding a triple-interaction term that is formed by multiplying a year 2012 indicator variable and the existing interaction term $Peak_h * After_{ymd}$ (the coefficient of which is α_1^i). The coefficient of this triple interaction term, which we label Δ_{2012}, captures the change in the effect of PyP in 2012 relative to its effect over

[24] Robustness tests of the estimates for non-working days, the results of which are not shown here, in some cases revealed significant daytime reductions in pollution. This would be consistent with a carryover of changes in working- day travel behavior. However, this carryover was confined to Saturdays. No significant reductions in daytime pollution were observed for Sundays and holidays alone.

the first 20 months of the program's existence. If the effect of PyP has been short-lived (using a liberal definition of the term), the sum of coefficients $\alpha_1^i + \Delta_{2012}$ should not be negative. The sum reflects the total effect of PyP on pollution in 2012. Table 15 presents the results of estimating the extended equation. For each station, the estimate of α_1^i is presented in the first column, that of Δ_{2012} in the second column, and the sum of the two in the third column. The estimates of Δ_{2012} are all positive, indicating that relative to the initial 20-month period, PyP had a diminished effect on pollution levels in 2012. However, only the coefficients for Belisario and Centro are significant. The third column reveals that despite this diminished effect, PyP did reduce CO concentrations in 2012 relative to the counterfactual, with the reductions ranging from 4% for Belisario to 13% for El Camal. The pooled estimates in the last row indicate that the average reduction is a still substantial 8%. Thus, though the effect of PyP has diminished, it continues to induce reductions in pollution levels well after its introduction.

There are a number of possible explanations for the diminished effect of PyP over time. One is that offered by Davis and others to explain the failure of Mexico City's HNC program: households buying additional cars to circumvent the restrictions. A second is diminished enforcement of the restrictions over time. Press reports and available data suggest that PyP continues to be vigorously enforced, which leads us to believe that diminished enforcement is not an important factor.[25] The limited available data on vehicle registrations does not suggest that there have been widespread attempts to circumvent the restrictions. The rate of increase in the number of registered vehicles has in fact slowed since the start of the program: in 2009 and in 2010 the number of registered vehicles increased by 8.4%; in the subsequent two years, the number increased by 6% and 2%, respectively (Municipio del Distrito Metropolitano de Quito, Secretaria de Movilidad 2012). Thus, available data indicates that there has been no uptick in vehicle registrations following the imposition of restrictions, unlike Davis and Bonilla's findings for Mexico City and Bogota, respectively.

[25] As noted in Section 3.1, 55,000 PyP violations were punished in the first 13 months of the program's existence; 40,691 were punished in 2012.

6. Conclusions

Our results indicate that PyP has significantly reduced ambient concentrations of carbon monoxide since its introduction in May 2010. The estimated reductions for peak hours are very similar in magnitude across our DD and DDD strategies, ranging from 9% to 11%. For an extended daytime period (6 am - 8 pm) the DD strategy that relies on same-hours pollution outside the restricted zone as a control yields an estimated reduction of approximately 6%.

Though our analysis is restricted to the effects of PyP on ambient CO concentrations, existing studies of the relationship between traffic flows and ambient CO concentrations indicate that these concentrations generally track the spatial and temporal distributions of traffic (as discussed in Section 3.2). This implies that the observed reductions in CO concentrations reflect reductions in vehicle flows. To the extent that this is true, the lower vehicle flows imply reductions in emissions of other pollutants emitted by motor vehicles, including carbon dioxide and nitrogen oxides.

Evidence that CO concentrations do in fact track vehicle flows in Quito can be found in a comparison of our estimates of changes in CO concentrations to estimates of changes in vehicle flows from a transportation engineering study of PyP commissioned by the municipal government (Municipio del Distrito Metropolitano de Quito 2010). The study measured vehicle flows over five working days at the end of April 2010 (i.e., immediately before introduction of PyP) at eight locations in the city and compared them to vehicle flows measured at the end of November 2010 (seven months later). Vehicle flows were estimated to be 8% lower during morning peak hours and 12% lower during evening peak hours.[26] Weighting these estimates by the length of the morning and evening peak hours yields a weighted-average reduction of 10% in vehicle flows. Given the spatially-averaged nature of this estimate and the time period over which it is calculated, it is best compared to our pooled estimate of the change in CO concentration before 2012 (reported in the first column of Table 14). The estimated reduction in CO concentration is 11%, it is not significantly different from the 10% reduction in vehicle flows.[27]

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[26] These estimates are for changes in the flows of all vehicles and not just those targeted by PyP, rendering them comparable to the estimated changes in CO concentrations.

[27] Estimating the change in CO concentration over the seven-month interval for which the change in vehicle

The above numbers imply that PyP has achieved some measure of success. It is natural to ask why this has been the case when the programs in Mexico City and Bogota have not. We believe that the answer lies, at least in part, in the vigorous enforcement of Quito's restrictions. There has been a substantial commitment of police resources to enforcing PyP, and the stiff penalties for noncompliance have not just existed on paper. Efforts to facilitate a switch to public transportation by establishing free parking areas on the periphery of the restricted zone with feeder buses into the city are also likely to have contributed to the program's success. There is little, firm evidence of increased usage of mass transit during peak hours. However, the abovementioned transportation engineering study found an 11% increase in the number of taxis on the road during peak hours. (Recall that taxis are exempt from PyP.)

The absence of an uptick in vehicle registrations following the introduction of PyP is unusual given experience in Mexico City and Bogota. A factor that might have contributed to this absence is the introduction of PyP as an experimental measure; one subject to review and re-evaluation every six months. These reviews have in fact been conducted, and reports in the press indicate that there is periodic uncertainty about the program being extended (Enteratecuador 2013) This uncertainty about the program's permanency may have induced households not to make large investments to circumvent it. This could change once the restrictions are viewed as being permanent. However, the municipal government is considering a proposal to alter the assignment of license plate digits to days of the week twice each year to undercut attempts to circumvent the restrictions by purchasing additional vehicles (Municipio del Distrito Metropolitano de Quito, Secretaria de Movilidad 2012).

Even though there has been no uptick in vehicle registrations, there is an ongoing increase in the number of registered vehicles. This increase undermines the reductions in traffic congestion and air pollution brought about by PyP. The municipal government is keenly aware of this. In mid-2012 it considered expanding the number of restricted hours per day, but chose instead to focus on strengthening enforcement measures. A recent assessment of the program by the

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flows were measured is infeasible because the pre-treatment period would only be a few days long. However, we used a one-year sample centered on the introduction of PyP to derive a pooled estimate of the reduction in CO concentration. The 8% reduction estimated (coefficient estimate of -0.0826, with a standard error of 0.0142) is also not significantly different from 10%. A drawback of using such a short sample period is that the effects of seasonality are unlikely to be controlled for adequately.

transport authority within the municipal government recommends evaluating measures to increase the stringency and scope of the program: by increasing the number of days a week that each vehicle is restricted, expanding coverage to vehicles that are currently exempt, and increasing the size of the restricted zone (Municipio del Distrito Metropolitano de Quito, Secretaria de Movilidad 2012). If implemented, these measures will provide additional opportunities to study the effectiveness of Quito's driving restrictions.

7. References

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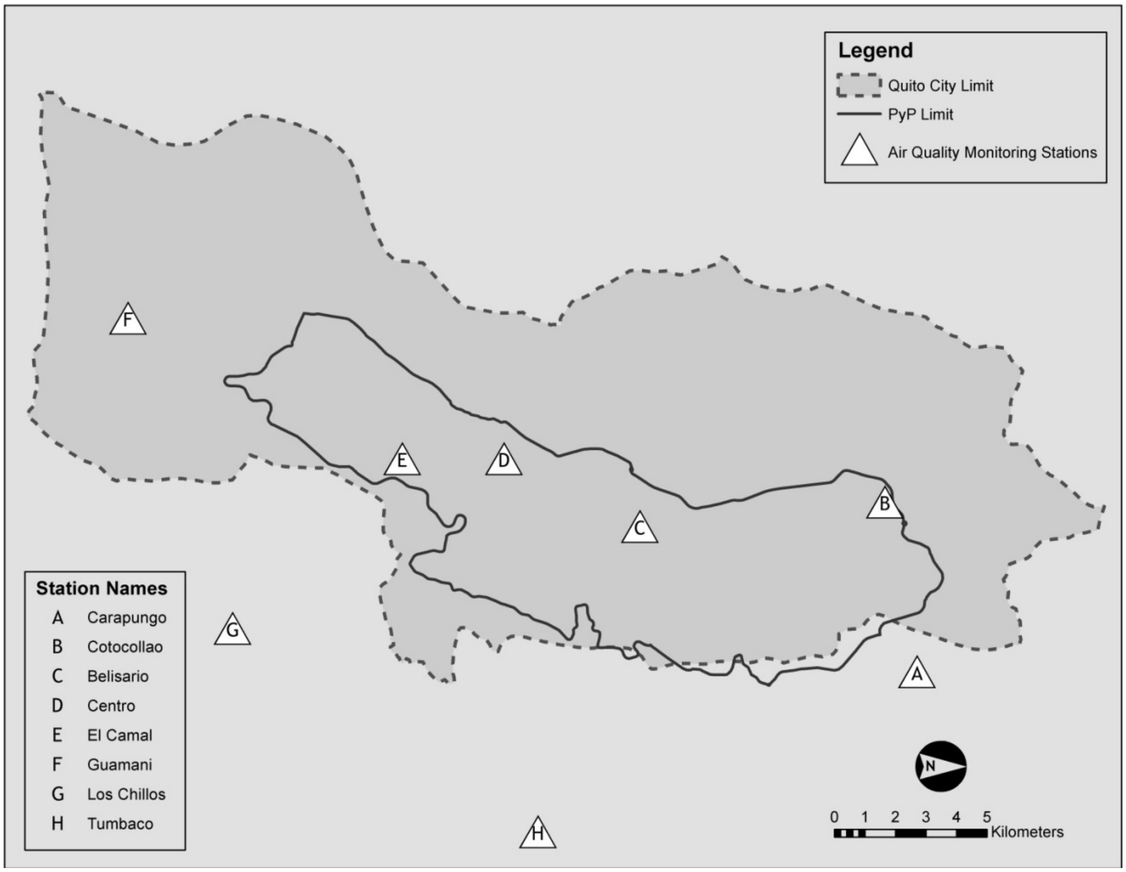


Figure 1. Map Showing City Limits, *Pico y Placa* Restricted Zone, and Monitoring Station Locations. CO not measured at Los Chillos (G) and Tumbaco (H).

Table 1. Summary Statistics for Hourly CO Concentrations (mg/m^3).

	Observations	Mean	Median	Std. Dev.	Min.	Max.
Belisario†	42215	0.88	0.77	0.49	0	4.62
Centro†	42172	0.86	0.75	0.49	0	8.38
El Camal†	42384	0.81	0.71	0.50	0	5.53
Carapungo	41917	0.58	0.50	0.36	0	6.51
Guamani	42406	0.60	0.54	0.30	0	6.43

†Indicates stations inside restricted zone.

Table 2. Correlation Coefficients for Hourly CO Concentrations across Stations.

	Belisario†	Centro†	El Camal†	Carapungo	Guamani
Belisario†	1				
Centro†	0.71	1			
El Camal†	0.56	0.77	1		
Carapungo	0.38	0.51	0.53	1	
Guamani	0.39	0.49	0.48	0.23	1

†Indicates stations inside restricted zone.

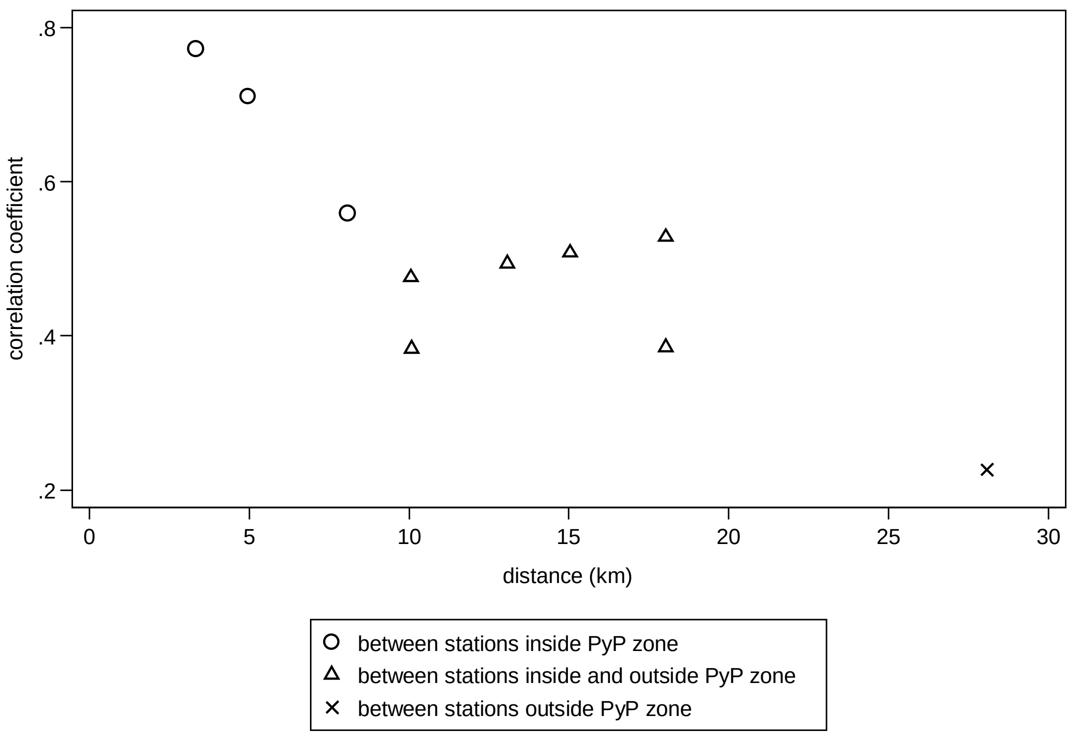


Figure 2. Distance between Stations and Correlation of Hourly CO Concentrations.

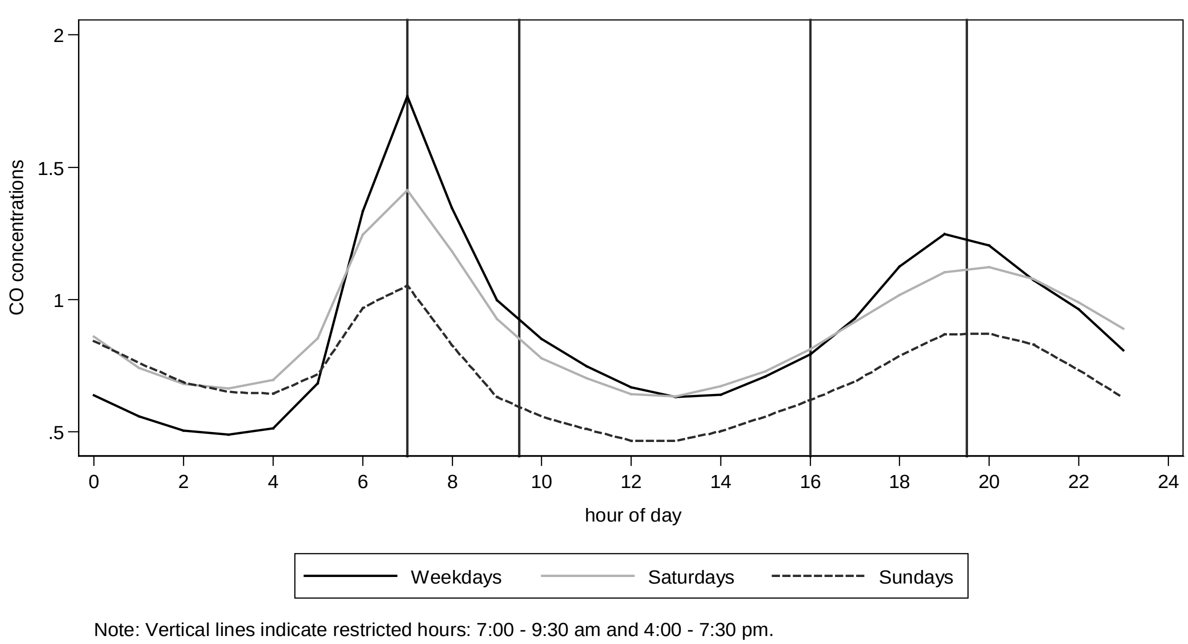
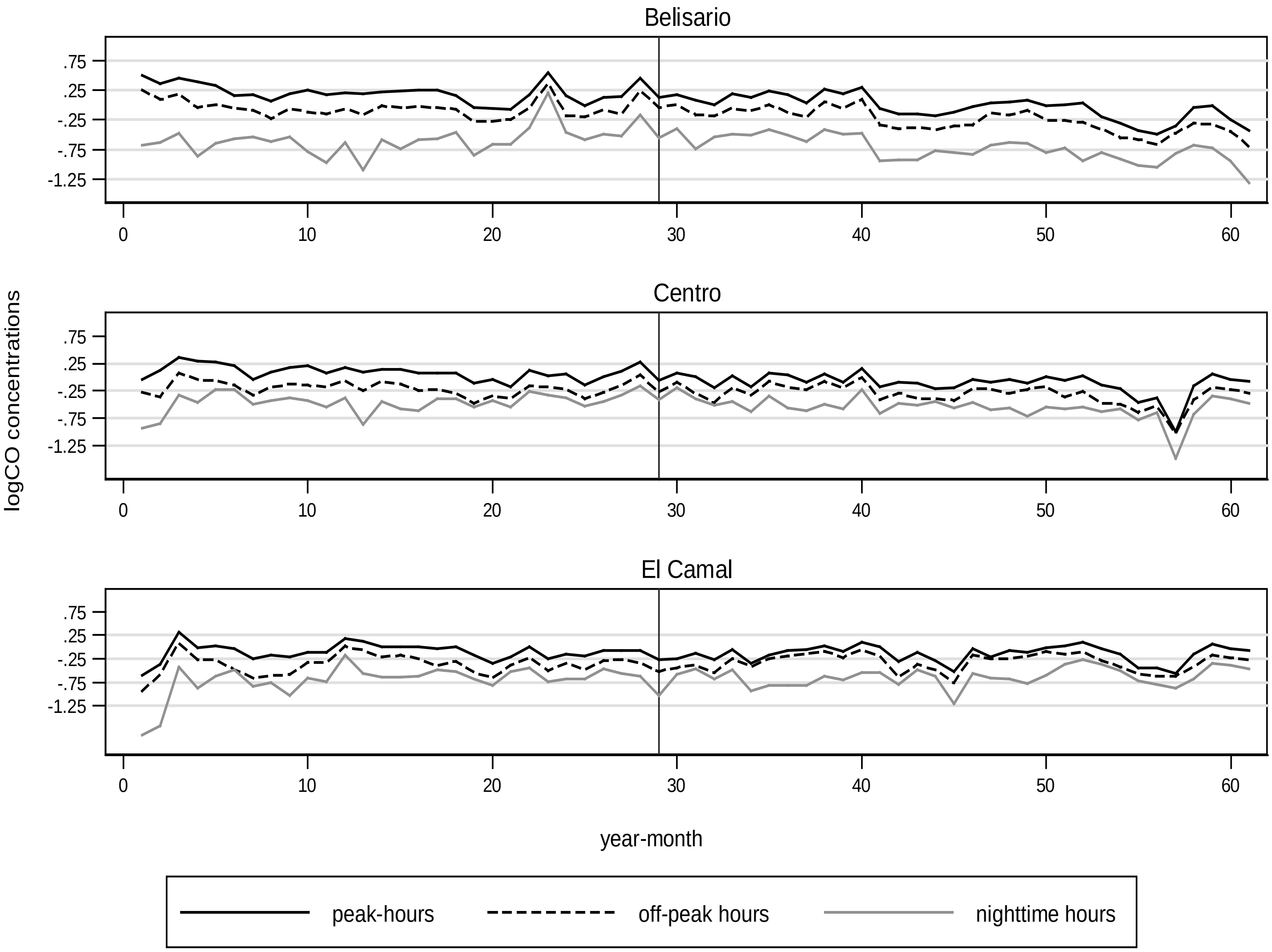


Figure 3. Diurnal Variation in CO Concentration at Centro.



Note: Vertical lines indicate the introduction of PyP.

Figure 4a. Monthly Averages of log CO for Selected Working-Day Hours—Stations Inside Restricted Zone.

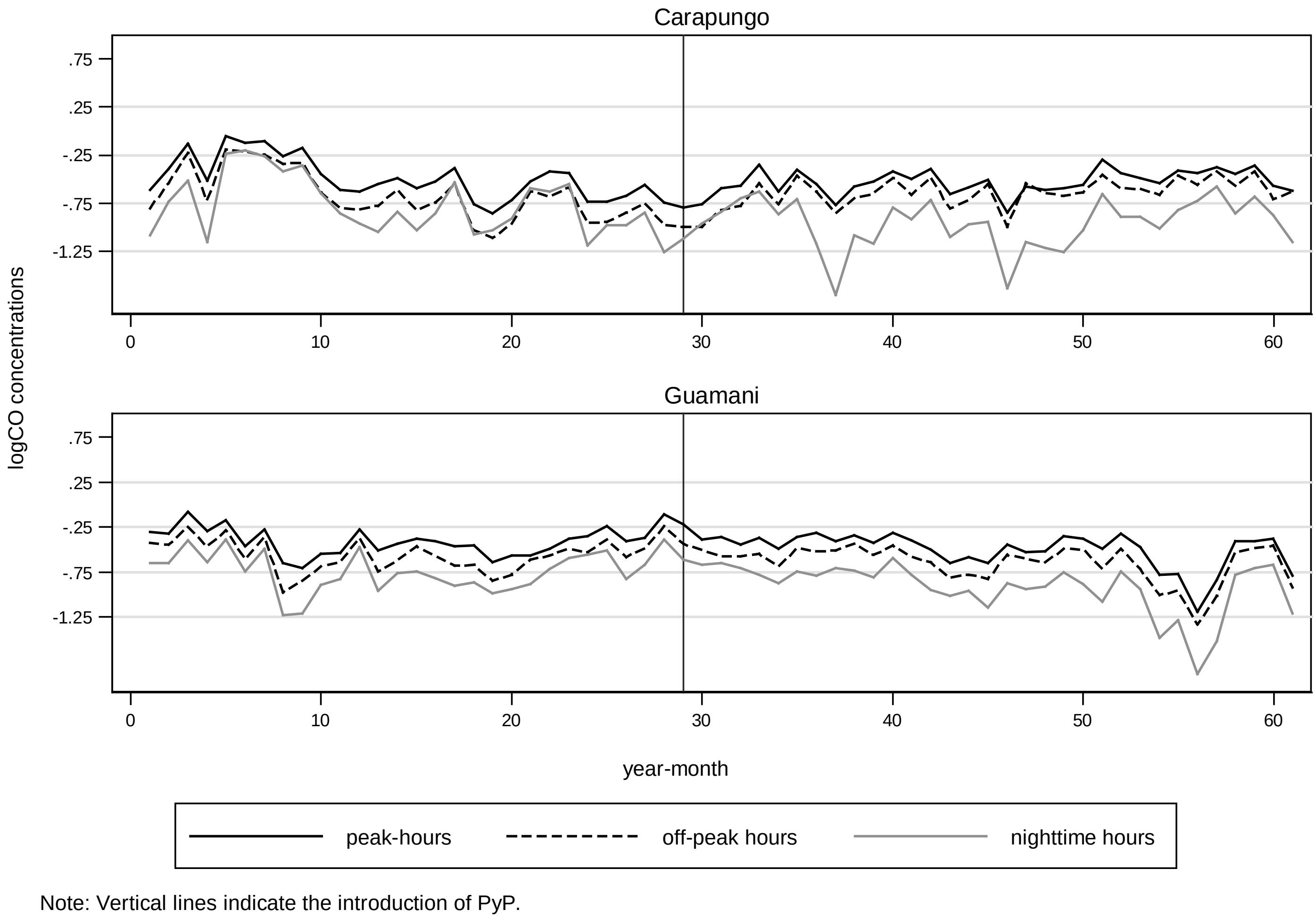


Figure 4b. Monthly Averages of log CO for Selected Working-Day Hours—Stations Outside Restricted Zone.

Table 3. Effect of PyP on Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	(1)	(2)	(3)	(4)
Belisario	-0.0571***	-0.0572***	-0.0596***	-0.0593***
	(0.0122)	(0.0123)	(0.0122)	(0.0101)
Centro	-0.1116***	-0.1101***	-0.1091***	-0.1004***
	(0.0123)	(0.0124)	(0.0123)	(0.0114)
El Camal	-0.1372***	-0.1375***	-0.1375***	-0.1462***
	(0.0155)	(0.0154)	(0.0154)	(0.0127)
Day-Hour Fixed Effects	no	yes	yes	yes
Year-Month Fixed Effects	no	no	yes	yes
Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level.
* p<0.05, ** p<0.01, *** p<0.001.

Table 4. Robustness Tests of Effect of PyP on Peak-Hours Pollution on Working Days: DD Estimates for Preferred Specification with Off-Peak-Hours Pollution as Control.

	Year-Week Fixed Effects	Symmetric Sample	Curtailed Peak Hours
Belisario	-0.0582***	-0.0548***	-0.0552***
	(0.0100)	(0.0109)	(0.0085)
Centro	-0.0984***	-0.0973***	-0.0844***
	(0.0114)	(0.0115)	(0.0105)
El Camal	-0.1391***	-0.1557***	-0.1463***
	(0.0130)	(0.0144)	(0.0118)

Note: Standard errors are clustered at the week level.
* p<0.05, ** p<0.01, *** p<0.001.

Table 5. Placebo Tests Using Non-Working Days of Effect of PyP on Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	(1)	(2)	(3)	(4)
Belisario	-0.0014	-0.0027	-0.0159	-0.0181
	(0.0126)	(0.0127)	(0.0164)	(0.0142)
Centro	-0.0579***	-0.0590***	-0.0605***	-0.0485***
	(0.0150)	(0.0148)	(0.0147)	(0.0134)
El Camal	-0.0534**	-0.0560***	-0.0611***	-0.0321
	(0.0170)	(0.0167)	(0.0169)	(0.0167)
Day-Hour Fixed Effects	no	yes	yes	yes
Year-Month Fixed Effects	no	no	yes	yes
Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level.
* p<0.05, ** p<0.01, *** p<0.001.

Table 6. Placebo Tests Using Stations Outside Restricted Zone of Effect of PyP on Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	(1)	(2)	(3)	(4)
Carapungo	-0.0683***	-0.0674***	-0.0675***	-0.0346**
	(0.0116)	(0.0114)	(0.0113)	(0.0120)
Guamani	0.0029	0.0025	0.0026	0.0089
	(0.0091)	(0.0091)	(0.0090)	(0.0096)
Day-Hour Fixed Effects	no	yes	yes	yes
Year-Month Fixed Effects	no	no	yes	yes
Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level.
* p<0.05, ** p<0.01, *** p<0.001.

Table 7. Effect of PyP on Evening Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	(1)	(2)	(3)	(4)
Belisario	-0.0438**	-0.0443**	-0.0451**	-0.0622***
	(0.0166)	(0.0167)	(0.0166)	(0.0124)
Centro	-0.1159***	-0.1164***	-0.1160***	-0.1101***
	(0.0168)	(0.0168)	(0.0168)	(0.0138)
El Camal	-0.0875***	-0.0879***	-0.0879***	-0.1297***
	(0.0195)	(0.0193)	(0.0192)	(0.0138)
Day-Hour Fixed Effects	no	Yes	yes	yes
Year-Month Fixed Effects	no	No	yes	yes
Weather Covariates	no	No	no	yes

Note: Standard errors are clustered at the week level.
* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 8. Placebo Tests Using Stations Outside Restricted Zone of Effect of PyP on Evening Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	(1)	(2)	(3)	(4)
Carapungo	0.0177	0.0191	0.0203	0.0018
	(0.0152)	(0.0150)	(0.0149)	(0.0139)
Guamani	0.0195	0.0197	0.0195	0.0004
	(0.0196)	(0.0197)	(0.0197)	(0.0191)
Day-Hour Fixed Effects	no	yes	yes	yes
Year-Month Fixed Effects	no	no	yes	yes
Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level.
* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 9. Effect of PyP on Peak-Hours Pollution on Working Days: Pooled DD and DDD Estimates.

	(1)	(2)	(3)	(4)
Pooled DD Inside	-0.1018***	-0.1014***	-0.1021***	-0.1017***
	(0.0095)	(0.0095)	(0.0095)	(0.0081)
Pooled DD Outside	-0.0324***	-0.0322***	-0.0323***	-0.0127
	(0.0079)	(0.0078)	(0.0077)	(0.0083)
Pooled DDD	-0.0693***	-0.0691***	-0.0699***	-0.0890***
	(0.0100)	(0.0101)	(0.0101)	(0.0104)
Station FE	no	yes	yes	yes
Station-Specific Day-Hour FE	no	yes	yes	yes
Station-Specific Year-Month FE	no	no	yes	yes
Station-Specific Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* p<0.05, ** p<0.01, *** p<0.001.

Table 10. Robustness Tests of Effect of PyP on Peak-Hours Pollution on Working Days: DDD Estimates for Preferred Specification.

	Year-Week Fixed Effects	Symmetric Sample	Curtailed Peak Hours	Without Carapungo
Pooled DDD	-0.0878***	-0.0822***	-0.0648***	-0.1062***
	(0.0102)	(0.0111)	(0.0077)	(0.0114)

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* p<0.05, ** p<0.01, *** p<0.001.

Table 11. Placebo Tests Using Non-Working Days of Effect of PyP on Peak-Hours Pollution: Pooled DDD Estimates

	(1)	(2)	(3)	(4)
Pooled DDD	0.0030 (0.0113)	0.0017 (.0112)	-0.0099 (0.0145)	-0.0212 (0.0143)
Station FE	no	yes	yes	yes
Station-Specific Day-Hour FE	no	yes	yes	yes
Station-Specific Year-Month FE	no	no	yes	yes
Station-Specific Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* $p<0.05$, ** $p<0.01$, *** $p<0.001$.

Table 12. Effect of PyP on Pollution Inside Restricted Zone on Working Days: DD Estimates with Pollution Outside Restricted Zone as Control.

	(1)	(2)	(3)	(4)
Peak Hours	-0.1330***	-0.1332***	-0.1330***	-0.1121***
(7 – 9 am and 4 – 7 pm)	(0.0227)	(0.0228)	(0.0229)	(0.0233)
Between Peak Hours	-0.0671*	-0.0690*	-0.0675*	-0.0044
(10 am – 3 pm)	(0.0295)	(0.0297)	(0.0297)	(0.0341)
Extended Daytime Hours	-0.0971***	-0.0971***	-0.0965***	-0.0653*
(6 am – 8 pm)	(0.0238)	(0.0240)	(0.0240)	(0.0257)
Nighttime Hours	0.1185***	0.1201***	0.1214***	0.1362***
(9 pm – 5 am)	(0.0317)	(0.0320)	(0.0323)	(0.0340)
Station FE	no	yes	yes	yes
Station-Specific Day-Hour FE	no	yes	yes	yes
Year-Month FE	no	no	yes	yes
Station-Specific Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* p<0.05, ** p<0.01, *** p<0.001.

Table 13. Robustness Tests of Effect of PyP on Pollution Inside Restricted Zone on Working Days: DD Estimates for Preferred Specification with Pollution Outside Restricted Zone as Control.

	Year-Week Fixed Effects	Symmetric Sample	Curtailed Peak Hours
Peak Hours	-0.1156***	-0.1189***	-0.1436***
(7 – 9 am and 4 – 7 pm)	(0.0232)	(0.0255)	(0.0237)
Between Peak Hours	-0.0124	0.0131	
(10 am – 3 pm)	(0.0338)	(0.0378)	
Extended Daytime Hours	-0.0681**	-0.0642*	
(6 am – 8 pm)	(0.0255)	(0.0281)	
Nighttime Hours	0.1309***	0.0811*	
(9 pm – 5 am)	(0.0343)	(0.0358)	

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* p<0.05, ** p<0.01, *** p<0.001.

Table 14. Placebo Tests Using Non-Working-Days of Effect of PyP on Pollution Inside Restricted Zone on Working Days: DD Estimates with Pollution Outside Restricted Zone as Control.

	(1)	(2)	(3)	(4)
Peak Hours (7 – 9 am and 4 – 7 pm)	-0.0480 (0.0274)	-0.0495 (0.0278)	-0.0526 (0.0279)	-0.0424 (0.0273)
Between Peak Hours (10 am – 3 pm)	-0.0629 (0.0332)	-0.0622 (0.0335)	-0.0667* (0.0338)	-0.0359 (0.0372)
Extended Daytime Hours (6 am – 8 pm)	-0.0496 (0.0284)	-0.0504 (0.0288)	-0.0536 (0.0289)	-0.0429 (0.0297)
Nighttime Hours (9 pm – 5 am)	0.0949* (0.0376)	0.0945* (0.0380)	0.1026** (0.0374)	0.0892* (0.0390)
Station FE	no	yes	yes	yes
Station-Specific Day-Hour FE	no	yes	yes	yes
Year-Month FE	no	no	yes	yes
Station-Specific Weather Covariates	no	no	no	yes

Note: Standard errors are clustered at the week level, with all stations in the same cluster.
* *p*<0.05, ** *p*<0.01, *** *p*<0.001.

Table 15. Change in 2012 of Effect of PyP on Peak-Hours Pollution on Working Days: DD Estimates with Off-Peak-Hours Pollution as Control.

	Pre-2012 Effect of PyP	Change in Effect in 2012	Total Effect in 2012
Belisario	-0.0714*** (0.0110)	0.0321* (0.0126)	-0.0394** (0.0128)
Centro	-0.1155*** (0.0124)	0.0408** (0.0139)	-0.0747*** (0.0143)
El Camal	-0.1545*** (0.0147)	0.0221 (0.0157)	-0.1324*** (0.0147)
Pooled	-0.1135*** (0.0091)	0.0317** (0.0102)	-0.0819*** (0.0099)

Note: Standard errors are clustered at the week level.
* p<0.05, ** p<0.01, *** p<0.001.

Appendix

Table A-1. Summary Statistics for Meteorological Variables.

		Observations	Mean	Median	Std. Dev.	Min.	Max.
Temperature	Belisario†	43470	13.68	12.82	3.21	5.98	23.66
(Celsius)	El Camal†	43534	13.94	13.06	2.99	7.06	23.84
	Carapungo	43417	14.32	13.11	3.43	6.22	24.71
	Los Chillos	43350	15.53	14.13	4.13	5.40	27.87
Relative Humidity	Belisario†	43469	70.95	72.68	19.67	4.94	100
(percent)	El Camal†	43536	69.95	72.58	17.40	8.60	98.51
	Carapungo	43427	73.23	77.39	18.42	7.69	100
	Los Chillos	43347	72.89	79.40	21.40	10.96	100
Wind Speed	Belisario†	43349	1.78	1.56	0.91	0	14.63
(meters per second)	El Camal†	43334	1.82	1.58	0.97	0.02	6.71
	Carapungo	43438	1.73	1.27	1.26	0.02	9.66
	Los Chillos	43336	1.57	1.20	1.10	0	9.24
Wind Direction	Belisario†	42845	146.71	149.49	91.23	0	360
(angular degree)	El Camal†	43246	150.41	159.82	93.83	0.01	360
	Carapungo	42972	250.55	269.93	84.70	0	359.99
	Los Chillos	43269	196.63	182.83	110.29	0	360
Precipitation	Belisario†	43712	0.14	0	0.88	0	47.90
(millimeters)	El Camal†	43716	0.15	0	1.04	0	45.20
	Carapungo	43616	0.08	0	0.68	0	37.40
	Los Chillos	43575	0.16	0	1.21	0	45.50
Solar Radiation	Belisario†	43488	192.53	10	286.87	0	1250.68
(watts per square meter)	El Camal†	43551	196.51	2.08	291.14	0	1237.35
	Carapungo	43444	211.76	2.97	300.90	0	1289.26
	Los Chillos	43388	214.46	1.72	317.73	0	1279.65
Atmospheric Pressure	Belisario†	43302	726.06	726.18	1.34	721.22	743.20
(millibars)	El Camal†	43493	726.38	726.32	4.27	720.24	865.75
	Carapungo	43194	742.55	742.48	1.58	736.45	749.91
	Los Chillos	43344	759.09	759.43	2.03	745.89	765.57

Notes: Meteorological data for Belisario and Los Chillos are used for Centro and Guamani, respectively. Wind direction is converted to one of eight dummy variables representing the eight principal wind directions.
†Indicates stations inside restricted zone.

Table A-2. Selected Estimates from Regressions Examining Effect of PyP on Peak-Hours Pollution on Working Days at Centro: DD with Off-Peak Hours Pollution as Control.

Panel 1: Simplest Specification

*Peak*After*	-0.1116*** (0.0123)
Peak	0.3867*** (0.0093)
After	-0.1096*** (0.0278)
Constant	-0.2025*** (0.0190)
N	18168
Adj. R^2	0.1384

Panel 2: Preferred Specification. Estimates for year-month fixed effects and day-of-week/hour-of-day interactions omitted.

*Peak*After*	-0.1004*** (0.0114)	*16*	0.1086** (0.0344)	*Temperature*	0.7209* (0.3540)
Hour-of-Day Indicators[a]		*17*	0.2014*** (0.0342)	*Temperature*^{2}	-0.0791* (0.0366)
7	0.5172*** (0.0242)	*18*	0.3044*** (0.0340)	*Temperature*^{3}	0.0034* (0.0016)
8	0.3911*** (0.0296)	*19*	0.3231*** (0.0314)	*Temperature*^{4}	-0.0001 (0.0000)
9	0.2185*** (0.0330)	*20*	0.1850*** (0.0317)	*Solar Radiation*[c]	0.0503* (0.0193)
10	0.0935** (0.0357)	Day-of-Week Indicators[b]		*(Solar Radiation)*^{2}	-0.0143* (0.0067)
11	0.0543 (0.0364)	*Tuesday*	0.1197*** (0.0266)	*(Solar Radiation)*^{3}	0.0020* (0.0009)
12	0.0574 (0.0367)	*Wednesday*	0.0389 (0.0277)	*(Solar Radiation)*^{4}	-0.0001* (0.0000)
13	-0.0280 (0.0360)	*Thursday*	0.0607* (0.0277)	*Relative Humidity*	-0.0476** (0.0140)
14	-0.0537 (0.0364)	*Friday*	0.1522*** (0.0277)	*(Relative Humidity)*^{2}	0.0014** (0.0004)
15	-0.0069 (0.0369)	Weather Variables		*(Relative Humidity)*^{3}	-0.0000* (0.0000)

Table A-2. (Continued)

(Relative Humidity)^4	0.0000
	(0.0000)
Precipitation	0.0584**
	(0.0189)
Precipitation^2	-0.0116
	(0.0059)
Precipitation^3	0.0008
	(0.0006)
Precipitation^4	-0.0000
	(0.0000)
Precipitation Dummy	0.0050
	(0.0113)
Atmospheric Pressure	-0.0152*
	(0.0075)
Wind Speed (interacted with wind direction)	
N	-0.0503
	(0.1547)
NE	-0.1878
	(0.1603)
E	-0.2043
	(0.1579)
SE	-0.1855
	(0.1481)
S	-0.0609
	(0.1407)
SW	-0.0567
	(0.1726)
W	0.7842**
	(0.2845)
NW	0.7703**
	(0.2476)
(Wind Speed)^2 (interacted with wind direction)	
N	-0.1605
	(0.1006)
NE	-0.0472
	(0.1050)
E	-0.0980
	(0.1035)
SE	-0.1175
	(0.0947)
S	-0.1596
	(0.0829)
SW	-0.0779
	(0.1250)
W	-1.4906***
	(0.3683)
NW	-1.4809***
	(0.2775)
(Wind Speed)^3 (interacted with wind direction)	
N	0.0644*
	(0.0278)
NE	0.0327
	(0.0286)
E	0.0550*
	(0.0278)
SE	0.0560*
	(0.0264)
S	0.0496*
	(0.0208)
SW	0.0124
	(0.0372)
W	0.6678***
	(0.1798)
NW	0.6592***
	(0.1207)
(Wind Speed)^4 (interacted with wind direction)	
N	-0.0069*
	(0.0027)
NE	-0.0037
	(0.0027)
E	-0.0062*
	(0.0026)
SE	-0.0058*
	(0.0026)
S	-0.0036
	(0.0019)
SW	0.0002
	(0.0038)
W	-0.0903**
	(0.0280)
NW	-0.0874***
	(0.0171)
Constant	9.3009
	(5.6832)
N	17770
Adj. R^2	0.6770

Note: Standard errors are clustered at the week level.
[a] 6 am is the reference time.
[b] Monday is the reference day.
[c] Solar radiation is rescaled by dividing by 100.
* p<0.05, ** p<0.01, *** p<0.001.