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Effects of environmental alerts and pre-emergencies on pollutant concentrations in Santiago, Chile

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HIGHLIGHTS

- ► Santiago's air quality policy significantly reduced pollutant's concentrations.
- ► Reductions in PM10 and PM2.5 were 5%–7% in alerts and 12% in pre-emergencies.
- ► The average decline in CO and NO_x was 10% in alerts and 20% in pre-emergencies.
- ► Restrictions led to significant reductions in CO, NO_x, PM10 and PM25 in weekdays.

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ABSTRACT

To reduce air pollution levels in Santiago, Chile on days when the weather is expected to create poor ventilation conditions and increased air pollutant concentrations, the responsible authorities impose temporary restrictions on motor vehicles and certain industrial activities. We estimate the impact of these restrictions on the city's air quality using data collected by a network of monitoring stations. The estimates show that the restrictions do reduce the average concentrations of coarse and fine particulate matter, carbon monoxide and nitrogen oxide (both gases are emitted mainly by vehicles). However, no significant changes were found in the sulfur dioxide concentrations, which are primarily the result of industrial processes.

1. Introduction

In 1996, the high concentrations of air pollutants in Santiago, Chile prompted the national authorities to declare the city a "saturated zone" for particulate matter (PM10), total suspended particulates (TSP), carbon monoxide (CO) and ozone (O). The Chilean capital was also declared a "latent zone" for nitrogen dioxide (NO_2) (see Supreme Decree No. 131 of June 12, 1996). In the wake of these declarations, the authorities implemented a series of steps aimed at reducing pollution levels, some of which were permanent and others only for critical episodes. The main objective of this study was to quantify the effects of the exceptional restrictions imposed during critical episodes on the concentrations of coarse and fine particulates (PM10 and PM2.5), carbon monoxide, sulfur dioxide (SO_2) and nitric oxides (NO_x) using data for the average daily pollutant concentrations for 2000–2008 collected by MACAM-II, the Santiago-area weather and air pollution monitoring network.

Policies to control air quality include the regular measurement of pollutant concentrations, the definition of pollution reduction goals, various requirements and controls for existing and new emission sources and the development of a special air quality plan for the autumn–winter period (April 1st–August 31st). Permanent measures adopted for these months include stationary source emission limits and vehicle use restrictions. Vehicles lacking catalytic converters, and therefore ineligible for a "sello verde" or green sticker (hereafter called "NGS vehicles"), cannot be driven within the city between 7:30 am and 9:00 pm one day a week, depending on the last digit of their license plate (similar to the "Hoy No Circula" system in Mexico City or "Pico y Placa" in Bogotá). The regulations apply to all types of private vehicles and taxis. Vehicles

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that do have catalytic converters and therefore green stickers (hereafter called "GS vehicles") are exempt, as are natural gas-powered, hybrid, police and emergency vehicles.

Other restrictions take effect only if a critical episode is forecast, which occurs when poor ventilation conditions are expected to lead to elevated particulate concentrations. The authorities may then declare an environmental alert, pre-emergency or emergency depending on the seriousness of the situation to prevent pollutants from rising above levels linked to adverse health effects. Additional license plate digits are then subjected to the driving ban, which, in the case of a critical episode, is applied to private vehicles as well as taxis, buses and trucks. Restrictions are also put on certain industrial activities, requiring them to shut down temporarily. The *Instituto Nacional de Estadísticas*, Chile's official statistics bureau, estimated that in 2007 these exceptional measures affected 46,000 cars per day during alert days and 296,000 during pre-emergency days. The following year, the *Secretaría Regional de Salud Metropolitana*, greater Santiago's regional health authority, reported that the restrictions were applied to 794 stationary emissions sources. In 2009 and 2010, all critical episodes were environmental alerts, and no environmental emergency has ever been declared.

Davis (2008) estimated the impact of a similar policy, "Hoy No Circula", which was implemented for Mexico City in 1989. This system bans vehicles from the roads on one day per week according to the last license plate digit. He found no evidence that the restriction improved air quality. The evidence showed an intertemporal substitution of trips toward hours when the restriction was not in place, and it also indicated that the restrictions increased the total number of vehicles in circulation, with a larger increase in high-emission vehicles. The environmental authorities for the Mexico City area have partially confirmed the rise in purchases of higher-emission vehicles to circumvent the restrictions, estimating that 22% of the cars acquired as a result of the system's creation fit that category (Cifuentes, 2007).

For the city of Santiago, De Grange and Troncoso (2011) showed that on pre-emergency days, when 20% of all GS vehicles were banned, the vehicle flows in the two morning hours before the restrictions take effect rise by approximately 7% compared to normal days. In other words, some drivers are making an intertemporal trip substitution to beat the restrictions. This broadly concurs with the results noted above for Mexico City, however, in the case of Santiago, pre-emergencies are declared only for critical pollution episodes. As a result, in Santiago, the incentive to buy a second car is weaker, and driving in the morning before the restrictions take effect is the simpler option.

Regarding the effect of short-term restrictions, Vecchi et al. (2006) investigated a particularly bad pollution episode in Milan, Italy that led to near total prohibition of vehicle use in the city on February 23, 2003 between 8:00 am and 8:00 pm. Studying driver behavior and PM10 and CO levels, the authors found that compared to the previous day, both the number of cars on the road and the pollution concentration levels after 8:00 pm rose significantly. However, this case does not illustrate potential long-term effects, such as buying higher-emissions vehicles.

Other examples of vehicle restrictions are the "Rodizio" system in Sao Paulo, Brazil and "Pico y Placa" in Bogotá, Colombia. In Sao Paulo, experimentation with restrictions based on license plate numbers began in 1995 (Viegas, 2001). At first, the restriction was applied for one week on a voluntary basis. Compliance was high (approximately 50%) for the first two days, then dropped to an average of 38% for the last three (Bull, 2003). In 1996, the system became mandatory (Sao Paulo State Law No. 9.358), with compliance oscillating approximately 95%. Carbon monoxide emissions were estimated to have diminished by 1171 tons, and 40 million fewer liters of fuel were consumed. The average traffic speed rose 20%, and congestion was down 40% at peak hours. The same restrictions were again imposed from June 23 to September 30 the following year across the entire greater Sao Paulo area.

In Bogota, the "Pico y Placa" vehicle restriction program was introduced in 1998. Four final licence plate digits are banned each weekday during the peak hour periods. According to city authorities (Bogota Secretary of Transit), upon implementation of the program, the average traffic speed increased 43%, while fuel consumption fell 8%, and air pollution decreased by 11%. In the case of Bogota, the authorities also introduced other measures to promote walking (by banning parking on sidewalks) and cycling (through construction of a cycle path network). Additionally, a high-capacity bus network using dedicated lanes known as Transmilenio was built. Taking advantage of Bogota's successful experience with "Pico y Placa", a variation was introduced in Medellin, Colombia in February 2005 to try and improve vehicular traffic. As of 2008, no data had been reported indicating its effectiveness.

More generally, Cantillo and Ortuzar (submitted for publication) used a simple microeconomic analysis based on evidence from cities with vehicle restriction policies to show that such approaches are only effective in the short-term and ultimately fail to fulfill the desired objectives.

Returning to the Chilean experience, various authors have reported deficiencies in the regulation of stationary emission sources under the Emission Compensation system, which has been in effect in Santiago since 1992. According to Palacios and Chávez (2005), for example, many companies were not abiding by the restrictions, especially in the early years, due to poorly drafted regulations. Montero et al. (2002) cited the uncertainty due to the poor regulations as well as the introduction of natural gas, which is cheaper than fuel oil, as the principal reasons for Chile's lack of a well-developed emissions trading market. O'Ryan (2002) and Lents et al. (2006) emphasized a dearth of human capital in the regulatory bodies as a major cause of the Emission Compensation system's failures. Coria (2009) studied the effect of pre-emergency day restrictions on the likelihood that an industrial firm will change from diesel fuel to less-polluting natural gas. The incentive to switch derives from the fact that during these episodes, high-emission operators that are on a list established for this purpose must suspend the offending activity. Adopting cleaner technology would allow them to be removed from the list and thus avoid being shut down when critical episodes are declared.

Despite efforts at reduction, Santiago's air pollution levels remain a significant problem, and the vehicle restrictions continue to be questioned. However, even though their effectiveness has still not been demonstrated, two license plate digits were added to the permanent measures for NGS vehicles in 2008, raising the total number of digits to four. With the growing proportion of GS vehicles on the road, two digits were also added the following year to the restrictions on pre-emergency days. With this modification, some 20% of the total, or about 490,000 vehicles, will, in theory, be off the road during pre-emergencies. However, De Grange and Troncoso (2011) showed that the reduction in vehicle flows on such days is only 5.5%, the equivalent of 117,000 vehicles.

The effects of different pollutants on health have been extensively studied. Empirical evidence suggests that significant harm is caused by exposure to course or fine PM, CO, NO_x and SO_2. Dominici et al. (2006), for example, concluded that short-term exposure to MP2.5 significantly increases the likelihood of hospital admissions for respiratory and cardiovascular diseases. Evidence for the effects of PM10, on the other hand, is less conclusive. After controlling for the proportion of fine PM in the atmosphere in various U.S. cities, Peng et al. (2008) did not find a significant relationship between increases in PM10 concentrations and health effects.

Regarding CO, Bell et al. (2009) discovered a positive and significant relationship between concentrations of the gas and increases in the risk of cardiovascular disease hospitalizations. The relationship was significant but attenuated when co-pollutants, particularly NO_X, were controlled for. A one part per million (ppm) increase in maximum CO concentration was associated with a 0.96% (95% posterior interval, 0.79%–1.12%) increase in cardiovascular disease admissions. When NO_2 was controlled for, the estimate fell to 0.55% (0.36%–0.74%).

The effects of coarse PM pollution in Santiago has been investigated by Ostro et al. (1999), who conclude that for a 50 μg m^{-1} increment in the PM concentration, hospital visits for low respiratory symptoms of children under 2 years old rise by 4%–12%. For those aged 3–15 years, this increase is from 3% to 9%. Meanwhile, Cifuentes et al. (2000) studied the effects of five pollutants on non-accidental deaths in Santiago, Chile. These researchers found that the increase in mortality associated with the mean levels of air pollution varied from 4% to 11%, depending on the pollutants and the season.

2. Santiago air quality policy

2.1. Permanent restrictions and critical episodes

Supreme Decree (*Decreto Supremo*) No. 16 of 1998 established the plan for prevention and air pollution control in the metropolitan region. The plan must be revised periodically, and since 1998, it has been updated four times through Supreme Decrees No. 20 of 2001, No. 58 of 2003 and No. 46 of 2007. The most significant change in terms of the severity of the restriction was in Supreme Decree No. 46 of 2007, which doubled the restriction on vehicles with catalytic converters.

The air quality policy for Santiago considers a “base” or permanent restriction during winter months for vehicles without catalytic converters and additional restrictions during “critical episodes”. During our sample period, the base restriction banned two license plate digits for most vehicles without catalytic converters during working days. De Grange and Troncoso (2011) estimated that the permanent restriction had no significant effect on the number of daily car trips and, therefore, would have no effects on pollution. In the authors’ view, this is because the proportion of vehicles without catalytic converters among the total number of Santiago-area vehicles is quite low (approximately 10%), and it is even lower for vehicles making regular trips in the city. Our objective is to estimate the impact of the restrictions on the concentration of pollutants during critical episodes.

The restrictions during critical episodes depend on the severity of the pollutant concentrations. Supreme Decree No. 59 of 1998 defined the air quality standards and three levels of severity depending on the concentration of PM10. The primary air quality standard is a concentration of 150 μg N m^{-3} during 24 h. The authority declares critical episodes when the expected concentration is above the norm. Expected concentrations of PM10 between 195 and 239 μg N^{-1} m^{-3} trigger an “alert”, between 240 and 329 μg N^{-1} m^{-3} triggers a “pre-emergency”, and above 330 μg N^{-1} m^{-3} triggers an “emergency”.

Critical episodes are forecast a day in advance by the *Centro Nacional del Medio Ambiente de Chile* (CENMA - the National Centre for the Environment) using an air quality model (Cassmassi, 1999). The Centre submits recommendations to the Santiago regional *Intendencia*, the authority responsible for declaring the corresponding alert, pre-emergency or emergency, based on the model’s predictions.

Alerts do not restrict the circulation of GS vehicles, but rather increases the number of license plate digits restricted. The restriction included two additional digits for NGS vehicles on both weekdays and weekends. The restrictions on weekends and holidays were eliminated in 2007.

During pre-emergencies, four extra license plate digits on NGS vehicles are banned from circulation, plus two digits on GS vehicles. Pre-emergencies also impose the suspension of industrial sources with PM10 concentrations above 32 mg N^{-1} m^{-3}. Since 2007, the number of restricted digits for GS vehicles has increased to four. This increase is a significant change in the restriction because GS vehicles represent the vast majority of circulating vehicles in Santiago.

Since 1998, an environmental emergency has never been declared in Santiago. If an emergency occurs in the future, the restrictions may include 6 additional digits for vehicles without catalytic converters (8 digits in total) and 4 digits for vehicles with catalytic converters. Environmental emergencies may also require the suspension of sources whose concentrations of particulate matter are above 28 mg N^{-1} m^{-3}.

In addition to these measures, during critical episodes, the streets of Santiago are washed and vacuumed more frequently; the burning of firewood for home heating is banned, and illegal burning is more tightly controlled. Enforcement of the restrictions is the responsibility of *Carabineros de Chile*, the country’s national police force, both on normal days or when a critical episode has been declared. Penalties for violations include fines ranging from 70 to 100 U.S. dollars and a possible driving license suspension; however, the probability of detection is relatively low. In a city with over one million vehicles, in 2007, 328 tickets were handed out for infractions on 2 pre-emergency days, 103 fines were levied on 27 alert days, and just 33 contraventions were ticketed on 125 non-critical days. In 2008, the corresponding figures were 1254 tickets on 8 pre-emergency days, 445 fines on 21 alerts and 1415 infractions on days with no additional restriction.

The number of critical episodes from 2000 through 2008 is shown for each year in Table 1. Note that no emergencies were declared in the entire 9-year period.

2.2. Air quality measurement

Air quality in Santiago is measured by the *Red de Monitoreo Automático de Contaminantes Atmosféricos y Meteorología* (automatic weather and air pollution monitoring network) operated under the authority of Chile’s Ministry of Health. Initially established in 1989 under the acronym MACAM I, it was upgraded in 1997 to the current setup known as MACAM II, which consists of eight monitoring stations distributed across the metropolitan region of greater Santiago.

Seven of the eight stations are classified as being “population representative”, meaning that they comply with the following criteria: i) there is a built-up area within a radius of 2 km; ii) the

Table 1
Critical episodes by year, 2000–2008.

Year	Alerts	Pre-emergencies
2000	27	11
2001	21	4
2002	22	11
2003	21	5
2004	13	2
2005	7	2
2006	21	3
2007	27	4
2008	21	8
Total	180	50

Source: Unidad Operativa de Control de Tránsito (UOCT).

stations are located more than 15 m from the closest street and more than 50 m from the closest street with a traffic flow of more than 2500 vehicles per day; and iii) they are located more than 50 m from any heating system outlet.

2.3. Sources of pollution

The National Environment Commission (CONAMA) and the *Dirección de Investigaciones Científicas y Tecnológicas* (DICTUC), a unit of the *Pontificia Universidad Católica de Chile*, estimate the contribution of different pollution sources from both natural and human activity responsible for the emission of major regulated pollutants affecting the health of the population (pollutants with air quality standards). Table 2 shows the share of the pollutants considered in this study attributable to each source estimated for 2005.

As shown in Table 2, the coarse and fine particulates are produced by both stationary and mobile sources. The principal sources are industry, the residential burning of firewood and trucks. The main sources of CO emissions are light vehicles with catalytic converters, while industry, trucks and light vehicles produce the most NO_x. Finally, industry is responsible for almost all emissions of SO_x.

From these data, we can gain some insight into how the levels of each pollutant would be affected by environmental alerts and pre-emergencies. For example, because alerts do not affect industrial activities, we would expect no reductions in SO_2 levels. The vehicle restrictions could be expected to impact primarily the levels of CO.

3. Data and methods

Our data corresponded to the daily averages of hourly pollutant concentrations and the weather variables supplied by the stations of the MACAM II monitoring network. The descriptive statistics for this data are shown in Table 3 for the summer period (October–March) and Table 4 for the winter period (April–September). As the data show, the pollutant concentrations are greater in winter. We used the weather variables to control for the ventilation conditions that determine the dispersion of the pollutants.

We consider the following weather variables: the temperature differences between the ground level and 8 and 22 m above ground (thermal inversion variables that indicate the degree of ventilation over the city), a dichotomous variable for the number of days with precipitation, atmospheric pressure, humidity, wind speed, temperature and radiation. For a detailed discussion of the effects of weather conditions and city morphology on ventilation, see Morales (2006).

Table 2
Share of total pollutant concentrations by emission source (%).

Source	Pollutant				
	CO	SO_x[a]	NO_x[a]	PM10	PM25
Industry	3.7	96.2	23.4	27.0	26.3
Residential burning of firewood	3.9	0.1	0.2	14.8	17.8
Other stationary	3.7	2.3	2.6	20.8	20.4
Total stationary	**11.3**	**98.6**	**26.2**	**62.7**	**64.5**
Buses	0.9	0.2	15.9	6.7	7.4
Trucks	1.7	0.3	21.2	16.3	17.8
Light veh. with catalytic conv.	30.9	0.4	19.2	4.1	0.0
Light veh. w/out catalytic conv.	51.2	0.1	13.7	0.9	0.0
Light diesel vehicles	0.6	0.1	1.8	6.0	6.6
Other mobile	3.4	0.3	2.0	3.4	3.8
Total mobile	**88.7**	**1.4**	**73.8**	**37.3**	**35.5**
Grand total	**100**	**100**	**100**	**100**	**100**

[a] Sulfur and nitrogen oxides. Source: Derived using data from DICTUC (2007).

Table 3
Data characteristics: summer period (october–march).

Variable	No. obs.	Mean	Std. dev.	Minimum	Maximum
Dependent					
CO ($\mu g\ m^{-3}$)	1639	0.5	0.3	0.1	2.3
SO_2 ($\mu g\ m^{-3}$)	1639	8.5	3.2	2.9	40.3
NO_x ($\mu g\ m^{-3}$)	1602	42.4	21.0	6.6	194.3
PM10 ($\mu g\ m^{-3}$)	1639	60.0	16.8	16.0	141.8
PM2.5 ($\mu g\ m^{-3}$)	1640	23.3	7.1	6.4	61.7
Explanatory					
Δtemp8 (°C)	1464	0.4	0.4	−0.7	2.1
Δtemp22 (°C)	1462	0.1	0.4	−1.4	3.1
Precipitation (>0)	1450	0.1	0.3	0.0	1.0
Pressure (hPa)	1638	893.0	1.9	882.7	899.6
Humidity (%)	1641	50.8	10.9	22.2	90.0
Wind ($m\ s^{-1}$)	1641	2.9	0.5	1.4	4.8
Temperature (°C)	1641	18.0	3.2	6.2	25.3
Radiation ($W\ m^{-2}$)	1641	290.6	68.9	16.7	565.4

We use linear multivariate regression models to estimate the effect of environmental alerts and pre-emergencies. For each case, the dependent variable of the model is the natural logarithm of the concentration of the pollutant. The control variables are the current and the lagged weather variables as well as the lags of the dependent variable. Among the explanatory variables, we also include dichotomous variables that distinguish between the critical episodes declared for weekdays and those declared for weekends or public holidays. The regression equation is as follows:

$$\begin{aligned} y_t = {} & \beta' x_t + D_A^{\text{Weekday}} A_t^{\text{Weekday}} + D_A^{\text{Weekend}} A_t^{\text{Weekend}} \\ & + D_P^{\text{Weekday}} P_t^{\text{Weekday}} + D_P^{\text{Weekend}} P_t^{\text{Weekend}} + \varepsilon_t, \end{aligned} \qquad (1)$$

where y_t is the natural logarithm of the daily average concentration of each pollutant (PM10, PM2.5, CO, NO_x and SO_2); x_t are the control variables, which include the weather variables for period t and lagged values, lags of the dependent variable and dichotomous variables indicating the day of the week, the month and the year; A_t^{Weekday} is a dichotomous variable indicating a weekday alert; A_t^{Weekend} is a dichotomous variable indicating a weekend/public holiday alert; P_t^{Weekday} is a dichotomous variable indicating a weekday pre-emergency; P_t^{Weekend} is a dichotomous variable indicating a weekend/public holiday pre-emergency; and ε_t is the stochastic error.

For a simpler interpretation of the estimation outputs, we do not display all of the original coefficients for vector β in equation (1). For instance, we do not display the coefficients for the lags of the dependent variable, nor for the weekdays, months and years dummy variables. The inclusion of the lagged values for both the

Table 4
Data characteristics: winter period (april–september).

Variable	No. obs.	Mean	Std. dev.	Minimum	Maximum
Dependent					
CO ($\mu g\ m^{-3}$)	1647	1.8	1.1	0.1	5.6
SO_2 ($\mu g\ m^{-3}$)	1647	12.0	5.4	3.1	42.3
NO_x ($\mu g\ m^{-3}$)	1641	164.2	110.0	17.0	648.0
PM10 ($\mu g\ m^{-3}$)	1647	88.2	41.1	7.1	240.4
PM2.5 ($\mu g\ m^{-3}$)	1647	44.3	21.6	4.4	125.6
Explanatory					
Δtemp8 (°C)	1616	0.8	0.6	−1.4	3.6
Δtemp22 (°C)	1617	0.7	0.6	−1.3	3.1
Precipitation (>0)	1616	0.4	0.5	0.0	1.0
Pressure (hPa)	1609	894.0	2.3	883.2	901.8
Humidity (%)	1635	49.6	14.7	12.5	89.7
Wind ($m\ s^{-1}$)	1635	2.0	0.5	0.7	4.6
Temperature (°C)	1635	11.7	3.5	1.5	21.0
Radiation ($W\ m^{-2}$)	1634	127.1	65.1	0.0	405.3

dependent and the explanatory variables make it difficult to interpret the coefficients individually. To better understand the relationship between the explanatory and the dependent variables, we report the long run marginal effects instead of the original coefficients. The long run marginal effect corresponds to the marginal effect considering the model in steady state. For example, in an equation such as:

$$y_t = c + \rho_1 y_{t-1} + \ldots + \rho_k y_{t-k} + \beta_0 x_t + \beta_1 x_{t-1} + \ldots + \beta_k x_{t-k} + \ldots, \quad (2)$$

the long run marginal effect is as follows:

$$\frac{\partial y}{\partial x} = \frac{\beta_0 + \beta_1 + \ldots + \beta_k}{1 - \rho_1 - \ldots - \rho_k}. \quad (3)$$

Notice that the long run marginal effects are nonlinear functions of the estimates. We calculate the standard errors and significance tests using the delta method.

The weather variables for any given day are as follows: the temperature difference between the ground level and 8 m above ground, the temperature difference between the ground level and 22 m above ground (temperature differences are associated with the ventilation conditions of the city), a dichotomous variable indicating whether there was precipitation, the natural logarithm of the average atmospheric pressure, the natural logarithm of the average humidity, the natural logarithm of the average wind speed, the natural logarithm of the average temperature, and the average radiation level. We measure the pollutant concentrations and the weather variables on a logarithmic scale, with the exception of the radiation and the temperature differences because the logarithm of these two did not exhibit sinusoidal behavior, and the temperature differences may be negative, for which the logarithm is not defined. However, using logarithmic values for all of the variables does not change the qualitative results of our regressions.

The most probable source of endogeneity in equation (1) is error autocorrelation. This stems from the fact that critical episodes are declared on the basis of information available up to the day previous to the declaration. If the errors are autocorrelated, they will be correlated positively with the dummy variables indicating the critical episodes. This finding implies that a positive pollution shock in period t will be associated with a critical episode in period $t+1$, and the error autocorrelation will produce endogeneity and, therefore, a biased estimate.

One obvious case of bias would be generated by only estimating with the critical episode dummies, without including the control variables. Because episodes are only declared when pollution levels are unusually high, the dummies will capture not only the effect of the restrictions but also the very fact of being in a high-pollution period. The estimates would therefore be biased upwards.

The endogeneity problem is dealt with by including variables that explain the environmental authorities' decisions as part of the explanatory variables, and by checking that the residual does not exhibit autocorrelation. Because critical episodes are declared for the following day based on pollution levels and expected ventilation conditions, our identification assumption is that by including weather variables (and other controls), their lags and the lags of the dependent variable, we would be explaining the authority's decision to declare a critical episode for the following day, except for a shock, which would be orthogonal to these variables, and, therefore, to the shock in the following period. In all of the regressions, we applied the Breusch–Godfrey autocorrelation test as our identification test. In every case, the null hypothesis of no autocorrelation was not rejected by a considerable margin. We included the lags of the dependent variable and all the explanatory variables until the residuals did not present autocorrelation. It resulted in 5 lags in the case of NO_x and 6 lags for the other pollutants. The experiments with different lag structures did not qualitatively change the results.

Another reason the error autocorrelation produces endogeneity is the inclusion of the dependent variable lags. In this case, however, the problem can be solved simply by eliminating them, though at the cost of losing some explanatory power.

Since the restrictions suffered an important modification in 2007, we estimated equation (1) for the complete period (2000–2008) and the subperiods (2000–2006 and 2007–2008). Notice that the differences in the estimates for different subperiods are not attributable exclusively to the change in the legislation, and they can only be interpreted as a reduced form of many possible causes. Among other factors that may determine changes in the effectiveness of the restrictions are the changes in the size of the city, the size, age and composition of the vehicle fleet, and a better knowledge of how to evade the restrictions.

4. Results

The estimates of the model given by equation (1) are shown in Tables 5 and 6 for the various pollutants and subperiods. To simplify the presentation of the results, we only show the coefficients of the dummy variables representing critical episode, and not the coefficients of the other control variables. Additionally, we grouped the coefficients by the type of restriction and subperiod, and not by the regression to make it easier to evaluate the evolution of the effectiveness of the restrictions for each pollutant.

Because the dependent variables are expressed in logarithms, we can interpret the coefficients in Tables 5 and 6 as percentage changes. Table 5 shows the estimates of alerts and pre-emergencies during weekdays for different subperiods. Considering the entire period, we found significant reductions in the concentration of pollutants during alerts, except for the SO_2. Curiously, however, the coefficient for SO_2, though significant only at the 10% level, had a positive sign.

We estimated that on weekdays between 2000 and 2008 the average decline in CO and NO_x was approximately 10% during alerts and 20% during pre-emergencies. The reductions in PM10 and PM2.5 were 5%–7% during the alerts and approximately 12% during pre-emergencies. The SO_2 concentrations, on the other hand, did not decrease during the alerts or the pre-emergencies. On weekends and public holidays, the impact of the alerts was generally not significant, except for CO between 2000 and 2006.

Alerts only produced significant reductions in the pollutant concentrations during the subperiod 2000–2006, and they had no significant effects between 2007 and 2008. These results are

Table 5
Effect of restrictions during weekdays.

Restriction	Period	CO	SO_2	NO_x	PM10	PM25
Alert	2000–2008	−0.106***	0.042*	−0.111***	−0.058**	−0.065**
		(0.03)	(0.025)	(0.028)	(0.024)	(0.026)
	2000–2006	−0.123***	0.049*	−0.135***	−0.081***	−0.072**
		(0.034)	(0.028)	(0.032)	(0.028)	(0.03)
	2007–2008	−0.066	0.025	−0.055	−0.002	−0.052
		(0.05)	(0.042)	(0.047)	(0.041)	(0.044)
Pre-emergency	2000–2008	−0.211***	−0.035	−0.206***	−0.125***	−0.125***
		(0.055)	(0.045)	(0.051)	(0.045)	(0.048)
	2000–2006	−0.153**	−0.017	−0.159***	−0.088*	−0.063
		(0.065)	(0.054)	(0.061)	(0.053)	(0.057)
	2007–2008	−0.333***	−0.076	−0.304***	−0.2**	−0.26***
		(0.095)	(0.078)	(0.088)	(0.078)	(0.083)

Standard errors in parentheses. *Indicates significance at the 10% level, ** at the 5% level and *** at the 1% level.

Table 6
Effect of restrictions during weekends.

Restriction	Period	CO	SO_2	NO_x	PM10	PM25
Alert	2000–2008	−0.076* (0.042)	−0.033 (0.034)	−0.033 (0.039)	0.028 (0.034)	0.001 (0.036)
	2000–2006	−0.094** (0.048)	−0.036 (0.039)	−0.03 (0.044)	0.016 (0.039)	−0.001 (0.042)
	2007–2008	−0.021 (0.079)	−0.025 (0.065)	−0.04 (0.073)	0.066 (0.065)	0.004 (0.069)
Pre-emergency	2000–2008	−0.132* (0.072)	−0.021 (0.06)	−0.087 (0.066)	−0.058 (0.059)	−0.066 (0.063)
	2000–2006	−0.152* (0.081)	−0.01 (0.067)	−0.098 (0.072)	−0.078 (0.066)	−0.056 (0.07)
	2007–2008	−0.056 (0.16)	−0.062 (0.132)	−0.049 (0.148)	0.013 (0.131)	−0.112 (0.139)

Standard errors in parentheses. *Indicates significance at the 10% level, ** at the 5% level and *** at the 1% level.

consistent with the decreasing relevance of NGS vehicles on the total number of trips.

In the case of pre-emergencies, Table 5 shows significant reductions in the pollutants, except for the SO_2. The pre-emergencies had a larger impact on the pollutants for the later subperiod, which is consistent with the extension of the restriction on GS vehicles in 2007. During the period 2007–2008, pre-emergencies reduced the concentration of the pollutants by nearly 30% in the case of CO and NO_x, 20% in the case of PM10, and 26% for PM25.

Table 6 shows the estimates for the weekends. We see that only CO was significantly reduced during alerts and pre-emergencies before 2007. All of the other pollutants show no significant marginal reductions in their concentrations during both alerts and pre-emergencies, and for the subperiod 2007–2008, the marginal effect on the concentrations of CO was no longer significant.

5. Discussion

Since alerts and pre-emergencies only apply during winter months it is not possible to identify their effects in other seasons of the year. Specifically, restrictions operate between April and August, which are the months with the highest concentrations of pollutants in the city due to poorer ventilation conditions in the valley of Santiago. So our results are only valid for this time of year.

We found that pre-emergencies during weekdays resulted in significant reductions in the concentrations of pollutants, both from a statistical point of view as of relevance for public policy. The exception was the case of SO_2 concentrations. However, the significant reduction of pollutants achieved by pre-emergency is not an overall evaluation of this public policy. We are leaving out important aspects such as the social cost of restricting the use of private vehicles and the operation of the industry; measure the benefits in terms of population health; or the long-term incentives to purchase a second vehicle, thereby increasing the vehicle fleet of the city, the number of trips and the emissions of pollutants.

Restrict the use of the automobile or the operation of the industry involves social costs. For this reason, the authority should consider a revision of the restrictions that do not produce significant reductions in pollutant concentrations. This may be the case of alerts and pre-emergencies during weekends. The lack of effectiveness of the restrictions during weekends might be caused by factors such as a looser enforcement or that the normally lower use of cars during the weekends gives families more opportunities to replace a vehicle with restraint.

When comparing the evolution of the effects of restrictions after 2007, we found that during weekdays, alerts no longer had significant effects, while the pre-emergencies about doubled its effectiveness for all pollutants, except in the case of SO_2, which remained without significant effect. The latter was expected since the Supreme Decree of 2007, specifically, increased restrictions during pre-emergencies.

According to our estimates, restrictions were not successful reducing the concentrations of SO_2. Alerts restrict the use of vehicles, while pre-emergencies also restrict industrial activities. Since in Santiago, diesel vehicles are not a relevant source of SO_2 emissions, we did not expect a relevant effect of alerts on this pollutant. According to Table 2, 98.6% of total concentrations of SO_x come from stationary sources (96.2% from industry) and only 0.1% comes from light diesel vehicles (1.4% from all mobile sources). In the case of pre-emergencies, we are not able to identify the reasons for the lack of impact, but the fact that during pre-emergencies the levels of CO decreases while the levels of SO_2 do not, indicates that restrictions on vehicles are more relevant, in the short run, than restrictions on industrial activities. This may be because restricted industries represent a smaller proportion of total industrial emissions, or that the restriction is not enforced properly.

Curiously, the estimates of the effects of alerts on SO_2 concentrations during weekdays (see Table 5) had an unexpected positive sign for the entire period 2000–2008 and for subperiod 2000–2006, although it is only significant at the 10% level. Alerts were certainly not expected to have much effect on reducing concentrations of this pollutant given that they originate almost exclusively from industrial activities (see Table 2) which are not subjected to alert restrictions; however, it was not expected to increase. A possible explanation for this result is that the industrial emitters interpret the alert declarations as predictors of a coming pre-emergency in which they could be shut down; therefore, to reduce possible losses, they actually increase production and their SO_2 emissions on alert days. The fact that one-half of all pre-emergencies were preceded by alerts reinforces the likelihood that they, or the general conditions associated with them, were used as a pre-emergency predictor.

6. Conclusions

The declaration of Santiago, Chile as a “saturated zone” due to high concentrations of air pollutants led to the implementation of a number of pollution control measures. These included the definition of three levels of critical environmental episodes denoted as alerts, pre-emergencies and emergencies. A series of restrictions on industrial, residential and transportation sources was defined for each episode to attempt to reduce pollutant concentrations. We estimate the effect of these restrictions on the concentrations of CO, SO_2, NO_x, PM10 and PM25. Because an emergency episode has never been declared, the estimates were confined to the impacts of alerts and pre-emergencies.

We find that the restrictions led to significant reductions in the concentrations of CO, NO_x, PM10 and PM25 during weekdays, while there is not a significant reduction in the concentration of SO_2. The effect of alerts on weekdays was not significant after 2007, while the effect of pre-emergencies increased significantly, doubling the size of their impact in the case of CO and NO_x and more than doubling the size of this impact in the case of PM10 and PM25.

For weekends, we only find significant marginal effects from the restrictions for CO before 2007. In 2007–2008, the estimates for CO were not significant. For the other pollutants, we found that both the alerts and pre-emergencies produced no significant reductions in their concentrations.

Although we are not able to estimate the isolated effect of each restriction during critical episodes, the fact that during pre-emergencies the levels of CO decreases while the levels of SO_2 do not indicates that restrictions on vehicles are more relevant, in the short run, than restrictions on industrial activities.

Appendix 1

Estimates of the average effects of the restriction for period 2000–2008.

Variable	Coefficient	Std. error	*t*	*p* value
Regression for CO concentrations model. Dependent variable: ln(CO)				
Alert weekend	−0.106	0.030	−3.543	0.000
Alert weekend	−0.076	0.042	−1.818	0.069
Pre-emergency weekday	−0.211	0.055	−3.851	0.000
Pre-emergency weekend	−0.132	0.072	−1.817	0.069
Holiday	0.011	0.030	0.367	0.714
Diff temp 8	0.380	0.127	2.999	0.003
Diff temp 22	0.519	0.130	3.993	0.000
Precipitation	0.001	0.152	0.008	0.993
Pressure	1.825	21.510	0.085	0.932
Humidity	−0.321	0.268	−1.196	0.232
Wind	−1.519	0.304	−4.988	0.000
Temperature	−0.602	0.211	−2.850	0.004
Radiation	−0.001	0.001	−1.406	0.160
No. of observations				2880
R-Squared				0.910
Breusch Godfrey autocorrelation test (*p* value)				0.814
Regression for SO_2 concentrations model. Dependent variable: ln(SO_2)				
Alert weekday	0.042	0.025	1.722	0.085
Alert weekend	−0.033	0.034	−0.953	0.341
Pre-emergency weekday	−0.035	0.045	−0.765	0.444
Pre-emergency weekend	−0.021	0.060	−0.347	0.729
Holiday	−0.067	0.025	−2.681	0.007
Diff temp 8	0.126	0.059	2.150	0.032
Diff temp 22	0.097	0.060	1.617	0.106
Precipitation	−0.095	0.069	−1.364	0.173
Pressure	42.838	10.087	4.247	0.000
Humidity	−0.171	0.122	−1.396	0.163
Wind	−0.492	0.138	−3.556	0.000
Temperature	0.028	0.095	0.300	0.764
Radiation	0.000	0.000	−0.168	0.867
No. of observations				2880
R-Squared				0.726
Breusch Godfrey autocorrelation test (*p* value)				0.519
Regression for NO_x concentrations model. Dependent variable: ln(NO_x)				
Alert weekday	−0.111	0.028	−4.012	0.000
Alert weekend	−0.033	0.039	−0.846	0.398
Pre-emergency weekday	−0.206	0.051	−4.035	0.000
Pre-emergency weekend	−0.087	0.066	−1.334	0.182
Holiday	−0.262	0.028	−9.252	0.000
Diff temp 8	0.246	0.058	4.254	0.000
Diff temp 22	0.408	0.059	6.900	0.000
Precipitation	−0.055	0.067	−0.819	0.413
Pressure	12.315	9.591	1.284	0.199
Humidity	−0.431	0.120	−3.586	0.000
Wind	−0.764	0.137	−5.583	0.000
Temperature	−0.321	0.094	−3.420	0.001
Radiation	−0.002	0.000	−4.517	0.000
No. of observations				2841
R-Squared				0.918
Breusch Godfrey autocorrelation test (*p* value)				0.955
Regression for PM10 concentrations model. Dependent variable: ln(PM10)				
Alert weekday	−0.058	0.024	−2.355	0.019
Alert weekend	0.028	0.034	0.828	0.408
Pre-emergency weekday	−0.125	0.045	−2.788	0.005
Pre-emergency weekend	−0.058	0.059	−0.983	0.326
Holiday	−0.169	0.025	−6.827	0.000
Diff temp 8	0.199	0.043	4.674	0.000
Diff temp 22	0.287	0.044	6.552	0.000
Precipitation	−0.253	0.051	−4.967	0.000
Pressure	9.217	7.248	1.272	0.204
Humidity	−0.105	0.089	−1.178	0.239
Wind	−0.945	0.102	−9.229	0.000
Temperature	−0.066	0.071	−0.938	0.348
Radiation	0.002	0.000	6.023	0.000
No. of observations				2880
R-Squared				0.792
Breusch Godfrey autocorrelation test (*p* value)				0.691
Regression for PM2.5 concentrations model. Dependent variable: ln(PM2.5)				
Alert weekday	−0.065	0.026	−2.496	0.013
Alert weekend	0.001	0.036	0.030	0.976
Pre-emergency weekday	−0.125	0.048	−2.610	0.009
Pre-emergency weekend	−0.066	0.063	−1.041	0.298
Holiday	−0.088	0.026	−3.335	0.001
Diff temp 8	0.189	0.062	3.046	0.002
Diff temp 22	0.251	0.064	3.910	0.000
Precipitation	−0.186	0.075	−2.492	0.013
Pressure	15.643	10.560	1.481	0.139
Humidity	−0.242	0.131	−1.854	0.064
Wind	−1.349	0.151	−8.962	0.000
Temperature	−0.289	0.104	−2.774	0.006
Radiation	0.002	0.001	4.293	0.000
No. of observations				2888
R-Squared				0.809
Breusch Godfrey autocorrelation test (*p* value)				0.957

Variable description: Restriction dummies are named according to the type of restriction (*Alert or Pre-emergency*) and the day of the week (*weekday* or *weekend*); *Holiday* is a dummy variable for holidays; *Diff temp 8* is the temperature differential between the ground and 8 m above; *Diff temp 22* is the temperature differential between the ground and 22 m above; *Precipitation* is a variable for days with precipitations; *Pressure* is the natural logarithm of atmospheric pressure (hPa); *Humidity* is the natural logarithm of average humidity (%); *Wind* is the natural logarithm of the average wind speed (m s^{-1}), *Temperature* is the natural logarithm of the average temperature (°C); and *Radiation* is the average radiation level (w m^{-2}). Dummies for the day of the week, the month and the year are not shown.

Appendix 2

Estimates of the average effects of the restrictions for two subperiods: 2000–2006 and 2007–2008.

Variable	Coefficient	Std. error	*t*	*p* value
Regression for CO concentrations model. Dependent variable: ln(CO)				
A wday 2000–2006	−0.123	0.034	−3.602	0.000
A wday 2007–2008	−0.066	0.050	−1.299	0.194
A wend 2000–2006	−0.094	0.048	−1.980	0.048
A wend 2007–2008	−0.021	0.079	−0.260	0.795
P wday 2000–2006	−0.153	0.065	−2.353	0.019
P wday 2007–2008	−0.333	0.095	−3.515	0.000
P wend 2000–2006	−0.152	0.081	−1.885	0.060
P wend 2007–2008	−0.056	0.160	−0.348	0.728
Holiday	0.012	0.030	0.400	0.689
Diff temp 8	0.376	0.127	2.966	0.003
Diff temp 22	0.508	0.131	3.876	0.000
Precipitation	0.008	0.152	0.051	0.959
Pressure	3.110	21.443	0.145	0.885
Humidity	−0.336	0.268	−1.256	0.209
Wind	−1.518	0.303	−5.002	0.000
Temperature	−0.580	0.211	−2.750	0.006
Radiation	−0.002	0.001	−1.462	0.144
No. of observations				2880
R-Squared				0.910
Breusch Godfrey autocorrelation test (*p* value)				0.993
Regression for SO_2 concentrations model. Dependent variable: ln(SO_2)				
A wday 2000–2006	0.049	0.028	1.726	0.085
A wday 2007–2008	0.025	0.042	0.611	0.541
A wend 2000–2006	−0.036	0.039	−0.925	0.355
A wend 2007–2008	−0.025	0.065	−0.380	0.704
P wday 2000–2006	−0.017	0.054	−0.311	0.756
P wday 2007–2008	−0.076	0.078	−0.965	0.334

(*continued*)

Variable	Coefficient	Std. error	*t*	*p* value
P wend 2000–2006	−0.010	0.067	−0.157	0.876
P wend 2007–2008	−0.062	0.132	−0.472	0.637
Holiday	−0.067	0.025	−2.677	0.007
Diff temp 8	0.122	0.059	2.075	0.038
Diff temp 22	0.104	0.061	1.711	0.087
Precipitation	−0.091	0.070	−1.315	0.189
Pressure	42.526	10.086	4.216	0.000
Humidity	−0.171	0.122	−1.396	0.163
Wind	−0.495	0.138	−3.575	0.000
Temperature	0.026	0.095	0.280	0.780
Radiation	0.000	0.000	−0.144	0.885
No. of observations				2880
R-Squared				0.726
Breusch Godfrey autocorrelation test (*p* value)				0.434
Regression for NO$_x$ concentrations model. Dependent variable: ln(NO$_{x>}$)				
A wday 2000–2006	−0.135	0.032	−4.268	0.000
A wday 2007–2008	−0.055	0.047	−1.182	0.237
A wend 2000–2006	−0.030	0.044	−0.673	0.501
A wend 2007–2008	−0.040	0.073	−0.547	0.585
P wday 2000–2006	−0.159	0.061	−2.631	0.009
P wday 2007–2008	−0.304	0.088	−3.452	0.001
P wend 2000–2006	−0.098	0.072	−1.355	0.175
P wend 2007–2008	−0.049	0.148	−0.330	0.741
Holiday	−0.261	0.028	−9.237	0.000
Diff temp 8	0.245	0.058	4.224	0.000
Diff temp 22	0.405	0.060	6.772	0.000
Precipitation	−0.054	0.067	−0.810	0.418
Pressure	12.950	9.586	1.351	0.177
Humidity	−0.439	0.120	−3.651	0.000
Wind	−0.767	0.137	−5.609	0.000
Temperature	−0.313	0.094	−3.325	0.001
Radiation	−0.002	0.000	−4.589	0.000
No. of observations				2841
R-Squared				0.918
Breusch Godfrey autocorrelation test (*p* value)				0.869
Regression for PM10 concentrations model. Dependent variable: ln(PM10)				
A wday 2000–2006	−0.081	0.028	−2.883	0.004
A wday 2007–2008	−0.002	0.041	−0.056	0.956
A wend 2000–2006	0.016	0.039	0.421	0.674
A wend 2007–2008	0.066	0.065	1.022	0.307
P wday 2000–2006	−0.088	0.053	−1.659	0.097
P wday 2007–2008	−0.200	0.078	−2.573	0.010
P wend 2000–2006	−0.078	0.066	−1.172	0.241
P wend 2007–2008	0.013	0.131	0.102	0.919
Holiday	−0.169	0.025	−6.792	0.000
Diff temp 8	0.200	0.043	4.679	0.000
Diff temp 22	0.279	0.044	6.307	0.000
Precipitation	−0.252	0.051	−4.968	0.000
Pressure	9.881	7.240	1.365	0.172
Humidity	−0.112	0.089	−1.253	0.210
Wind	−0.943	0.102	−9.232	0.000
Temperature	−0.057	0.071	−0.806	0.420
Radiation	0.002	0.000	5.956	0.000
No. of observations				2880
R-Squared				0.792
Breusch Godfrey autocorrelation test (*p* value)				0.521
Regression for PM2.5 concentrations model. Dependent variable: ln(PM2.5)				
A wday 2000–2006	−0.072	0.030	−2.436	0.015
A wday 2007–2008	−0.052	0.044	−1.171	0.242
A wend 2000–2006	−0.001	0.042	−0.021	0.984
A wend 2007–2008	0.004	0.069	0.057	0.955
P wday 2000–2006	−0.063	0.057	−1.121	0.262
P wday 2007–2008	−0.260	0.083	−3.140	0.002
P wend 2000–2006	−0.056	0.070	−0.793	0.428
P wend 2007–2008	−0.112	0.139	−0.807	0.420
Holiday	−0.088	0.026	−3.333	0.001
Diff temp 8	0.180	0.063	2.882	0.004
Diff temp 22	0.259	0.065	3.971	0.000
Precipitation	−0.179	0.075	−2.393	0.017
Pressure	15.762	10.600	1.487	0.137
Humidity	−0.250	0.131	−1.908	0.057
Wind	−1.356	0.151	−8.973	0.000
Temperature	−0.288	0.105	−2.748	0.006
Radiation	0.002	0.001	4.282	0.000
No. of observations				2888
R-Squared				0.810
Breusch Godfrey autocorrelation test (*p* value)				0.966

Variable description: Restriction dummies are named according to the type of restriction (*A* for alerts and *P* for pre-emergencies), the day of the week (*wday* for weekdays and *wend* for weekends), and the subperiod (2000–2006 or 2007–2008); *Holiday* is a dummy variable for holidays; *Diff temp 8* is the temperature differential between the ground and 8 m above; *Diff temp 22* is the temperature differential between the ground and 22 m above; *Precipitation* is a variable for days with precipitations; *Pressure* is the natural logarithm of atmospheric pressure (hPa); *Humidity* is the natural logarithm of average humidity (%); *Wind* is the natural logarithm of the average wind speed (m s^{-1}), *Temperature* is the natural logarithm of the average temperature (°C); and *Radiation* is the average radiation level (w m^{-2}). Dummies for the day of the week, the month and the year are not shown.

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