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Impacts of vehicle restrictions on urban transport flows: The case of Santiago, Chile

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ABSTRACT

Regression models are employed to quantify the effects of vehicle restrictions on private and public transport passenger flows in Santiago, Chile using trip flow data for cars, buses and the city's Metro rail system. Estimates are derived for the effects of two restrictions: a permanent measure applied from April through August 2008 to vehicles without catalytic converters and additional measures that banned the use of vehicles with catalytic converters between 7:30 am and 9 pm on days declared as environmental "pre-emergencies" due to high air pollution levels. The estimates show that the permanent restriction had no impact on the use of private cars while the additional restriction curtailed their use by 5.5%. Also, on pre-emergency days the flow of passengers to the Metro increased by about 3% while the bus network showed no statistically significant increase. The pre-emergency restrictions thus had an effect on the ridership of the Metro but not on the bus network as alternatives to the use of private cars.

1. Introduction

This study presents an empirical analysis that determines the impact of a vehicle use restriction policy implemented in Santiago, Chile on public transit (bus and Metro) passenger flows and vehicle flows through the city's streets in 2008. Two types of vehicle restrictions were applied in Santiago that year. The first one was a permanent (i.e., annual) restriction, in force during the southern hemisphere winter from April to August, that bans 40% of cars without a catalytic converter. Such vehicles are not eligible for a *sello verde* ("green sticker") and thus will also be referred to as NGS. The second restriction was an additional measure imposed during "environmental pre-emergencies" (declared by the authorities when the Santiago air pollution index reaches certain levels) that extended the prohibition to 60% of NGS vehicles and 20% of those that did have catalytic converters (GS vehicles). For both restrictions, the vehicles affected on a given day are determined by specifying the corresponding number of final licence/registration plate digits that are banned. In all cases the measures were in force from 7:30 am to 9:00 pm.

The analysis was based on data drawn from actual bus, Metro and private vehicle flow measurements taken during 2008 and generated three main results. The first is that the permanent restriction on NGS vehicles (April through August) had no significant impact on vehicle flows. This was due in part to the fact that, of the 1,200,000 vehicles in Santiago (INE, 2008), only 120,000, or 10%, have no catalytic converter (and therefore date back at least to the mid-1990s) so that the permanent restriction affected only 4% of the total (40% of 10%). Another reason was that NGS vehicles tend to be older and therefore cheaper ones driven mainly by lower-income persons who typically cannot afford the gasoline and maintenance costs of driving on a regular basis.

The second main result is that during the environmental pre-emergencies, with 2 licence plate digits banned for cars with catalytic converters and 6 banned for vehicles without them, the restrictions reduced vehicle flows by 5.5% on an average weekday. This translated into 176,000 fewer car trips, which is significantly less than the 20% of GS vehicles that were theoretically affected by the additional pre-emergency restriction. The difference may be explained by various factors. First, some drivers whose main vehicle was affected by the restrictions had a second vehicle for use on those days; second, as we discovered during our research, a certain percentage of drivers set out earlier in the morning to beat the 7:30 am cutoff; and finally, a certain number simply disregarded the restrictions (police checks on pre-emergency days covering only a small part of the Santiago road network issued approximately 150 tickets for restriction violations).

The third main result of our analysis is that on pre-emergency days the daily inflow of passengers to the Metro network increases by about 3.1%, or 70,000 additional trips. This is less than the reduction in car trips (some 187,000 per day), suggesting that many drivers resort to a variety of other alternatives. These may include using another car, staying at home, disobeying the restriction, trip

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chaining, omission (or re-scheduling to another day) of non-mandatory trips and car pooling. If a significant number of those affected by the restrictions opted to travel by bus instead of private car, bus use statistics would show a strong increase. Our estimates, however, show that bus journey numbers on pre-emergency days remain at their usual levels.

To obtain these results we employed multiple linear regression models developed for this study. We estimated the percentage change in the number of trips taken on restricted days in both GS and NGS vehicles on weekdays, controlling for weekdays and legal holidays (excluded from the sample), day of the week and, in the case of car trips, time of the day.

The decision to use 2008 statistics for the model estimations was motivated simply by the fact that in 2009 and 2010, no pre-emergencies were declared and thus no restrictions affecting GS vehicles were imposed in those years. The vehicle flow data were provided by the *Unidad Operativa de Control de Tráfico* (UOCT) and consisted of hourly measurements for all 365 days at 46 arcs in the Santiago road network. The daily passenger flow data for each station in the Metro system were facilitated by the operator, Metro S.A. and the bus passenger flow data were made available by Transantiago, the city's transit authority.

In Section 2 of this paper we review the literature on vehicle use restriction policies in various cities around the world together and provide other background information on the operation of these traffic measures in Santiago over recent years, focussing on 2008. In Section 3 we introduce our econometric model with its different specifications and also set out and interpret the results of the model estimates. Section 4 presents the main conclusions of our empirical analyses. The data used for the estimates are given in the Appendix A. Finally, we note that the main contribution of this study of vehicle restrictions is empirical rather than theoretical.

2. Background information

2.1. Review of the literature

Kornhauser and Fehlig (2003) propose vehicle restriction (road space rationing) as a road demand management technique that, instead of charging a fee for driving (as in road pricing), restricts the days or hours in which a driver can use congested roads. Although in their view, road space rationing is a more equitable way of mitigating road congestion than road pricing (Rouwendal and Verhoef, 2006), in Santiago the vehicle restriction system is quite heterogeneous in its impact on different classes of users (Ortúzar, 2003). Among the reasons advanced for this are the following: (i) it is easier for some users than others to find substitutes for car trips (for example, those living close to a Metro station or to their place of work); (ii) as noted earlier, some users have a second car, which they can use on restricted days; (iii) the importance (willingness to pay) of different trips is not taken into account.

Some specialists have argued against the vehicle restriction approach, calling it unjust and inefficient. Using a time-series analysis, Eskeland and Feyzioglu (1995) find that in the long run the restriction method actually increases congestion and pollution. This is due to the tendency of motorists to acquire an additional car, which typically will be older and therefore more polluting, and the possibility they may actually drive more than previously on unrestricted days, thus offsetting any benefits of the system. Those actually affected by this type of measure are thus primarily lower-income drivers without a second vehicle.

Despite these drawbacks, various major Latin American cities have implemented restrictive policies for private cars that prohibit their use on certain days based on the licence plate number (Bull, 2003). In the 1970s, a vehicle restriction system implemented in Buenos Aires banned one-half of all the cars from entering the city center on a given day depending on whether the last digit of the plate number was odd or even. This method was also used in Caracas in the 1980s and in Athens between 1985 and 1991. Analyses of the results were not very encouraging, however, as it was discovered that many users did indeed buy a second (and older) vehicle, thus upping the average age of cars on the road, while the number of motorcycles, which pollute more than cars, increased. Non-observance of the restrictions by drivers also grew.

In Managua (Nicaragua), restrictions in place since 2001 allow only half of the city's taxi fleet to ply the streets during certain hours in order to reduce congestion caused by the large number of existing vehicles. Cabs with even-number licence plates numbers can circulate from 6 am to 2 pm while those with odd-number plates are permitted from 2 to 10 pm.

In Mexico City the local government introduced the "Day Without a Car" (Spanish initials: HNC) program in 1989, prohibiting vehicles one day in a week as determined by the last licence plate digit. Thus, between 5 am and 10 pm on weekdays cars are banned on Mondays if their plates end in 0 or 1, on Tuesdays if they end in 2 and 3, etc. When pollution levels are high, the restriction is extended to half of all vehicles (odd or even plate numbers). Studies have shown that the negative impacts of the program outweigh the positive ones, however, as once again, many drivers get around the restriction by purchasing a second car. Indirect evidence suggests that pollution has in fact worsened since the program was implemented (Tovar, 1995). Davis (2008) reports that hourly data from the city's air quality monitoring stations indicate no improvement, and use of public transport has not increased. The author also notes that gasoline sales rose more than expected and so, therefore, did air pollution. In sum, households negatively affected by the expropriation of part of their vehicle's flow of services reacted defensively to the restriction program, in the end completely neutralizing it.

In 1992, HNC was expanded to vehicles using liquefied or compressed natural gas. Five years later an exemption was granted for low-emission gasoline-powered vehicles, defined as cars sold since 1993 and equipped with a catalytic converter, which were identified with a "0" hologram sticker. To encourage the introduction into the Mexican market of vehicles complying with international standards, these models, identified by a double "0" hologram, were also exempted from HNC beginning in 1999 and were furthermore not subjected to emission inspections for the first two years.

The original objective of the HNC program was to lower the harmful emission levels by applying daily restrictions to 20% of the total number of cars in the Mexico City area. This brought about reductions of 11,500 barrels per day in gasoline consumption and 30,000 tonnes per year in pollutants so that compliance with the 2001 emissions standards was already achieved in 1999 and 2000 (Dirección General del Aire, 2004).

The argument that HNC induced families to acquire an additional older car to get around the restrictions and that these vehicles generally incorporate inferior technology and impact the environment more heavily has been partially confirmed by the Mexico City environmental authorities. An estimated 22% of the cars acquired when HNC was first launched fit this description (Cifuentes, 2007).

In Sao Paulo, various trials were conducted beginning in 1995 with a vehicle restriction system known as "rodizio" that controls vehicle use based on licence plate number (Viegas, 2001). As in the original Mexico City approach, two digits were prohibited on each weekday. It was first applied experimentally for a week on a voluntary basis, the State Secretary of the Environment merely suggesting that drivers leave their vehicles at home on the day indicated by their car licence plates. Compliance was high (about 50%) during the first two days, then dropped to an average of 38% for the last three (Bull, 2003).

In 1996 the system was made mandatory (Sao Paulo State Law No. 9.358) and fines for infractions were set at 100 reales. It was applied from 5 to August 30 between 7 am and 8 pm, with compliance oscillating around 95%. Carbon monoxide emissions were estimated to have diminished by 1171 tonnes while 40 million fewer litres of fuel were consumed. Average traffic speed rose 20% and congestion was down 40% at peak hours. The same restrictions were imposed the following year from June 23 to September 30 in the greater Sao Paulo area, with fines for violations reduced to 78 reales. Compliance was again relatively high at 90% in the morning and 85% in the afternoon/evening. Emissions of carbon monoxide fell by 42,460 tonnes while those of particulate matter were 200 tonnes lower.

Beginning in October 1997 the system was applied solely in the city center during morning and afternoon rush hours (7–10 am and 5–8 pm). Studies of the impact of the restriction for the October 1997–May 1998 period reported a number of relevant findings. First, congestion declined by 18% from 7 am to 8 pm, 37% during the morning peak and 26% during the afternoon peak; second, average speed along a busy artery used as a benchmark was up to 23% in the morning rush and 24% in the afternoon rush; and third, benefits of the program were estimated at US$2.57 million per day, of which 78% were due to time savings and 10% to fuel consumption reductions. The initiative has been promoted and adopted by city residents as a civic participation project in which everyone makes their contribution to the battle against congestion.

In Bogota (Colombia), a vehicle restriction program known as "Pico y Placa" has been in effect since 1998. Four final licence plate digits are banned each weekday during the peak hour periods of 7–10:30 am and 5:30–7:30 pm, thus subjecting each car to the restriction two days a week. According to figures supplied by the city authorities (Bogota Secretary of Transit), upon implementation of the program average traffic speed increased 43%, fuel consumption fell 8% and air pollution was cut by 11%. Significantly, other measures were adopted to promote walking (by banning parking on sidewalks) and cycling (through construction of a cycle path network), and a high-capacity bus network running on dedicated lanes, known as Transmilenio, was built. Steps were also taken to discourage automobile use. For seven hours every Sunday, 150 km of city streets are closed to vehicular traffic and turned over to bicycles. The first Thursday in February is Bogota's Car-Free Day during which residents are encouraged to leave their automobiles at home between 6:30 am and 7:30 pm. Support for the latter initiative has been strong.

The need for some sort of vehicle restriction also arose in the Colombian city of Medellin, and taking advantage of Bogota's positive experience with its "Pico y Placa" system a variation on it was inaugurated in February 2005. The arrangement covered 10% of individual (taxi) and special (white plate) public transit vehicles, the latter being affected on a rotating basis for a month at a time. The specific day of application cycled through the work week every 5 months (information supplied by the Municipality of Medellin). Six months after going into operation, however, the restriction was modified and extended to one whole day every 15 days from 6 am to 8 pm. Whatever issues the program might raise regarding pollution from mobile sources such as motor vehicles, Medellin's version of "Pico y Placa" has concentrated its focus on the general goal of improving vehicular traffic. As of 2008 no data indicating its effectiveness had been reported.

In Manila a restriction scheme bans certain vehicles, identified by their licence plate number, from using specified high-traffic arteries during peak hours (GTZ, 2002).

Finally, a paper by Cantillo and Ortuzar (2010) makes use of a simple microeconomic analysis bolstered by evidence collected from some of the cities where vehicle restriction policies have been implemented to show that such approaches are only viable in the very short term, and in the end do not fulfill the desired objectives.

To summarize our literature survey, in recent years vehicle restrictions have been implemented in a number of major cities as a regulatory policy for reducing congestion and air pollution. Their consequences have so far been little studied, but what data do exist indicate that the impacts on congestion and pollution have been less than initially hoped and actually diminish as users adapt to the measures. Still, it should be kept in mind that the effects of similar policies in different locations will not necessarily be the same. Each city is a unique context and direct comparisons cannot always be made.

2.2. Case study description

Vehicle restriction began in Chile in 1986 as a measure to deal with the ongoing air pollution crisis in Santiago as reflected in the high levels of breathable particulate matter (PM10). Later in the decade it was decided to maintain the restrictions for the whole of the winter months between May and August. In the early nineties the measures were extended to additional months and other major cities around the country (Del Favero et al., 2000).

The restrictions are traditionally in force from March through December for all four (or more) wheeled motorized vehicles that do not have a green sticker (NGS), that is, that are not equipped with a catalytic converter. The restricted days for each vehicle depends on the last licence plate digit. The controls are in effect Monday through Friday except legal holidays from 7:30 am to 9 pm and initially covered 20% of NGS vehicles, but were subsequently extended to 40%. The same setup applies to school transport between 9 pm and 6:30 am the next day, heavy vehicles (trucks) between 10 am and 6 pm within a section of Santiago defined by certain major routes, and public transit buses between 10 am and 4 pm.

Originally, the system was confined to NGS vehicles as a way of encouraging owners to switch to vehicles fitted with catalytic converters, and it did indeed bring about a general upgrading to lower-emissions models. However, new vehicle restrictions were eventually required to deal with periods when air pollution rises beyond acceptable levels. In such situations the authorities may declare the existence of a "critical episode," which depending on the degree of severity is classed either as an alert, a pre-emergency or an emergency. These additional restrictions include an increase in the number of prohibited licence plate digits for NGS vehicles and the broadening of the controls to GS vehicles. The extent of this extra coverage will vary in accordance with the class of episode declared.

Among other exceptional emission-reduction provisions currently implemented in Santiago during alerts and pre-emergencies, one involving transport is the closure of main routes to all traffic except buses. This measure has the added advantage of improving traffic speeds. Studies and evaluations of these strategies using systems dynamics modeling of various scenarios are presently being conducted with a view to optimize the application of the vehicle restrictions within the framework of the city's current urban development and environmental policies (Cifuentes, 2007; CONAMA, 2007). Though no results on the city's exclusive busways have yet been published, their impact is expected to be negligible in terms of the total number of public and private transport trips given that the total length of these routes is less than 1% of Santiago's public transport network.

Table 1
Characteristics of base and additional restrictions, 2000–2008.
Source: CONAMA Supreme Decrees D.S. 16/1998, D.S. 58/2003 and D.S. 46/2007.

Period	Vehicle	Day	Base	Alert	Pre-emergency	Emergency
2000–2006	NGS	Weekday	2	4	6	8
		Weekend	0	2	4	6
	GS	Weekday	0	0	2	4
		Weekend	0	0	2	4
2007–2008	NGS	Weekday	4	4	6	8
		Weekend	0	0	6	8
	GS	Weekday	0	0	4	6
		Weekend	0	0	4	6

GS: green sticker vehicles (with catalytic converter).
NGS: non-green sticker vehicles (without catalytic converter).

Table 2
Critical episodes by year, 2000–2008.
Source: Unidad Operativa de Control de Tránsito (UOCT).

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

Since 2001, the additional restriction for pre-emergencies has covered 20% of GS vehicles whereas the emergency restriction extends to 40% of them (Bull, 2003). In 2008, the year of interest in the present study, the additional restrictions were applied on 8 pre-emergency days to 20% of GS vehicles (see Table A1 in the Appendix A). The base or permanent restriction, the original system exclusively for NGS vehicles that applies when no critical episode is in force, was implemented from April through August. As already mentioned, 2009 and 2010 were not suitable for analysis as no pre-emergencies were declared in those years. This was perhaps due to a downward trend in pollution in the city combined with favorable weather conditions and the implementation of Transantiago, which has cut the number of vehicles in the bus system from 9000 to 6000.

The evolution in certain characteristics of both the base or permanent restriction and the additional (critical episode) restrictions for the period 2000–2008 is set out in Table 1. For each period and class of critical episode (alert, pre-emergency and emergency), the number of digits banned from circulation is indicated. Although restrictions during critical episodes are also imposed on heavy vehicles and fixed sources (industry), since we are concerned here with the behavior of private car users the data in Table 1 refer only to restrictions on light vehicles. These measures apply from 7:30 am to 9 pm.

Enforcement of the restrictions is the responsibility of Carabineros de Chile, the country's national police force, both on normal days and those when a critical episode has been declared. Penalties for violations include fines ranging from 70 to 100 US dollars and a possible driving licence suspension. In 2007 a total of 238 tickets were handed out for vehicle restriction infractions on 2 pre-emergency days (164 per day), 103 fines were levied on 27 alert days (3.8 per day) and just 33 infractions were ticketed on 125 non-critical episode days (0.264 per day). In 2008, the corresponding figures were 1254 tickets on 8 pre-emergency days (156 per day), 445 fines on 21 alerts (21 per day) and 1415 infractions on days with no additional restriction (11.3 per day). On pre-emergency days, though not for simple alerts, the increase in police checks on main arteries is clearly noticeable.

The number of critical episodes from 2000 through 2008 is broken down by single year in Table 2. Note that no emergencies were declared during the 9-year period.

3. Data, methodology and results

3.1. Data and methodology

The private car trip data for building our models were obtained from hourly measurements of the number of cars (vehicle flow) through 46 arcs in the Santiago road network. Eleven of the arcs were discarded as complete data for the period investigated were lacking. The Metro and bus trip data refer to the total number of persons using the various train lines and bus routes. Statistics relating to these data sets are summarized in Table 3.

Table 3
Summary of trip statistics.

Mode	Observations	Mean	Std. dev.	Min	Max
Metro					
All lines	105	2,231,438	99,866	1,987,639	2,504,089
Line 1	105	979,517	45,693	862,920	1,101,325
Line 2	105	431,428	20,928	378,141	497,771
Line 4	105	416,876	17,669	365,410	460,017
Line 4a	105	68,506	3029	59,714	75,983
Line 5	105	335,111	14,627	298,154	368,993
Bus					
All trips	105	3,754,236	169,822	3,102,220	4,152,343
Short trips	105	1,311,309	60,759	1,122,197	1,420,092
Long trips	105	2,442,928	127,991	1,980,023	2,759,450
Cars					
All hours	52,512	836	706	11	3563
7–21	31,138	1186	659	11	3563
5–7	4195	226	269	11	1660

The analysis of the effects of pre-emergency restrictions was based on data for weekdays between April and August of 2008. The effects of the permanent restriction on vehicles without catalytic converters were determined by analyzing the days on or around the start and end dates (April 1 and August 31, respectively) of the measure's period of application that same year. Since beginning in 2007 the measures adopted on alert days coincide, as far as moving sources of pollution (i.e., vehicles) are concerned, with those for the base or permanent restrictions (see Table 1), data on alerts were not considered in the modeling.

To study the behavior of Metro and bus trips on pre-emergency days, the following model was formulated and separately estimated for both cases:

$$y_t = \alpha + \gamma'_d D_t + \beta \times Preemergencia_t + \varepsilon_t \quad (1)$$

where D_t is a vector containing 6 dichotomous variables that take the value of 1 on a given weekday and 0 on all other days, $Preemergencia_t$ is a dichotomous variable equal to 1 on pre-emergency days and 0 otherwise and ε_t is the stochastic error.

The dependent variable y_t measures the effect of the restrictions on Metro or bus trips and is the natural logarithm of the total number of daily such trips. This means that β, the parameter of interest, will approximate the percentage change in the total number of trips (Metro or bus). Strictly speaking, exp(β) represents the increase (or decrease) in Metro or bus passenger flows on pre-emergency days with respect to normal days. The number of these trips can be expected to rise in pre-emergencies and thus the parameter will be positive.

Since the private car data included observations for each arc and each hour of the day, the regression model for automobile journeys was specified as follows:

$$y_{it} = \alpha + \gamma_a' A_i + \gamma_h' H_t + \gamma_d' D_t + \beta \times Preemergencia_t + \varepsilon_{it} \quad (2)$$

where the subindex i indicates the arc and subindex t the period, in this case hourly; A_i is the set of dichotomous variables for each arc and H_t is the set of dichotomous variables for each hour of the day. The dependent variable is the natural logarithm of the number of trips recorded through arc I in period t. Only flows between 7:00 am and 9:00 pm were considered so that β would estimate the percentage change in vehicle flows for the hours when the restriction is in effect. In contrast to the case of bus and Metro trips, the parameter sign is expected to be negative. To avoid bias due to abnormal events (traffic accidents, diversions/detours, road repairs, etc.), measurements of less than 10 vehicles were excluded (the use of other cutoffs, such as 50 or 100 cars, has no effect on the results).

The model in Eq. (2) was also used to test the hypothesis that private car drivers advance the timing of their trips in the morning by setting out before the restrictions take effect. Thus, the formulation was estimated using only the observations for the 5–7 am interval. The estimator of parameter β would then give the percentage change in trips during those 2 h due to the declaration of a pre-emergency.

To test for the effects of the permanent restrictions on the use of vehicles without catalytic converters between April and August, a third regression model was defined as follows:

$$y_{it} = \alpha + \gamma_a' A_i + \gamma_h' H_t + \beta RNC_t + \varepsilon_{it} \quad (3)$$

where RNC_t is a dichotomous variable that equals 1 when the restriction on vehicles without catalytic converters is in force and 0 otherwise. The parameter β can be interpreted as the average change in vehicle flow due to the measure.

As noted above, the permanent restriction on NGS vehicles was investigated by examining the average change in flows caused by the measure on days around the start (April 1) and end (August 31) of its application period. Six versions of the average flow change were analyzed to determine the robustness of the estimates. The first version compared the average change on the first day of the restriction with that for the same day the previous week while the second version compared the first 5 days of the restriction with the 5 weekdays of the previous week. Similarly, the third version compared the first day after the end of the restriction with the same day the previous week and the fourth compared the first 5 days after the end of the restriction with the 5 weekdays of the previous week. Finally, the fifth and sixth versions combined the single-day and 5-day versions, respectively, for the start and end of the restrictions.

In the next two subsections we present the results of the three models for the pre-emergency and permanent restrictions on Metro, bus and traffic flows.

3.2. Effects of pre-emergency restrictions

3.2.1. Metro network

The estimates generated by the model (Eq. (1)) of the effects of the pre-emergency restrictions on Metro user flows are shown in column 1 ("All Trips") of Table 4a. The estimator indicates that trips on the Metro network as a whole show a statistically significant jump of 3% on pre-emergency days. Analyzing the various lines separately, all but Line 1 show a statistically significant rise. The increase on Line 1 becomes significant only at 83.7%, the reason being that it normally operates at capacity and is therefore unable to carry additional passengers.

The last column of Table 4a ("Comb/Total") displays the variations in the proportion of trips at bus-Metro transfer stations with respect to the total Metro flow. The parameter sign is negative and significant, thus demonstrating that on pre-emergency days, users who leave their cars at home are more likely to go directly to a Metro station than take a bus-Metro combination.

Table 4a
Effects of pre-emergency restrictions on Metro network (complete sample).

	All trips	Line 1	Line 2	Line 4	Line 4a	Line 5	Comb/total
Coeff.	0.03**	0.023	0.039**	0.036***	0.03***	0.03**	−0.002***
	(0.014)	(0.016)	(0.016)	(0.009)	(0.011)	(0.012)	(0.001)
R^2	0.109	0.082	0.168	0.179	0.165	0.071	0.399
F test	0.072	0.264	0.013	0.000	0.002	0.097	0.000
Observations	105	105	105	105	105	105	105

Standard errors in parentheses.

** Indicates significance at the 5% level.
*** Indicates significance at the 1% level.

Table 4b
Effects of pre-emergency restrictions on Metro network (excluding outlier).

	All trips	Line 1	Line 2	Line 4	Line 4a	Line 5	Comb/total
Coeff.	0.028*	0.02	0.036**	0.033***	0.027**	0.027**	−0.002***
	(0.014)	(0.017)	(0.016)	(0.009)	(0.011)	(0.012)	(0.001)
R^2	0.108	0.079	0.167	0.187	0.167	0.073	0.394
F test	0.096	0.303	0.020	0.000	0.003	0.115	0.000
Observations	104	104	104	104	104	104	104

Standard errors in parentheses.

* Indicates significance at the 10% level.
** Indicates significance at the 5% level.
*** Indicates significance at the 1% level.

Table 5a
Effects of pre-emergency restrictions on bus network (complete sample).

	All trips	Short trips	Long trips
Coeff.	0.012	0.015*	0.011
	(0.011)	(0.008)	(0.013)
R^2	0.025	0.029	0.018
F test	0.575	0.152	0.790
Observations	105	105	105

Standard errors in parentheses.

* Indicates significance at the 10% level.

Table 5b
Effects of pre-emergency restrictions on bus network (excluding outlier).

	All trips	Short trips	Long trips
Coeff.	0.008	0.011	0.006
	(0.009)	(0.007)	(0.012)
R^2	0.027	0.032	0.018
F test	0.656	0.243	0.858
Observations	104	104	104

Standard errors in parentheses.

The model was estimated a second time after eliminating from the data a single outlier representing a one-day labor stoppage by public servants that caused a major reduction in both public and private transport traffic. Note that since there was no pre-emergency that day, its elimination raises the average number of trips on days without restrictions. The new results, presented in Table 4b, are very similar to those in Table 4a, demonstrating the model's robustness.

3.2.2. *Bus network*

The estimates produced by the model (Eq. (1)) of the effects of pre-emergency restrictions on users flows in the Santiago bus system as a whole are shown in column 1 (''All Trips'') of Table 5a. Separate estimates of the variations in trips were also generated for feeder routes (''Short Trips'') and trunk routes (''Long Trips''). These results show that only for feeder routes is there a statistically significant increase in trips, and even then, only at 90%. If we eliminate the above-mentioned data outlier from the sample (Table 5b), none of the parameters are significant.

From these two sets of results we may conclude that on pre-emergency days in Santiago, private car drivers do not turn to the bus system but do tend to use the Metro.

3.2.3. *Traffic flows*

The pre-emergency restrictions apply to 6 final licence plate digits for NGS vehicles and 2 final digits for GS vehicles. The estimates generated by the model (Eq. (2)) of the effects of these restrictions on traffic flows are set forth in Tables 6a and 6b. They were derived from hourly vehicle flow data for 2008. In both tables, the first column refers to 24 h days, the second to the 7 am–9 pm interval and the third to the 5–7 am interval.

These results show that the daily vehicle flow declines significantly by an average of about 5.5% on restriction days (''Day with Restriction'' in Tables 6a and 6b). Given that the number of daily car trips in Greater Santiago on a representative weekday is about 3.4 million according to a 2006 origin-destination survey (www.sectra.cl), this percentage implies that the number of daily car trips on pre-emergency days falls by $0.055 \times 3{,}400{,}000 = 187{,}000$.

If we then analyze vehicle flow within the application period of the pre-emergency restriction (''Hours with Restriction'' in Table 6a), we arrive at a flow reduction of 7.4%. This is significantly less than the theoretical decline of 20%, and is due in part to the fact that a certain proportion of drivers set out earlier in the morning to avoid the restricted period. Disregarding the restriction and using a second vehicle may also partially account for difference.

Complementing the above analysis, we studied the phenomenon of car drivers advancing the timing of their trip departures to avoid the 7:30 am start of the restriction. It was found that during the 5–7 am interval (the best possible approximation to the two hours preceding the restriction period given that the available measurements were taken hourly on the hour), the flow on pre-emergency days increased 3.5% (''Hours before Restriction'' in Table 6a). Since the 2006 origin-destination survey gives the number of car trips during the 2 h interval on a typical weekday as 132,000, we estimate that approximately $0.035 \times 132{,}000 \approx 4620$ private car trips advance their trip times to get around the restriction.

As with our previous analyses, the above estimates are restated (Table 6b) after eliminating a data outlier, the results being almost identical.

Table 6a
Effects of pre-emergency restrictions on vehicle flow (complete sample).

	Day with restriction	Hours with restriction	Hours before restriction
Coeff.	−0.055***	−0.074***	0.035***
	(0.012)	(0.014)	(0.016)
R^2	0.853	0.584	0.944
F test	0.000	0.000	0.000
Observations	52,512	31,138	4195

Standard errors in parentheses.

*** Indicates significance at the 1% level.

Table 6b
Effects of pre-emergency restrictions on vehicle flow (excluding outlier).

	Day with restriction	Hours with restriction	Hours before restriction
Coeff.	−0.057***	−0.075***	0.032**
	(0.012)	(0.015)	(0.016)
R^2	0.853	0.584	0.944
F test	0.000	0.000	0.000
Observations	51,970	30,823	4151

Standard errors in parentheses.

** Indicates significance at the 5% level.
*** Indicates significance at the 1% level.

Table 7
Effects of permanent restrictions on vehicle flow.

	Start of restriction		End of restriction		Both	
	Week	Day	Week	Day	Week	Day
Coeff.	−0.026	0.004	0.012	0.002	−0.01	−0.006
	(0.019)	(0.04)	(0.013)	(0.028)	(0.011)	(0.024)
R^2	0.576	0.608	0.624	0.656	0.593	0.620
F test	0.000	0.000	0.000	0.000	0.000	0.000
Observations	3108	623	3382	678	6490	1301

Standard errors in parentheses.

3.3. *Effects of permanent restrictions*

3.3.1. *Traffic flows*

The permanent restrictions were applied in 2008 to 4 final licence plate digits for GS vehicles between April 1 and August 31.

Since almost 10% of vehicles in Santiago (or about 120,000) do not have a catalytic converter (INE, 2008), this restriction potentially affects $0.4 \times 120{,}000 = 48{,}000$ vehicles.

The estimates generated by our permanent restrictions model (Eq. (3)) are reported in Table 7. Six specifications of the model were estimated. In each case, it was discovered that the restriction did not produce a significant change in vehicle flows. The percentage changes were very close to zero and in some cases the sign was the opposite of what was expected.

These results suggest that the permanent restrictions on NGS vehicles do not curtail vehicle flows. As pointed out earlier, vehicles without catalytic converters make up to only 10% of the total number of cars in Santiago and tend to be owned by low-income individuals for whom gasoline and maintenance costs rule out regular driving and who therefore generally use public transit.

It should be pointed out here that the permanent restrictions may have generated certain long-term effects on driver behavior (buying a new car, switching to public transport, rearranging daily schedules, etc.) that are not captured by a before–after indicator of the sort presented in Table 7. Identifying such impacts would require data for earlier years that are not available, and even if they were, isolating these influences from other factors such as economic growth, population variations and technological change is a highly complex task beyond the scope of the present study.

4. Conclusions

This article presented an empirical study estimating the effects on certain trip demand patterns of implementing a vehicle restriction policy in Santiago, Chile. Our analysis estimated the impacts of the measure on vehicle flows in the city, the shift of some drivers from private cars to public transit (bus and Metro), and the tendency of other motorists to avoid the restrictions by advancing their morning trip departure times.

The estimates were derived using multiple linear regression models developed for the purpose. The endogenous variables were the observed trip flows for the different transport modes while the exogenous or explanatory variables were dichotomous phenomena that enabled us to separate out the effects of the restrictions on trip flows independently of the influences of time of day, day of the week, month of the year or legal holidays.

Two types of restrictions were analyzed. One is a permanent measure and covers vehicles without catalytic converters from April through August; the other is imposed only on days when environmental pre-emergencies are declared and extends to vehicles that do have catalytic converters. Both restriction types are applied on the basis of the last digit in a vehicle's licence plate number.

Our results revealed that the permanent restriction did not generate vehicle flow reductions given that it only affected 4% of all cars in Santiago, in most cases owned by lower-income individuals for whom the cost of using them on a daily basis would be prohibitive. By contrast, the additional or pre-emergency restriction did produce a reduction in car use, but it was significantly smaller than what was theoretically expected. When in effect, the latter measure applies to 60% of vehicles that have no catalytic converter and 20% of those that have one, or about 25% of the total number of vehicles in Santiago. It was found, however, that this restriction cut vehicle flow by only about 5.5% on average, or about 187,000 fewer car trips.

There are various reasons for this last percentage being lower than the theoretical figure. First, many households have two or more cars whose licence plates end in different numbers, allowing them to get around the digit-based restriction. Second, many drivers do in fact advance their morning departures to beat the restriction so that part of the usual vehicle flow is simply transferred to a different time period. Third, it is likely some motorists simply disregard the restriction, as is suggested by the number of violations ticketed by traffic police. And finally, some car owners simply do not use their cars on a daily basis, getting around instead by public transit, and thus would not be affected by the restriction.

Another interesting finding of our research is that on days when the pre-emergency restriction is in force, affected drivers tend to switch to the Metro rather than the bus system. This is confirmed by the model estimates, which indicate a statistically large increase in Metro trips but no significant rise in bus journeys when the restriction is in effect. Data from other countries tends to corroborate this conclusion. The implication is that the quality of Metro services is generally higher than that of buses, as evidenced by urban rail systems' shorter waiting and travel times and greater reliability and safety. In addition, regular car drivers are often unfamiliar with bus routes but tend to know the Metro network, thus reducing its uncertainty for such users.

Finally, it should be noted that the results of this study are based on aggregates and thus cannot be used to infer the details of individual choices. They do, however, suggest the general pattern of user behavior and provide evidence in support of the Metro as perhaps the most preferred alternative for regular automobile users.

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Appendix A

See appendix Table A1 below.

Table A1
Critical episodes in 2008.

Class of episode	Day	Date	Final licence plate digits	
			No Green Sticker	Green Sticker
Environmental alert	Sunday	10-08-2008	3-4	
Environmental alert	Saturday	09-08-2008	1-2	
Environmental alert	Friday	25-07-2008	7-8-9-0	
Environmental alert	Tuesday	15-07-2008	5-6-7-8	
Environmental alert	Wednesday	09-07-2008	0-9-1-2	
Environmental alert	Thursday	03-07-2008	3-4-5-6	
Environmental alert	Wednesday	02-07-2008	9-0-1-2	

Table A1 (*continued*)

Class of episode	Day	Date	Final licence plate digits	
			No Green Sticker	Green Sticker
Environmental pre-emergency	Tuesday	01-07-2008	5-6-7-8-9-0	5-6
Environmental alert	Monday	30-06-2008	1-2-3-4	
Environmental pre-emergency	Sunday	29-06-2008	9-0-1-2-5-6	3-4
Environmental alert	Saturday	28-06-2008	7-8	
Environmental alert	Friday	27-06-2008	7-8-9-0	
Environmental alert	Thursday	26-06-2008	3-4-5-6	
Environmental pre-emergency	Wednesday	25-06-2008	9-0-1-2-3-4	1-2
Environmental pre-emergency	Tuesday	24-06-2008	5–6-7-8-9-0	9-0
Environmental alert	Monday	23-06-2008	1-2-3-4	
Environmental alert	Saturday	21-06-2008	5-6	
Environmental pre-emergency	Monday	16-06-2008	1-2-3-4-5-6	7-8
Environmental alert	Saturday	14-06-2008	1-2	
Environmental alert	Tuesday	10-06-2008	5-6-7-8	
Environmental pre-emergency (suspended)	Tuesday	03-06-2008	3-4-5-6-7-8	5–6
Environmental alert	Monday	02-06-2008	1-2-3-4	
Environmental pre-emergency	Sunday	01-06-2008	1-2-3-4-9-0	3-4
Environmental alert	Saturday	31-05-2008	7-8	
Environmental pre-emergency	Friday	30-05-2008	5-6-7-8-9-0	1-2
Environmental alert	Friday	16-05-2008	7-8-9-0	
Environmental alert	Wednesday	14-05-2008	0-9-1-2	
Environmental alert	Tuesday	13-05-2008	5-6-7-8	
Environmental alert	Monday	12-05-2008	1-2-3-4	

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