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# Determinants of compliance in the emissions compensation program in Santiago, Chile

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ABSTRACT. The Emissions Compensation (EC) Program in Santiago, Chile, has been affected from the beginning by the incidence of individual violations of maximum-emission capacity permits. Based on information at the individual source level, in this paper we develop and estimate a model explaining the individual compliance decision with emission capacity permits. Our results indicate that the compliance behavior of sources during the period 1993–1999 do in fact depend on their individual characteristics. Among other factors, type of equipment used, industrial sector to which the source belongs, fuel type used, the initial allocation of emission capacity permits to the source, and population density as well as average income in the area where the source is located, turn out to be relevant. Furthermore, the evidence does not allow us to reject the presence of structural change in the individual decision to comply with permit holdings because of the introduction of natural gas in the Metropolitan Region of Santiago at the end of 1997.

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## 1. Introduction

In recent years, there has been a growing interest in the use of economic incentives to solve the problems of atmospheric pollution. Even though emission trading programs have been implemented primarily in developed countries, a few developing countries have begun to implement different forms of incentive-based regulation (World Bank, 1997). In effect, Chile is among the first developing countries implementing a market-based environmental policy to improve air quality. Chilean authorities established in 1992 the Emissions Compensation (EC) Program, which created and allocated transferable property rights to participant sources in order to control emissions of total suspended particles (TSP) generated in the capital city.[1]

The efficiency gains arising from the application of a transferable permit system have been widely discussed in the literature. However, a number of authors have noted that these gains depend on the compliance rates achieved (Stranlund *et al.*, 2002). The literature dedicated to the analysis of the EC program has primarily focused on the description of its general design and the evaluation of market performance for emissions capacity rights (see, for example O'Ryan, 2002; Montero *et al.*, 2001, 2002). To our knowledge, there are no research efforts specifically devoted to the analysis of enforcement design and source compliance behavior in the program thus far. More generally, relatively little research effort has been carried out on the study of compliance and enforcement of environmental regulation in developing countries. This paper is intended to contribute to the analysis of compliance behavior in the EC Program, which has not received attention in the previous literature.

The empirical analysis of enforcement design and compliance results in the context of environmental regulations has usually focused on the determinants of the regulated agents' compliance decisions. On the one hand, the results of previous empirical studies suggest that inspection efforts have a positive effect on the compliance decision. It means that regulated agents are more likely to comply if they perceive a greater enforcement pressure (see, for example, Laplante and Rilstone, 1995; Gray and Deily, 1996; Dasgupta *et al.*, 2001; Dion *et al.*, 1998). On the other hand, the empirical evidence also suggests that there are individual characteristics that tend to influence the decision to comply (see, for example, Laplante and Rilstone, 1995; Pargal and Wheeler, 1996; Gray and Deily, 1996; Cohen, 1999; Dasgupta *et al.*, 2000, 2001). To our knowledge, all of this literature has considered the analysis of individual compliance behavior in the context of command-and-control environmental regulations. This paper contributes to this line of research in the context of the EC Program, an originally designed incentive-based environmental regulation.

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[1] Perhaps surprisingly, the EC Program was being implemented contemporaneously with two of the most prominent transferable permit systems in the United States; namely, the 'Sulfur Dioxide Allowance Trading Program (EPA-$SO_2$)' and the 'Regional Clean Air Incentives Markets (RECLAIM)' program. While the first one was designed to control acid rain, the second one was implemented to alleviate the contamination problems of the urban area of Los Angeles, California.

One of the problems faced by authorities responsible for environmental policies in developing countries is the limited availability of specialized staff and restricted budgets devoted to monitoring and enforcement. In this context, it is relevant for environmental agencies not wasting money and efforts when implementing and enforcing environmental regulations. In the context of the EC Program, learning about the determinants of sources' compliance behavior might help authorities to refine their current enforcement strategies to induce adequate levels of compliance in a cost-effective way. The result of this work might help to shed light on the desirability of targeting enforcement efforts, as well as on the identification of variables on which such targeted enforcement strategies should be directed. From a broader perspective, the results of this study can also be useful to properly implement and design enforcement strategies for future market-based environmental regulations.

To study the sources' decision to comply with maximum emission capacity permits during the period of 1993–1999, our research uses information available from the individual sources participating in the EC Program of Metropolitan Santiago, Chile. Specifically, we estimate a binary choice model to identify the determinants of the compliance decision of sources. We also investigate to what extent the compliance decision was affected by the arrival of natural gas to Metropolitan Santiago in 1997.[2] Finally, based on the model's estimations, we quantify the impact of the determinant factors on the compliance decision, and we estimate the compliance probability associated among different sources.

The paper is organized in five sections. In section 2, we briefly present the design and functioning of the Metropolitan Santiago's EC Program. Along with a general description, we discuss enforcement and monitoring design to induce compliance with transferable emission capacity rights in the program. We conclude this section describing aggregate and individual compliance results achieved thus far.

Our review of the existing literature as well as our preliminary exploration of the available data allow us to obtain two relevant conclusions. First, the EC Program exhibits a reduced number of transactions in the period considered. Even though it was designed as a system of transferable emission capacity permits, it has in practice functioned more like a system of emission standards in which most of the sources have kept their initial allocation of emission capacity rights for compliance purposes. Second, the EC Program has been affected from the beginning by individual violations, suggesting weak enforcement of the system. However, the incidence of these violations diminished in number and magnitude over time during the period considered.

In section 3, we present the theoretical model that motivates the empirical analysis of this paper. Based on the analysis of section 2, we review a theoretical model in which a firm chooses its emission level in the

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[2] The motivation of this analysis is based in the hypothesis raised in Montero *et al.* (2001). These authors attributed the marked drop in TSP by the industrial sources participating in the EC Program after 1997 to their rapid implementation of natural gas in their industrial processes.

context of a transferable emission permit system with the possibility of non-compliance. The possibility of over-compliance is also explored. The model considers the presence of transaction costs.[3] Our conceptual analysis suggests that, while the compliance decisions of firms do not depend on their individual characteristics in a frictionless permit market, this does not hold when there are transaction costs. In effect, in the latter case the characteristics of individual sources, along with the regulatory authority's enforcement strategies, play a role in the decision whether or not to comply with emission permits. Based on this theoretical model, we specify an econometric model for the estimation of a source's compliance decision. This specification is used to identify the determinants of the source's compliance behavior and quantify the impact of these factors on it. We conclude this section with a description of the data used to perform the estimations.

In section 4, we present and discuss the results of the estimates of our compliance decision model. This section begins with the presentation of the results obtained from the estimates of the compliance decision using a probit model. We analyze the signs and significance of the estimates for different specifications of the decision model. The results suggest that differences in source characteristics do affect the compliance decision of individual sources participating in the EC Program. We then go on to test whether or not the introduction of natural gas to Metropolitan Santiago affected sources' compliance with emissions capacity permits. According to our results, it is not possible to reject the hypothesis that, along with the introduction of natural gas to the Metropolitan Region, there was a structural change in sources' compliance decision. Next, we quantify the impact associated with a change in the determinant factors of the compliance decision on the probability of a source being compliant with emission capacity permit holdings. Additionally, we calculate the compliance probabilities for different types of individual sources based on our estimates and considering the period before and after the introduction of natural gas to Santiago. In section 5, we present the conclusions obtained from the empirical study.

## 2. The Emission Compensation (EC) Program

To provide a context for our theoretical and empirical analysis, we briefly describe the design and functioning of the EC Program in Metropolitan Santiago.[4] First, we present a general description of the program, highlighting its original objective and practical operation. Second, we present details of the monitoring and enforcement design to induce

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[3] Evidence that transaction costs and weak enforcement have in fact limited the development of the market for daily emission capacity rights in Santiago's program is provided by Montero *et al.* (2002).

[4] For a more detailed description of the EC Program and details of the enforcement design and compliance results, see Palacios and Chávez (2002). An analysis of the design of the EC Program and the functioning of the emission capacity permit market is presented in Montero *et al.* (2001, 2002) and O'Ryan (2002).

compliance. Third, we present the compliance results achieved during the period 1993–1999.

### *2.1. General design of the EC Program*

To help solve the problem of deficient air quality caused by total suspended particles (TSP) in Metropolitan Santiago, the Chilean government established the EC Program in March 1992 [Supreme Decree No. 4 (DS-4)]. The objective of the EC Program is to control and reduce emissions of TSP coming from fixed industrial sources of certain sizes.[5] The sources included in the EC Program where industrial furnaces, heat boilers, and vapor generators where the flow volume was greater than or equal to 1,000 $m^3/hr$.

The Program classified the sources as either 'existing' or 'new'. Existing sources were defined as those that were registered or had initiated the registration process before the publication of DS-4. All the sources registered after March 1992 were considered as 'new' ones.

The existing sources were allocated maximum emission capacity permits, called 'initial daily emission' (IDE), which were distributed on this one occasion without cost. The initial allocation of permits was proportional to the sources' emission flow and a predetermined uniform emissions concentration (Montero *et al.*, 2001).[6] Each unit of IDE allows the release of one kilogram of TSP daily, and has no expiration date. Facilities may sell or buy IDE as they see fit; however, IDE can be used only for current compliance purposes. Indeed, the Program does not contemplate a banking option–sources cannot borrow from future allocations, and they are not allowed to save credits for future use or sale.[7]

The amount of IDE assigned to the 562 existing sources in March 1992 was 4,604.1 kg/day, or 1,657.5 ton/year.[8] Any addition of new sources or expansion of existing sources would need to be compensated for by

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[5] Breathable particle material (PM10) is considered as part of the total suspended particle classification (TSP).

[6] The rate used uniformly for the permits assignment calculation was 56 $mg/m^3$. Specifically, the formula used to assign the IDE for the existing sources was given by: $\text{IDE (kg/day)} = F_o\,(m^3/hr) \times 24\,(hr/day) \times C_o\,(mg/m^3) \times 10^{-6}\,(kg/mg)$. Where $F_o$ is the emission flow corrected by the excess of air and measured at full charge, which is the maximum functioning capacity of the source independent of the production process considering the design parameters of the source, and $C_o$ represents the predetermined uniform emission concentration.

[7] Even though the possibility of annually renting emission capacity permits between sources was not part of the original design of the EC Program, it is interesting to mention that this has occurred on at least one occasion (Montero *et al.*, 2001). Apparently the option of renting emission capacity permits has not been clearly established.

[8] To have an idea of the relative importance of the program in the control of pollution from TSP in Santiago, consider the 1997 emission inventory performed by the National Environmental Commission (*Comisión Nacional del Medio Ambiente* CONAMA). According to it, the sources included in the EC Program were responsible for approximately 4 per cent of the total TSP emissions. Although this figure might appear to be low, these are PM 10 emissions that are more dangerous

the purchase of existing permits from already existing sources with prior approval of the regulating entity, the Sub-department of Air Quality of the Metropolitan Environmental Health Service (Air Quality-SESMA).

From an operational point of view, the existing sources should cover their daily declared emission (DDE) with the assigned IDE. Any surplus of IDE to DDE may be traded as long as the observed concentration does not exceed the maximum concentration limit, which was set at 112 mg/m$^3$. New sources must present an emission capacity permit project to Air Quality-SESMA. Once the project is approved, the new source has a permit emission known as daily permitted emission (DPE), which has the same characteristics as the IDE.

The EC Program was originally designed to create a market for transferable maximum daily emission capacity permits. Sources were allowed to trade (buy or sell) emission capacity permits and emit up to the level that is consistent with the permits that they possess. In reality, the sources have not traded their emissions capacity permits, however. In fact in the period studied in this paper, there was a reduced number of transactions – indicating poor market development (Montero *et al.*, 2001). Furthermore, Montero *et al.* (2002) provide evidence that the presence of transaction costs is an important factor behind the limited development of the market for emission capacity permits in Santiago.[9]

### *2.2. Monitoring and enforcement of the EC Program*

Like other market-based environmental policies, the EC Program relies on self-reporting by regulated sources. The existing and new sources participating in the EC Program annually report their DDE to the program's authorities (Air Quality-SESMA). To comply with reporting requirements, sources must contact an independent and certified laboratory to conduct monitoring of the flow and concentration of emissions. This monitoring is conducted once a year and its results are then reported, in the form of a paper document, to the Air Quality office. Sources that do not comply with the reporting requirement face sanctions that can be imposed through an administrative procedure.[10]

Apart from the existing monitoring requirement on sources, Air Quality-SESMA is responsible for ensuring reliability of reported flow

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to health than the rest of particulates that account for most of particulate emissions. We are grateful to an anonymous referee for clarifying this to us.

[9] Although transaction costs may not be the only factor that explains the low level of trading, it appears to us that transaction costs are in fact very important. Regulatory uncertainty, weak enforcement, and the presence of market power have also been mentioned as determinants of poor market development (see Montero *et al.*, 2001). We have two reasons for this. First, according to its definition, the owner of an emission capacity permit is able to emit up to a one kg of TSP per day in perpetuity, and, therefore, potential sellers may have been reluctant to transfer the permit because of the possibility of not being able to buy them back in the future. Second, institutional barriers to trade, such as the need of approval of compensation, have also been present in the program.

[10] Personal contact with program's official Marta Zamudio, SESMA (2002).

and concentration monitored by independent laboratories. To that end, the agency is responsible for certifying these laboratories. Furthermore, program authorities can also conduct monitoring using their own equipment, and observe the monitoring procedures performed by the laboratories (SESMA, 1996).

The general perception from the regulatory agency's officials is that data on emissions (flow and concentration) provided by certified laboratories are reliable. The cost of conducting the monitoring to provide the annual DDE's report for each source is about US$600 to US$900.

Finally, the annually reported level of DDE is compared with the assigned IDE or DPE plus any net transfer to the source, determining its compliance status. In the case that the source is in violation – source's DDE exceeds its IDE or DPE plus any net transfer – it faces administrative procedures that may end with the imposition of sanctions.

Two important features of the sanctions in the EC Program of Santiago are that they are not clearly specified, and are not automatically imposed. In fact, sanctions considered in this program might include a note of violation as well as a wide range of lump sum monetary sanctions, which range from US$4.50 to US$90,000.00. The level of the sanction actually imposed depends in an unclear way on each particular case, considering the extent of the emissions capacity permits violation and backsliding of the source, among other things. In addition, a prohibition on a source's operation is also possible.[11]

### *2.3. Compliance results in the EC Program*

The possible violations considered in the EC Program framework includes:

(i) existing and new sources exceed the maximum concentration limit of 112 $mg/m^3$;

(ii) the DDE of existing sources exceed the assigned IDE plus any net transfer; and

(iii) new sources do not obtain the necessary permits to cover their emissions as established by Air Quality-SESMA [see DS-4].

In the audits performed by Air Quality-SESMA during the program, detected violations have included:[12] (a) new sources not covering their daily emissions with permits; (b) existing sources exceeding their IDE; (c) sources emitting with the dirtiest fuel, violating the seal on it; (d) dual sources (diesel and gas) compensating on paper with the use of the cleaner fuel (gas), when in reality they are using the dirtiest fuel (diesel); and (e) source calibration, hoping that the violation will not be detected when sampled. In this study, we only considered violations (a) and (b).[13]

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[11] Unfortunately, information on individual sanctions actually imposed in the context of this program is considered private. Consequently, we have not been able to use that information in the empirical analysis.

[12] Personal contact with program's official Marta Zamudio, SESMA (2001).

[13] Our empirical analysis is based on sources' annual reports of maximum daily emissions capacity (DDE); therefore, compliance status is reported compliance. We acknowledge that this implies that we are assuming that sources provide

Table 1. *Emission capacity permits violations in the EC program of Santiago, 1993–1999*

| *Sources* *Total* | *1993*<br>*680* | *1995*<br>*690* | *1996*<br>*631* | *1997*<br>*576* | *1998*<br>*566* | *1999*<br>*573* |
|---|---|---|---|---|---|---|
| Added emissions (kg/day) – DDE | 7,442.5 | 6,500.2 | 5,195.1 | 3,535.0 | 1,953.6 | 1,636.6 |
| Permits (kg/day) – IDE | 4,604.1 | 4,604.1 | 4,604.1 | 4,087.5 | 4,087.5 | 4,087.5 |
| Added violation (kg/day) | 2,838.5 | 1,896.2 | 591.0 | 0 | 0 | 0 |
| Maximum violation (kg/day) | 93.8 | 83.5 | 67.9 | 65.0 | 28.3 | 25.6 |
| Minimum violation (kg/day) | 0.03 | 0.03 | 0.03 | 0.03 | 0.05 | 0.05 |
| Average violation (kg/day) | 8.1 | 7.7 | 6.5 | 4.8 | 3.5 | 3.2 |
| No. of non-complying sources | 344 | 294 | 224 | 144 | 46 | 36 |
| % non-complying sources | 50.6 | 42.6 | 35.5 | 25 | 8.1 | 6.3 |
| Natural gas users | 0 | 0 | 0 | 1 | 144 | 179 |

*Source*: Calculated by the authors based on information provided by the Sub department of Air Quality-SESMA (2002).

The enforcement design used in the Santiago EC Program was not able to induce adequate compliance levels with emission capacity permits during the initial years of the program. In fact, despite the improvement in the compliance indicators during 1998 and 1999 (the last two years of the period studied), individual violations, consisting of sources' emissions exceeding their permits, continue.

A summary of emission capacity permit violations is provided in table 1. During the first three years of the EC Program, the aggregate daily declared emissions (DDE) have exceeded the initial daily emission (IDE) permits. However, this situation changed in 1997. Certainly, while the evidence indicates the incidence of these violations at the aggregate level from 1993 to 1996, there has been aggregate over-compliance during 1997, 1998, and 1999. As for compliance performance at the individual level, the results are different from those obtained at the aggregate level. Specifically, the EC Program experienced individual violations (that is, sources which DDE exceeded their IDE during each year of the period 1993–1999). The incidence of violations in both number and magnitude has decreased during the analyzed period. Furthermore, the magnitude of the largest detected

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truthful reports of their maximum daily emissions capacity to program authorities. Although the assumption is unavoidable, reports on emissions flow and concentration are perceived as reliable. We thank an anonymous referee of this journal for raising this point.

individual violation has been trending downwards over time, especially since 1997 when natural gas was introduced.[14]

The positive evolution of the compliance results exhibited by the EC Program – a higher level of violations during the first years of program operation and a pronounced reduction in the last years analyzed – led us to ask what the determinants of this trend were. Although we respond in greater detail to this question in section 4, it is likely that the availability of natural gas in the Santiago area in 1997 was an important element in this change of behavior. We hypothesize that a greater compliance level in the EC Program was induced by a reduction in the emission abatement costs provided by the new availability of a cleaner fuel, rather than by the effectiveness of a greater enforcement effort in terms of violation detection and sanctioning. However, the evidence also suggests that violations of emission capacity permits still continue.

## 3. Compliance decision model

In this section, we present the theoretical framework for our empirical analysis. Considering that the EC Program was originally designed as an incentive-based environmental regulation, we briefly review a model of a firm's compliance decision in the context of a transferable emission permit system. Our conceptual review considers both, the possibility of no-perfect compliance outcomes (non-compliance, over-compliance) and the presence of transaction costs in the market for emission permits.[15] Based on the review of the theoretical model, we are able to conclude that, while compliance decisions of firms in a frictionless permit market do not depend on their individual characteristics, this does not hold in the presence of transaction costs. Effectively in the latter case, individual source characteristics–including initial allocation of permits–, along with the regulatory authority's enforcement strategies, play a role in the decision whether or not to comply with emission permits.

### *3.1. Compliance decision in an emission trading program in the presence of transaction costs*

The model presented in this section is largely based on Stranlund and Dhanda (1999) and Chávez and Stranlund (2004). Consider a risk-neutral

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[14] Considering from our dataset only those sources of observation that contain all the required information necessary to perform estimations, we conclude that the incidence of violations in the period 1993–1997 for new sources was in the range of 30 per cent to 50 per cent depending on the specific year. The incidence of non-compliance for the case of existing sources during the same period of time varies between 63 per cent in 1993 to 36 per cent in 1997. Frequency of sources (existing and new) being in non-compliance with emission capacity permits shows a significant reduction after the arrival of natural gas.

[15] The presence of transaction costs is expected to limit the development of an emission permit market. Evidence that transaction costs and weak enforcement have in fact limited the development of the market for daily emission capacity rights in Santiago's program have been discussed in section 2. We are grateful to an anonymous referee of this journal for suggesting to us to pursue this conceptual review.

firm that operates in a transferable emission permit system. The firm's abatement cost function is $c(e, \alpha)$, which is strictly decreasing and convex in emissions $e$ (that is, $C_e(e, \alpha) < 0$ and $C_{ee}(e, \alpha) > 0$). We distinguish between firms under regulation by the vector $\alpha$, which includes the individual firm characteristics.[16] Let $l_0$ denote the initial allocation of permits to the firm and $l$ the number of permits that the firm holds after trade.

When a firm is non-compliant, its emissions exceed the number of permits it holds, and the level of its violation is $e - l > 0$. Otherwise, the firm is compliant. We assume that the aggregate emission target is fixed and that permits trade at a price $p$.

The firm faces a probability of being audited, $\pi$. An audit provides the regulatory agency with perfect information with respect to a firm's compliance status. If the source is audited and found to be in violation, a penalty of $f\,(e - l)$ is imposed. We assume that the penalty is zero in the case of zero violation, but the marginal penalty for a zero violation is greater than zero; in other words, $f(0) = 0$ and $f'(0) > 0$. In the case of a positive violation, the penalty is strictly increasing and strictly convex.

We follow Stavins (1995) in order to consider the presence of transaction costs. Assume that transaction costs are represented by a function, $t$, which depends on the number of permits transferred between trading parties. We define the number of permits transferred, $\tau$, as the absolute difference between the number of permits a firm holds and its initial allocation, and we denote it by $\tau = |l - l_0|$. Let $d\tau/dl = \tau_l$, and note that $\tau_l = +1$ if a firm is a net buyer of permits ($l > l_0$) and $\tau_l = -1$ if the firm is a net seller of permits ($l < l_0$). Then, transactions involve costs summarized by $t(\tau) = t(|l - l_0|)$. The marginal effect on the effective permit price of a change in permit demand depends on whether a firm is a net buyer or seller of permits. Specifically, while at the margin the effective price that a seller of permits faces is given by $p - t'(|l - l_0|)$, the effective price that a buyer pays is $p + t'(|l - l_0|)$. Marginal transaction costs may be decreasing, increasing, or constant.

We also assume that the firm never chooses to be over-compliant ($e \geq l$), and it will always hold a positive number of permits. Shortly we will relax the no over-compliance assumption. Furthermore, we assume that the enforcement strategy (probability of being audited and the penalty function) is communicated to all firms. A firm chooses its emissions and permit demand to solve (1) taking the enforcement strategy as given

$$\begin{aligned} &min\; c(e) + p(l - l_0) + t(|l - l_0|) + \pi f(e - l) \qquad (1) \\ &s.t.\; e \geq l > 0 \end{aligned}$$

The Lagrange equation is $\theta = c(e) + p(l - l_0) + t(|l - l_0|) + \pi f(e - l) - \beta(e - l)$, and the Kuhn–Tucker conditions are

$$\theta_e = c'(e) + \pi f'(e - l) - \beta = 0 \qquad (2a)$$

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[16] The source's abatement costs can vary for different reasons: production and emission abatement technology, prices of inputs and products, and other specific factors related to the different industrial sectors.

$$\theta_l = p + t'(|l - l_0|)\tau_l - \pi f'(e - l) + \beta = 0 \qquad (2b)$$

$$\theta_\beta = l - e \leq 0, \quad \beta \geq 0, \quad \beta \times (l - e) = 0 \qquad (2c)$$

We assume that these conditions are necessary and sufficient to uniquely determine the firm's optimal choices of emission levels and permit demand.

In the presence of transaction costs, a firm chooses its level of emissions so that $p + t'(|l - l_0|)\tau_l + c'(e) = 0$ (Stavins, 1995; Chávez and Stranlund, 2004). This result implies that marginal abatement costs are not equal across firms when there are marginal transaction costs; this is in contrast to competitive and frictionless permit trading, where each firm chooses its emissions so that its marginal abatement costs are equal to the permit price.

Let us to now turn our attention to the firm's compliance choice. In the presence of transaction costs, the firm will decide to comply if and only if $p + t(|l - l_0|)\tau_l - \pi f'(0) \leq 0$.[17] In contrast, in a frictionless and perfectly competitive permit system it is possible to show that a firm is compliant if and only if $p - \pi f'(0) \leq 0$.[18] In the presence of transaction costs, the firm's compliance decision depends not only on the authority's enforcement strategies, but also on individual firm characteristics, including initial allocation of permits. In effect, since buyers and sellers of permits face different effective permit prices in the presence of transaction costs, their marginal abatement costs are different in equilibrium and they have different compliance incentives (see Chávez and Stranlund, 2004). Specifically, in the presence of transaction costs, buyers of permits face higher prices than sellers, and given uniform monitoring and penalties, are more likely to choose to be non-compliant. Further, in the case that marginal transaction costs are either increasing or decreasing with the size of the transaction, a firm's compliance decision depends on its initial allocation of permits. Differently, in the absence of transaction costs, a firm is compliant if and only if the price per permit that the firm faces is not greater than marginal expected penalty of a slight violation. Interestingly, as long as monitoring and penalties are applied uniformly, the compliance condition has nothing to do with firm-level characteristics. Furthermore, this condition is independent of the firm's initial allocation of permits.

The previous model assumes that a market for emission permits develops in such a way that trade occurs at price $p$. Unfortunately, the EC Program of Santiago does not represent an example of a well-functioning transferable emission permit system. As was previously reported in section 2, the EC program can be characterized within the studied period not only by the

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[17] A proof follows. If a firm is compliant, [2-b] becomes $\theta_l = p + t'(|l - l_0|)\tau_l - \pi f'(0) + \beta = 0$. Since $\beta \geq 0$, a firm is compliant only if $p + t'(|l - l_0|)\tau_l - \pi f'(0) \leq 0$. Furthermore, suppose that $e > l$, while $p + t'(|l - l_0|)\tau_l - \pi f'(0) \leq 0$. Since $e > l, \beta = 0$. Furthermore, $e > l$ and $p + t'(|l - l_0|)\tau_l - \pi f'(0) \leq 0$ imply $p + t'(|l - l_0|)\tau_l - \pi f'(e - l) < 0$. Therefore, $\theta_l = p + t'(|l - l_0|)\tau_l - \pi f'(e - l) < 0$, indicating that non-compliance is a sub-optimal choice when $p + t'(|l - l_0|)\tau_l - \pi f'(0) \leq 0$. Thus, a firm is compliant if and only if $p + t'(|l - l_0|)\tau_l - \pi f'(0) \leq 0$. Q.E.D.

[18] Versions of this result have been presented by a number of authors (see, for example, Malik, 1990 and Stranlund and Dhanda, 1999), so we have decided not to present the proof here.

presence of individual violations, but also by the presence of individual (over) compliance, as well as a lack of market development possibly caused by significant transaction costs. In order to capture these specific features of the program, we reconsider the previous model in a situation where transaction costs are high enough to impede market development.

Let us assume that transaction costs are high enough so that for a potential net seller (or a firm that would be a net seller of permits) $p - t'(|l - l_0|) \leq 0$ holds for $l \leq l_0$. The firm would like to sell permits from its initial allocation, but transaction costs are an impediment to that end. Then, if the initial allocation of permits exceed the firm's unconstrained emissions choice, $e^0$, the following relations must hold: $e = e^0 < l = l_0$. In such a case, no abatement effort occurs and we conclude that the firm will be (over) compliant.

Interestingly, there are three features of the EC Program that may actually generate individual firm (over) compliance. First, the initial allocations of emission capacity permits were generous during the first years of the program's implementation to gain acceptability from the regulated sources. Second, the introduction of natural gas may have lowered firms' marginal abatement costs so that their unconstrained emissions were then below their allocation of permits. As is shown in table 1, the excess of aggregate IDE over aggregate DDE; that is, the aggregate over-compliance experiences a significant increase after the introduction of natural gas in the Metropolitan Region of Santiago. Third, in the presence of weak enforcement of a transferable emissions system, the equilibrium price could be expected to be low enough, so that the condition for sellers that $p - t'(|l - l_0|) \leq 0$ holds for $l \leq l_0$, is more likely.

In the same fashion, under the presence of high transaction costs, a potential buyer of permits (a firm that would be a net buyer of permits) may not be able to find a seller to trade with. If so, a would-be buyer-firm problem is to choose the level of emissions to solve

$$\begin{aligned} &min\, c(e,\alpha) + \pi f(e - l_0) \qquad (3) \\ &s.t.\; e - l_0 \geq 0 \end{aligned}$$

Having specified the would-be buyer-firm problem, we can turn to its choice of whether or not to be compliant in this specific context. The firm will decide to comply if and only if $c_e(l_0,\alpha) + \pi f'(0) \geq 0$.[19] The model suggests that, in this case, the decision to comply is based on a comparison between the expected marginal costs with the marginal benefits obtained by violating its initial allocation of permits. The expected marginal cost of choosing an emissions level that exceeds the initial allocation of permits is the expected marginal penalty. The marginal benefit of violating the permit holding is the firm's marginal abatement costs evaluated at its initial allocation. When the expected marginal penalty exceeds the marginal abatement costs of the source, it will choose to comply with its emission permits. Otherwise, the

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[19] The Kuhn–Tucker condition for [3] is $c_e(e,\alpha) + \pi f'(e - l_0) \geq 0$, if $> 0, e = l_0$. It follows that a firm is compliant if and only if $c_e(l_0,\alpha) + \pi f'(0) \geq 0$ or, $-c_e(l_0,\alpha) \leq \pi f'(0)$.

source will select an emissions level and the resulting violation in such a way that the marginal abatement cost will be equal to the expected marginal penalty. If the source is in violation, it can be shown that the would-be buyer's choice of emissions and extent of its violation ($v$) are given by $e(l_0, \pi)$ and $v = e(l_0, \pi) - l_0$, respectively.[20]

### *3.2. Determinants of the compliance decision*

The theoretical model suggests that under the presence of transaction costs a firm's compliance decision depends on individual characteristics along with enforcement strategies from the regulatory authority. Motivated by the conceptual analysis for the firm's compliance decision in the presence of transaction costs, we now turn our attention to present the econometric specification to study actual source compliance decisions in the EC Program in the city of Santiago, Chile.

#### Marginal abatement costs

The marginal abatement costs (*MAC*) function is sensitive to the emission level (*e*) and to a variety of individual source characteristics. We consider the following characteristics: type of source, the existence of abatement equipment, age of the combustion equipment, fuel type used, size of the source firm, and industrial sector.[21]

Considering the results of other empirical studies, it is possible to sustain several hypotheses related to the impact of source characteristics on the *MAC* function (see, for example, Laplante and Rilstone, 1995; Gray and Deily, 1996; Henriques and Sadorsky, 1996; and Dasgupta *et al.*, 2000). Among others, it is expected that those sources that have some type of abatement equipment will have lower marginal abatement costs. Similarly, newer source combustion equipment will have lower marginal abatement costs than the older sources. Further, we expect that marginal abatement costs will vary according to the type of fuel being used. Similarly, we infer that the marginal costs will vary according to the source's industrial sector. We cannot infer anything specific with respect to the effect that the size of a firm has on a source's marginal abatement; however, we acknowledge that recent empirical research suggests that lower marginal abatement costs is correlated with factors such as larger source size and multi-plant company (see World Bank, 2000).

In summary, the marginal abatement cost function for source $i$ is given by

$$MAC_i = MAC(e_i, te_i, ea_i, a_i, c_i, q_i, z_i) \tag{4}$$

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[20] The described model suggests as well some comparative static results. It is clear that the magnitude of the source's violation (and eventually its compliance status) decreases with the probability of being audited and with the expected marginal penalty. Furthermore, the extent of the violation decreases with a reduction in the marginal abatement costs.

[21] These characteristics are included in the vector $\alpha$, described in the previous theoretical review.

The arguments of the function are the emission level (*e*), the type of source (*te*), existence of abatement equipment (*ea*), age of combustion equipment (*a*), type of fuel used by the source (*c*), source firm size (*q*), and the source's industrial sector (*z*).

### Expected marginal penalty

The expected marginal penalty (*EMP*) represents the expected value that should be paid by the source for the excess of emissions over the level of permit holdings if a violation is detected. Concretely, we consider factors that influence the expected marginal penalty for the source's emission levels (*e*), the probability of inspection of the source ($\pi$), the initial allocation of daily emission capacity permits to the source, and enforcement actions for violations taken on the source (*g*).

The expected marginal penalty of source *i* is given by

$$EMP_i = EMP(e_i, \pi_i, l_{0i}, g_i) \tag{5}$$

Critical pieces of information for the empirical analysis are the determination of the probability of inspection and the information on enforcement actions for violations. Unfortunately, we were not able to obtain information on SESMA's inspections or on enforcement actions for violations within the EC Program's sources during the period studied. However, we did obtain information on SESMA's criteria used to inspect the sources. These are location (sources in sectors of deficient air quality are inspected more frequently), individual TSP emission levels (sources with a greater emissions flow are inspected more frequently), and source size (bigger sources are inspected more frequently). Additionally, earlier empirical studies suggest that the inspection probability depends on factors such as location of the source (*u*), daily production capacity (*k*), and the industrial sector to which the source belongs (*z*) (see, for example, Dion *et al.*, 1998; Laplante *et al.*, 1995). Considering the information on the criteria used by SESMA to define inspections as well as the results of prior empirical studies, the probability that source *i* will be inspected is represented by

$$\pi_i = \pi(e_i, q_i, u_i, z_i, k_i) \tag{6}$$

Considering that the factors mentioned before are determinants of the probability of inspection, and replacing equation (6) in (5); the expected marginal penalty of source *i* can be specified in the following way

$$EMP_i = EMP(e_i, u_i, z_i, k_i, l_{0i}, g_i) \tag{7}$$

While the marginal effect on the compliance decision from variables such as the type of source (*te*), the industrial sector (*z*), the size of the firm to which the source belongs (*q*), the type of fuel used (*c*), and its location (*u*) are uncertain, we expect a negative effect for the variables such as the existence of abatement equipment (*ea*), age of combustion equipment (*a*), the source's initial allocation of emission capacity permits ($l_0$), and the daily capacity of production *(k)*.[22]

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[22] We acknowledge that, as a consequences of not having data on inspections and enforcement actions, the model that we specify does not allow us to properly

### 3.3. Econometric model specification and data description

Our objective is to evaluate the probability that source *i* complies with its daily emission capacity permits. The equation used to estimate the compliance decision is

$$\begin{aligned} COMPL_i = \ & COMPL\,(\text{FURNACE, GENVAPOR, NEW, EQ\_ABAT,} \\ & \text{FUEL1, FUEL2, FUEL3, NAT\_GAS, FOOD\_BEV, TEXTIL,} \\ & \text{CHEM, SERVIC, IDE, FAC\_SIZE, POP\_DEN, AVE\_INC}) \end{aligned} \quad (8)$$

Where $COMPL_i$ is equal to 1 in the case that the source's daily declared emissions are not higher than its daily emission capacity permits ($\text{DDE}_i \leq \text{IDE}_i$); otherwise the variable takes a value of zero. Assuming that the error is normally distributed, the probability to observe $COMPL_i = 1$ is given by the value of the normal distribution function evaluated using the estimated parameters based on the specification of equation (8).

The independent variables considered are classified in three groups: (i) technical characteristics of the source (ii) the source's industrial sector and size, and, lastly (iii) the exogenous characteristics of the source.[23]

The first group of variables consists of FURNACE, GENVAPOR, NEW, EQ_ABAT, FUEL1, FUEL2, FUEL3, and NAT_GAS. FURNACE is a variable that indicates whether the source is an industrial furnace. GENVAPOR specifies whether the source is a vapor generator. NEW shows if the source was installed after March 1992. EQ_ABAT indicates whether the sources have abatement equipment. While FUEL1 indicates whether the source uses a fuel that contains less than 0.02 per cent sulfur, FUEL2 shows whether the source uses fuel that contains between 0.02 per cent and 0.3 per cent sulfur, FUEL3 indicates whether the source uses fuel that contains between 0.3 per cent and 1 per cent sulfur. Finally, NAT_GAS indicates whether the source uses natural gas as a fuel source.

The second group of variables refers to the source's industrial sector, the initial allocation of maximum emissions capacity permits, and source's size: FOOD_BEV, TEXTIL, CHEM, SERVIC, IDE, FAC_SIZE.[24] While FOOD_BEV refers to source from the food and beverage industrial sector, TEXTIL refers

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disentangle the abatement cost effects on compliance decision from the expected marginal penalty effects. If the information provided by SESMA on the criteria to audit firms is accurate, we clearly have the problem in the case of two variables; namely, the source's emissions and the source's industrial sector. Both are determinants of MAC and EMP functions in equations (4) and (7), respectively. However, the limitation may be even greater in the case that SESMA uses other variables to target its inspections. We are grateful to an anonymous referee of this journal for raising this point.

[23] The details of the construction of the independent variables are presented in Appendix 1.

[24] Originally, daily capacity of production was considered in the econometric model. However, by performing correlation tests, we found that there is a problem of multicollinearity between the production capacity and the IDE variables. We even tested for other potential problems of multicollinearity. However, we did not find evidence of this problem neither between the variables IDE and plant size (FAC_SIZE), nor between PROD_CAP and FAC_SIZE. For that reason, we decided

Table 2. *Summary of analyzed sources*

| *Year* | *Total number of sources* | *Total number of analyzed sources* | *% of analyzed sources* |
|---|---|---|---|
| 1993 | 680 | 499 | 73.4 |
| 1995 | 690 | 491 | 71.2 |
| 1996 | 631 | 474 | 75.1 |
| 1997 | 576 | 402 | 69.8 |
| 1998 | 566 | 342 | 60.4 |
| 1999 | 573 | 342 | 59.7 |

*Source*: Based on information provided by SESMA (2002).

to a source from the textile sector. Further, CHEM indicates a source from the chemical and plastic sector and SERVIC indicates if the source belongs to the service sector. IDE specifies the maximum amount of TSP emissions (in kg/day) authorized by the emission capacity permit, while FAC_SIZE indicates the size of the plant to which the source belongs.

The third group of variables includes POP_DEN, which indicates the population density in the area where the source is located; and AVE_INC, which specifies the average income in the neighborhood where the source is located.[25]

The data used for the econometric estimation include sources participating in the EC Program from 1993 to 1999, except for 1994 since there is no information available for this year. We have considered observations of only those sources that contain all the required information according to our specification. As a result, the number of sources analyzed is less than the total number of sources that exist each year (see table 2). The total number of observations considered in the model is 2,550.

Table 3 presents the definition of the variables considered in the model, as well as their means, standard deviations, and the expected sign of the parameters.

## 4. Econometric results

In this section, we present the econometric results for the emission capacity permit compliance decision in the Santiago EC Program, according to the specification provided by equation (8). We first present the results obtained considering all the available information for the period of 1993–1999. Then, motivated by the observed reduction in the frequency and magnitude of the transgressions as described in section 2, we proceed to evaluate the hypothesis of structural change in the compliance decision due to the

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to eliminate the variable production capacity from the estimated model. We are grateful to an anonymous referee for pointing this potential problem to us.

[25] We also attempted to use the variable CONCPROM, which indicates the average concentration of TSP every half-hour registered in the source's location. Due to problems of information availability for the entire period analyzed for all sources and considering the high correlation of this variable with population density, we decided to exclude it from the model.

Table 3. *Variable definitions, means, standard deviations, and expected signs of parameter*

| | *Average* | *Standard deviation* | *Expected sign*[a] |
|---|---|---|---|
| Dependent variable | | | |
| COMPL: 1 if the source complies; otherwise 0 | 0.603 | 0.489 | — |
| Independent Variables | | | |
| FURNACE: 1 if the source is an industrial furnace; otherwise 0 | 0.205 | 0.404 | ? |
| GENVAPOR: 1 if the source is vapor generator; otherwise 0 | 0.610 | 0.488 | ? |
| NEW: 1 if the source was installed prior to March 1992; otherwise 0 | 0.056 | 0.230 | + |
| FOOD_BEV: 1 if the source belongs to the food and beverages sector; otherwise 0 | 0.249 | 0.433 | ? |
| TEXTIL: 1 if the source belongs to the textile industry; otherwise 0 | 0.246 | 0.431 | ? |
| CHEM: 1 if the source belongs to the chemical and plastics sector; otherwise 0 | 0.099 | 0.298 | ? |
| SERVIC: 1 if the source belongs to the service sector; otherwise 0 | 0.258 | 0.438 | ? |
| EQ_ABAT: 1 if the source has abatement equipment; otherwise 0 | 0.105 | 0.306 | + |
| FUEL1: 1 if source uses fuel with less than 0.02% of sulfur; otherwise 0 | 0.205 | 0.404 | ? |
| FUEL2: 1 if source uses fuel contains between 0.02% and 0.3% of sulfur; otherwise 0 | 0.069 | 0.254 | ? |
| FUEL3: 1 if source uses fuel contains between 0.3% and 1% of sulfur; otherwise 0 | 0.678 | 0.467 | ? |
| NAT_GAS: 1 if the source uses natural gas; otherwise 0 | 0.067 | 0.250 | + |
| AVE_INC: average income per month per neighborhood expressed in thousand of Chilean Pesos | 614.305 | 446.724 | + |
| IDE: emission capacity permit expressed in kg/day | 8.208 | 23.642 | + |
| FAC_SIZE: factory size expressed in the number of sources owned by the plant to which the observed source belongs each year | 2.430 | 1.791 | ? |
| POP_DEN: population density expressed as number of habitants/km$^2$ | 6,578.740 | 4,025.780 | + |

*Note*: [a] The symbol '?' indicates uncertainty about the impact of the independent variable on the compliance decision. The symbol '+' indicates that the expected sign is positive, while the symbol '−' indicates that the expected sign is negative.
*Source*: Elaborated by the authors based on information provided by SESMA (2002).

Table 4. *Parameter estimates of the compliance decision, 1993–1999*

| *Variable* | *Coefficient* | *Standard deviation* |
|---|---|---|
| Constant | −0.13635 | 0.17307 |
| FURNACE | −0.40308* | 0.09728 |
| GENVAPOR | −0.39043* | 0.08533 |
| NEW | 0.29100* | 0.12614 |
| EQ_ABAT | −0.09069 | 0.09714 |
| FUEL1 | 0.26562** | 0.14179 |
| FUEL2 | 0.46712* | 0.16159 |
| FUEL3 | 0.67791* | 0.12508 |
| NAT_GAS | 1.97622* | 0.20954 |
| FOOD_BEV | 0.24740* | 0.08930 |
| TEXTIL | 0.41053* | 0.09472 |
| CHEM | 0.20644** | 0.11196 |
| SERVIC | 0.00216 | 0.10456 |
| IDE | 0.00469* | 0.00169 |
| FAC_SIZE | −0.05050* | 0.01521 |
| POP_DEN | −0.00002* | 0.00001 |
| AVE_INC | 0.0002* | 0.0001 |
| Maximum likelihood function, unrestricted | −1,566.04 | |
| Maximum likelihood function, restricted | −1,713.30 | |
| Maximum likelihood statistic | 294.52 | |
| Pseudo-$R^2$ | 0.09 | |
| Chi-squared ($\chi^2$) | 28.85 | |
| No. observations | 2,550 | |

*Notes*: * Significant at 5%, two-tailed test.
** Significant at 10%, two-tailed test.
*Source*: Elaborated by the authors based on econometric results (2002).

introduction of natural gas in the Santiago Metropolitan area in 1997. The section concludes with the quantification of the impact of relevant independent variables on the compliance decision.

### 4.1. Compliance decision model results

Considering the nature of the dependent variable, we estimated the parameter of interest by using the probit model. Table 4 presents the compliance decision model results considering all the observations available for the period 1993–1999.

From a global perspective, the estimated model is statistically significant. We evaluated the null hypothesis where all the parameters are equal to zero against the alternative hypothesis, which considers all the parameters to be different from zero. For this evaluation, we used the criteria of the maximum likelihood statistic, the index of likelihood or pseudo-$R^2$, and the percentage of certainty.[26] The value of the statistic of maximum

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[26] Maximum likelihood statistic $= -2^*(\ln L_r - \ln L)$; pseudo-$R^2 = 1 - \ln L / \ln L_r$; where $L_r$ is the value of the maximum likelihood function for the restricted model, and $L$ is the value of the maximum likelihood function for the unrestricted model.

likelihood is 294.53, where the critical chi-squared value with 16 degrees of freedom is 28.84. Consequently, we reject the null hypothesis that the parameters of the independent variables are all equal to zero. Additionally, we calculated the index of likelihood or pseudo-$R^2$, whose value was 0.09. Even though this value is relatively low, the maximum likelihood statistic (chi-squared) shows that the variables considered in the model have significant explanatory power (see table 4). Equally, the model predicts correctly 1,647 of the 2,550 observations, or 64.6 per cent.

As for the estimated individual parameters, our results indicate that the coefficients associated with the variables FURNACE and GENVAPOR are negative and significant. Such results suggest that, controlling for other factors, if the source is an industrial furnace or a vapor generator, the probability that the source complies with maximum emission capacity permits diminishes. According to this analysis, the sources that have a greater probability of complying with emission capacity permits are heater furnaces.

The coefficient of the variable NEW has the expected positive sign, and it is significant at 5 per cent. This result indicates that sources participating in the Santiago's EC Program installed after March 1992 (new sources) are more likely to comply than the existing sources.

In the case of the existence of abatement equipment (EQ_ABAT), the estimated parameter was not significant. This result suggests that contrary to what we expected, the existence of abatement equipment such as filters, electrostatic precipitators.

The coefficients of the variables FUEL1, FUEL2, and FUEL3 are positive and significant, which indicates that if the source uses some type of fuel containing less than 1 per cent sulfur, the probability that its daily declared emission will not exceed their emission capacity permits increases. According to this result, for those sources that use fuels containing more than 1 per cent of sulfur, the probability that its daily declared emission would not exceed their emission capacity permits decreases. As expected, the coefficient associated with the variable NAT_GAS is positive and significant, which means that while maintaining the rest of the variables constant, there is a greater probability that those sources using natural gas will comply with their emission capacity permits.[27]

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[27] We also explored in detail the possibility of simultaneity in the determination of equipment for pollution abatement and the choice of fuel type. First, we performed correlation tests between the variable that identifies whether the source owns equipment for abatement or not (EQ_ABAT) and the fuel type variables (FUEL1, FUEL2, and FUEL3). The results that we did obtain suggested to us that these variables were not correlated because their correlation coefficients were rather low (between 0.10 and 0.20). We checked again the dataset and found that there was not a behavioral pattern; in other words, we could not say that most of the sources that used certain abatement equipment consumed a particular type of fuel, among those previously considered. Second, we then explore deeply what has happened with the existence of pollution abatement equipment for sources participating in this program. We found that during the period 1993–1997, about 12 per cent of the total sources have installed some type of equipment for pollution abatement. After the introduction of natural gas, this figure was reduced to about 5 per cent of them

With respect to the variables indicating the type of industrial sector, the coefficients of the variables FOOD_BEV and TEXTIL are positive and significant. This result indicates that it is more likely for those sources that belong to the industrial sectors of food and beverage, or textile to be compliant than those of other industrial sectors such as pulp and paper, steel, iron, or other metallic products industries. The estimated parameter for the variable CHEM is positive and significant at 10 per cent, but not at 5 per cent. Furthermore, we found that the probability of compliance is independent if the source belongs to the service sector.

According to the results of our estimations, and consistent with the theoretical model presented in section 3, those sources having a greater allocation of daily emission capacity permits (IDE), have a greater probability of being compliant. In addition, the sources that belong to larger firms (FAC_SIZE) exhibit a lower compliance probability than those sources belonging to small ones.

The estimated parameter for the variable POP_DEN is significant; however, and perhaps surprisingly, it has a non-expected sign. In effect, the results suggest that, maintaining all other factors equal, those sources located in more densely populated areas (habitants/km$^2$) exhibit a lower compliance probability.

Finally, the estimated parameter for the variable AVE_INC is significant and it has the expected sign. In effect, the results suggest that, maintaining all other factors equal, those sources located in more wealthy areas exhibit a higher compliance probability.

In summary, the results of the specification estimations provided in equation (8) suggest that the compliance decision for the period 1993–1999 was determined by several characteristics associated as much with the marginal abatement costs as with the marginal expected penalty. The estimated model indicates that the variables that are relevant as determinants of the compliance decision are the type of source, the age of the combustion equipment, the industrial sector to which the source belongs, the type of fuel used, the plant size, the average income, and the population density of the zone where the source is located.

Considering the significant drop in the TSP emissions after 1997 as well as the marked reduction in the number and extent of emissions capacity permits violations, we decided to evaluate if the compliance decision was affected by the arrival of natural gas to Metropolitan Santiago. To explore this hypothesis, we proceed to divide the observations into two periods: 1993–1997 and 1998–1999. Specifically, we evaluated the null hypothesis

(period 1998–1999). We found evidence that this, perhaps surprisingly, reduction in the frequency (and number) of sources having equipment for pollution abatement, occurred as a consequence of the adoption of cleaner fuels, including among others, natural gas. We then performed a correlation test between EQ_ABAT and NAT_GAS. We even found a lower correlation coefficient than those found in the case of other fuel types. Consequently, we decided not introduce any specific control for simultaneity between equipment for pollution control and choice of fuel type. We thank an anonymous referee of this journal for raising this point.

where all the parameters are equal between periods: $H_0\colon \beta_{(1993-1997)} = \beta_{(1998-1999)}$, against the alternative hypothesis, $H_1\colon \beta_{(1993-1997)} \neq \beta_{(1998-1999)}$.

Performing the estimation for each period, we obtained estimates for the parameters and variances. Then, we calculated Wald's statistic according to $W = (\beta_{(1993-1997)} - \beta_{(1998-1999)})' \, (\mathrm{Var}_{(1993-1997)} + \mathrm{Var}_{(1998-1999)})^{-1} \, (\beta_{(1993-1997)} - \beta_{(1998-1999)})$. The value obtained was 210.95, and thus we rejected the null hypothesis. This result suggests that the arrival of natural gas in 1997 generated structural differences in the compliance decision of sources participating in the program.[28] In table 5, we present the results of the estimations for each period.

As it is shown in table 5, for both periods, 1993–1997 and 1998–1999, the values of the maximum likelihood statistic were higher than the critical values of chi-squared with 15 degrees of freedom; we consequently rejected the null hypothesis that all coefficients of the independent variables are equal to zero.[29] Even though the values of the likelihood index or pseudo-$R^2$ in both periods are small, the maximum likelihood statistic shows that the variables considered in the model have significant explanatory power. Furthermore, the model correctly predicts 59.9 per cent of the observations for the 1993–1997 period, and 88.8 per cent of them for the 1998–1999 period (see table 5).

With respect to the significance of the parameters for 1993–1997, the coefficients of FURNACE and GENVAPOR are negative and significant. This result is similar to the result for the entire period considered: 1993–1999. For the period 1998–1999, both coefficients are significant, but they are positive. This result reveals that if the source is not an industrial furnace or vapor generator, the compliance probability diminishes.

As for the coefficient of the variable NEW, the results for the 1993–1997 analysis are similar to those for the entire period. However, this variable is not significant for the period 1998–1999.

For the industrial sector variables FOOD_BEV, TEXTIL, and CHEM, the coefficients for the period 1993–1997 are positive and significant. But for the period 1998–1999, only the variables FOOD_BEV and TEXTIL are significant, which indicates that only those sources belonging to the food-and-beverage or textile sectors have a greater probability of compliance.

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[28] Additionally, it is possible to analyze the structural change estimating a restricted model and an unrestricted model for the period 1993–1999. The restricted model considers all of the original model's variables and the unrestricted model considers the original model's variables as well as the dichotomous variable associated with the availability or unavailability of gas. This dichotomous variable interacts with all the parameters of the original model. The null hypothesis is that all of the parameters that interact with the created dichotomous variable in the unrestricted model are equal to zero. Using the estimated values for the maximum likelihood function for the restricted and unrestricted models, a maximum likelihood test was performed and the null hypothesis was rejected.

[29] To determine if we should consider the data corresponding to the first year of the EC Program (1993), we estimated the compliance decision model for the periods 1993–1997 and 1995–1997. The results for both periods indicated that there is no important difference between them. Consequently, we decided to include the information for 1993.

Table 5. *Parameter estimates of the compliance decision: periods 1993–1997 and 1998–1999*

| | *1993–1997* | | *1998–1999* | |
|---|---|---|---|---|
| *Variable* | *Coefficient* | *Standard deviation* | *Coefficient* | *Standard deviation* |
| Constant | −0.12052363 | 0.1955739 | 0.7226222* | 0.3723540 |
| FURNACE | −0.57915339* | 0.1118795 | 0.1504546* | 0.2328228 |
| GENVAPOR | −0.60020454* | 0.0991176 | 0.3330565* | 0.1959621 |
| NEW | 0.31933577* | 0.1405344 | 0.5951116 | 0.4652496 |
| EQ_ABAT | −0.01923157 | 0.1048433 | −0.2733424 | 0.3032782 |
| FUEL1 | 0.21966891 | 0.1540420 | −0.2810594 | 0.3381618 |
| FUEL2 | 0.25874847 | 0.1772724 | | 0.2361856 |
| FUEL3 | 0.51815876* | 0.1373219 | 0.2632664 | |
| NAT_GAS | | | 0.9677100* | 0.3537551 |
| FOOD_BEV | 0.26113360* | 0.1010027 | 0.7675435* | 0.2469013 |
| TEXTIL | 0.43430841* | 0.1068278 | 0.9825998* | 0.2773685 |
| CHEM | 0.30458683* | 0.1260770 | 0.4222940 | 0.2907377 |
| SERVIC | −0.03408943 | 0.1212500 | 0.1259633 | 0.2474381 |
| IDE | 0.00545929* | 0.0021120 | 0.1847517 | 0.0226897 |
| FAC_SIZE | −0.02605027 | 0.0163058 | −0.1324417* | 0.0541898 |
| POP_DEN | −0.00001267** | 0.0000083 | −0.2875459 | 0.0004206 |
| AVE_INC | 0.00013829** | 0.0000848 | 0.1163025 | 0.0000062 |
| Maximum likelihood function, unrestricted | −1,236.21 | | −205.13 | |
| Maximum likelihood function, restricted | −1,292.71 | | −240.79 | |
| Maximum likelihood statistic | 113.00 | | 71.32 | |
| Pseudo-$R^2$ | 0.04 | | 0.15 | |
| Chi–squared | 27.49 | | 27.49 | |
| No. observations | 1,865 | | 685 | |

*Notes*: * Significance at 5%, two-tailed test.
** Significance at 10%, two-tailed test.
[a] For the period 1993–1997, we did not consider the variable NAT_GAS, because this variable did not display variation in the sources during these years (no source used natural gas until late 1997). For similar reasons, we did not consider the variable FUEL2 for the period of 1998–1999.
*Source*: Elaborated by the authors based on econometric results (2002).

For the fuel variables FUEL1, FUEL2, and FUEL3, not all the coefficients for the periods 1993–1997 and 1993–1999 are significant. Despite this result, the conclusions are similar: those sources that use fuel with less than 1 per cent sulfur have a greater probability of being compliant with emission capacity permits.

As expected, the coefficient for NAT_GAS is positive and significant, which implies that, maintaining other variables constant, sources using natural gas have a greater compliance probability.

Table 6. *Marginal effects of changes in independent variables on the compliance probability*[a]

| | *1993–1997* | *1998–1999* | *Entire period 1993–1999* |
|---|---|---|---|
| FURNACE | −0.2310 | 0.2157 | −0.1529 |
| GENVAPOR | −0.2394 | 0.4775 | −0.1481 |
| NEW | 0.1274 | – | 0.1104 |
| EQ_ABAT | – | – | – |
| FUEL1 | – | – | 0.1008 |
| FUEL2 | – | – | 0.1772 |
| FUEL3 | 0.2067 | – | 0.2572 |
| NAT_GAS | – | 0.1387 | 0.7497 |
| FOOD_BEV | 0.1042 | 0.1100 | 0.9386 |
| TEXTIL | 0.1733 | 0.1409 | 0.1557 |
| CHEM | 0.1215 | – | 0.7832 |
| SERVIC | – | – | – |
| IDE | 0.0022 | – | 0.1781 |
| FAC_SIZE | – | −0.1899 | −0.1916 |
| POP_DEN | 0.0000 | – | −0.6627 |
| AVE_INC | 0.0001 | – | 0.6405 |

*Note*: [a] Considers only variables significant at 10%.
*Source*: Elaborated by the authors based on econometric results (2002).

The coefficients of the variables POP_DEN and AVE_INC are significant at the 10 per cent level for the period 1993–1997. However, they are not significant for the period 1998–1999.

The coefficient of the variable IDE is significant for the period 1993–1997 but not for the period 1998–1999, while the variable FAC_SIZE is significant for the second period but not for the first one. With respect to abatement equipment, the coefficient is not significant for both periods.

### 4.2. *Effects of the independent variables on the compliance decision*

Considering the results obtained by the estimation of the compliance model, we decided to quantify the impact of the independent variables on the compliance probability. The results obtained for the marginal impact of statistically significant independent variables on the compliance probability are presented in table 6.

Using model results for the period 1993–1999, we are able to conclude that:

- If the source is an industrial furnace or a vapor generator, its compliance probability tends to diminish by 0.15 compared against the heater furnaces.
- If the source was installed after March 1992, the compliance probability increases by 0.11.
- The compliance probability increases by 0.94 if the source belongs to a firm from the food-and-beverage industrial sector, by 0.16 if it belongs to

the textile sector, and by approximately 0.78 if it belongs to the chemical sector.
- With respect to the type of fuel used, our results suggest that, if the source uses natural gas (which contains less than 0.02 per cent sulfur), the compliance probability increases by 0.75.

However, according to our evaluation of the hypothesis of a structural change in the compliance decision, these results differ if we consider the results before and after 1997. The main results for the period 1993–1997 indicate that:

- If the source is an industrial furnace or a vapor generator, the compliance probability tends to diminish by 0.23 and 0.24 respectively compared with heater furnaces.
- If the source was installed after March 1992, the compliance probability increases by 0.13.
- Belonging to the food-and-beverage or textile industrial sector increases the compliance probability by 0.10 and 0.17, respectively. In the case that the source belongs to the chemical sector, the compliance probability tends to increase by 0.12.
- As for the fuel type, a higher content of sulfur implies a higher compliance probability.

With respect to the effects of the independent variables on the compliance probability during the period 1998–1999, our calculations suggests that:

- If the source is an industrial furnace or a vapor generator, the compliance probability tends to increase by 0.22 and 0.48 respectively compared with a heater furnace.
- The compliance probability increases by 0.11 if the source belongs to a firm from the food-and-beverage industrial sector and by 0.14 if it belongs to the textile sector.
- Similarly, the results for the period 1998–1999 indicate that sources using natural gas increased their compliance probability by 0.14.

Using the coefficients obtained by the econometric estimation of the compliance model for the periods studied (table 5) and considering the sample mean of the continuous variables reported in table 3, it is possible to write the compliance probabilities for the periods 1993–1997 and 1998–1999, respectively, as

$$\begin{aligned}
&\text{Probability}_{1993-1997}(\text{COMPL}=1)\\
&\quad = \Phi[-0.58^{*}\text{FURNACE} - 0.60^{*}\text{GENVAPOR} + 0.32^{*}\text{NEW}\\
&\qquad + 0.26^{*}\text{FOOD\_BEV} + 0.43^{*}\text{TEXTIL} + 0.30^{*}\text{CHEM} + 0.52^{*}\text{FUEL3}\\
&\qquad + 0.005^{*}8.21] \qquad (9)
\end{aligned}$$

$$\begin{aligned}
&\text{Probability}_{1998-1999}(\text{COMPL}=1)\\
&\quad = \Phi[0.72 + 0.15^{*}\text{FURNACE} + 0.33^{*}\text{GENVAPOR} + 0.77^{*}\text{FOOD\_BEV}\\
&\qquad + 0.98^{*}\text{TEXTIL} + 0.97^{*}\text{NAT\_GAS} - 0.13^{*}2.430] \qquad (10)
\end{aligned}$$

Where Φ represents the normal standard distribution function. We use the expressions (9) and (10) to evaluate the compliance probabilities for the different periods. Our reference source is an industrial furnace that uses fuel with a content of sulfur between 0.3 per cent and 1 per cent, belongs to the food-and-beverage sector, and was installed after March 1992. We assume that the assigned IDE and the number of sources per firm are equal to the sample's mean (that is 8.2 and 2.4, respectively).

We then proceed to change initial source's characteristics. Among others, we considered the type of source, the industrial sector, and the age of the combustion equipment. In each of the results, we only changed one of the initial characteristics of the reference source.

We present the results in table 7. We observe there that independent of the source type, the compliance probabilities differ between periods. Specifically, for each type of source, the compliance probability is greater in the period 1998–1999 than during the period 1993–1997. For example, the compliance probability for the period 1993–1997 is 0.71 for our reference source, while for the period 1998–1999 the compliance probability was 0.91. However, the difference in the magnitude of the estimated probabilities does depend on the source type considered; for example, the vapor generators exhibit a greater compliance probability for the period 1993–1997.

Additionally, the results presented in table 7 suggest differences in the compliance probability according to the industrial sector. Our results reveal that industrial furnaces from the textile sector have the greatest compliance probability for both periods. On the one hand, if we compare a food sector industrial furnace to one with similar technical characteristics belonging to the textile sector, we find that the former has a compliance probability for the period 1993–1997 of 0.71, which is less than the compliance probability of the latter (0.77). On the other hand, for the period 1998–1999, a food sector industrial furnace has a compliance probability of 0.91, which is less than the one obtained by a textile sector industrial furnace (0.94).

Finally, the results also suggest differences in the compliance probabilities if the source was installed before or after March 1992. For both periods analyzed, the compliance probability is lower if the industrial furnace was installed before March 1992 than if it was installed after this date.

## 5. Conclusions

In this paper we have argued that the individual decision whether to comply or not with emissions permits in the presence of transactions costs depends on firm's characteristics, along with regulator's enforcement strategies. That is in direct contrast with the case of a competitive frictionless market for emission permits, where such a decision does not depend on any individual firm's characteristics.

Using the information available at the individual source level, we estimated the compliance decision for the maximum emission capacity permits owned by participating sources in the Emissions Compensation Program in Metropolitan Santiago, Chile. Specifically, we estimated an econometric model where the compliance decision was determined by a series of factors, including type of source, industrial sector to which the source belongs, fuel type used, type of abatement equipment, the initial

Table 7. *Probabilities of being in compliance with emissions capacity permits, 1993–1997 and 1998–1999*

| | *Type of source* | | | *Industrial sector* | | | *Source age* |
|---|---|---|---|---|---|---|---|
| *Variable modified* | *Industrial furnace Fuel with sulfur between 0.3% and 1%* | *Heater furnace Fuel with sulfur between 0.3% and 1%* | *Vapor generator Fuel with sulfur between 0.3% and 1%* | *Industrial furnace Fuel with sulfur between 0.3% and 1%* | *Industrial furnace Fuel with sulfur between 0.3% and 1%* | *Industrial furnace Fuel with sulfur between 0.3% and 1%* | *Industrial furnace Fuel with sulfur between 0.3% and 1%* |
| Industrial sector | Food and beverage | Food and beverage | Food and beverage | Textile | Chemical | Others | Food and beverage |
| Source age | After March 1992 | After March 1992 | After March 1992 | After March 1992 | After March 1992 | After March 1992 | Before March 1992 |
| Probability period 1993–1997 | 0.71 | 0.71 | 0.87 | 0.77 | 0.73 | 0.62 | 0.60 |
| Probability period 1998–1999 | 0.91 | 0.93 | 0.88 | 0.94 | 0.71 | 0.71 | 0.91 |

*Source*: Elaborated by the authors based on econometric results (2002).

allocation of permits, and the population density and average income of the zone where the source is located.

Our results indicate that the compliance behavior of sources in the EC Program during the period 1993–1999 do in fact depend on their individual characteristics. Further, we have been able to identify the specific factors that influence the individual compliance decision. The results can be used to refine the current authorities' enforcement strategies in order to induce adequate compliance levels in a cost-effective way. These results can also be useful in the general design of future market-based environmental regulations and in particular in the design of enforcement for other environmental quality recovery programs.

As for the purpose of refining enforcement strategies to improve compliance, our results clearly call for targeting authorities' enforcement efforts on some sources or group of sources. According to our results, efforts to induce compliance should focus on older heater furnaces and vapor generators, having relatively low levels of allocated maximum emissions capacity permits, which are located in lower income and highly populated density neighborhoods. Furthermore, and more specifically, the result that indicates that in some of the periods considered, those sources located in densely populated areas tended to exhibit a lower compliance probability than those sources located in less densely populated areas is troublesome due to the negative effects that air pollution as TSP has on human health. Consequently, we suggest that the EC Program authorities introduce changes in their enforcement strategies and actions to reverse this tendency.

Interestingly, while our conceptual work suggested that under the presence of transaction costs, the initial allocation of permits might have a role in improving or deteriorating compliance results in a market-based environmental regulation, we found evidence that it does in the context of the Santiago's EC Program. This implies that enforcement authorities have a new instrument available for the purpose to induce compliance; namely, reallocating maximum emissions capacity permits among regulated sources. Specifically, increasing the allocation of maximum emissions capacity permits to the less likely compliant sources is expected to increase the program's compliance. This implies further, that the initial allocation of permits can also be used as a substitute for greater enforcement efforts.

Equally, our estimates produced unexpected results. Specifically, one surprising result is that sources' compliance choice is independent of the existence of abatement equipment; that is, sources with abatement equipment do not necessarily comply more than those without this equipment. Thus, authorities should not use the available information on sources' ownership of abatement equipment to target enforcement efforts.

We also evaluated the hypothesis of structural differences in the compliance decision due to the arrival of natural gas to Metropolitan Santiago at the end of 1997. Our results indicate that a structural change in the compliance decision occurred in 1997, a fact that could explain the marked drop in the number and magnitude of the emission–capacity–permit violations observed after 1997.

The introduction of natural gas can be seen as a change in an exogenous variable, which we expected to modify sources' behaviour and program's performance. First, it is likely that the introduction of natural gas reduced the source's marginal abatement costs, so that for at least some sources, unconstrained emissions were then below the initial allocation of emissions capacity permits. The conceptual model used in this paper predicts that in the presence of high transaction costs, if the initial allocation of permits exceed the source's unconstrained emissions choice, no abatement effort occurs and would-be sellers sources will be (over) compliant. Further, in such a situation would-be buyer sources would not be able to find partners for trading, and, depending on their specific circumstances, they might be in violation. We observe that the excess of aggregate initial daily emissions (IDE) over aggregate daily declared emissions (DDE) exhibit a significant increase after the introduction of natural gas in Metropolitan Region of Santiago, suggesting the presence of individual (over) compliance. Furthermore, we have also shown that individual violations have coexisted with individual and aggregate over-compliance. Therefore, we offer a new explanation for (over) compliance in emissions trading programs when considering the presence of transaction costs.

Second, by properly direct testing, we have been able to learn that compliance behaviour in the EC Program is different before and after the introduction of gas. The results suggest that exogenous unanticipated changes in the program might produce important changes in the actual operation and performance of a market-based environmental policy. The arrival of natural gas to Santiago–a cleaner and cheaper fuel–caused a significant change in sources' compliance behavior. This suggests the existence of a new opportunity for environmental authorities of the country in order to obtain additional environmental improvement at low cost, not only by considering sources currently participating in the program, but also by perhaps extending the program to consider other sources as well.

Finally, we think that our empirical analysis can be extended in different directions. For example, our estimation considered the compliance decision as a discrete variable. Future research should consider not only whether or not the source decides to comply but also the magnitude of the imperfect compliance when it exists. This type of analysis has not received much attention in the literature and is particularly important in the case of air quality improvement programs based on economic incentives. In particular, empirical studies about the determinants of individual over-compliance are, to our best knowledge, scarce. In general, follow-up and evaluation of environmental regulation efforts need to continue. This is especially important considering that the principal objective of the Emissions Compensation Program is to improve air quality for the habitants of Metropolitan Santiago, Chile.

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## Appendix 1. Description of variables

According to our econometric model, source's compliance decision is determined by a series of variables as defined in equation (8). These independent variables are quantitative and qualitative. The following explains the construction of each one.

1. *Type of source*

   There are three types of sources: industrial furnaces, vapor generators, and heater furnaces. We used two dichotomous variables: FURNACE and GENVAPOR.

   FURNACE = 1 if it is an industrial furnace and 0 if it is another type of source.

   GENVAPOR = 1 if it is a vapor generator and 0 if it is another type of source.
2. *Age of the combustion equipment*

   Sources in the EC Program were divided in two groups; namely, original sources (installed before March 1992) and new sources (installed after March 1992). The dichotomous variable used was NEW.

   NEW = 1 if the source was installed after 1992 and 0 if the source was installed prior to 1992.
3. *Industrial sector*

   We classified the sources into the five most relevant sectors: food and beverages, textile, chemical, services (which includes banks, housing complexes, movie theatres, restaurants, etc.), and others.

   We used four dichotomous variables: FOOD_BEV, TEXTIL, CHEM and SERVIC. FOOD_BEV = 1 if the source belongs to the food-and-beverage sector and 0 if the source belongs to other sector.

   TEXTIL = 1 if the source belongs to the textile sector and 0 if the source belongs to other sector.

   CHEM = 1 if the source belongs to the chemical, rubber, plastic and derivates sector and 0 if the source belongs to other sector.

   SERVIC = 1 if the source belongs to the service sector and 0 if the source belongs to other sector.
4. *Abatement equipment*

   The impact of the emissions of each source can vary if technology has been installed at the 'end of the tube'. Included in the abatement equipment are filters, electrostatic precipitators, cyclones, and gas washers.

   The ownership of abatement equipment is captured by a dichotomist variable called EQ_ABAT, defined as:

   EQ_ABAT = 1 if the source possesses abatement equipment and 0 otherwise.
5. *Fuel type*

   According to the information provided by SESMA, the sources included in the EC Program have utilized or utilize some of the following fuels: sawdust, wood chips, logs, gas, propane, natural gas, kerosene, bituminous carbon, diesel no. 2, diesel no. 5, diesel no. 6, LEF, SUPERLEF, LMFO-30, LMFO-180, LMFO-380, SKYGARD 5, SKYGARD 30–80.

We grouped the fuels in four categories according to their sulfur content. This classification is based on the sulfur content because this is the element that makes a fuel more or less contaminating. Consequently, we defined three dichotomous variables:

FUEL1 = 1 if the fuel used contains less than 0.02 per cent of sulfur and 0 if the fuel has another sulfur content.

FUEL2 = 1 if the fuel used contains between 0.02 per cent and 0.30 per cent of sulfur and 0 if the fuel has another sulfur content.

FUEL3 = 1 if the fuel used contains between 0.30 per cent and 1.00 per cent of sulfur and 0 if the fuel has another sulfur content.

6. *Use of natural gas*
   Since one of the objectives of this work is to evaluate the impact of natural gas on the compliance decision, and the fuel type variable only considers the sulfur content without indicating the type, we created a variable indicating the use of Natural Gas, NAT_GAS, by each source. The variable is defined as:
   NAT_GAS = 1 if the source uses natural gas and 0 otherwise.
7. *Initial allocation of maximum emissions capacity permits*
   This variable is defined in the econometric model as the initial daily emissions (IDE) or daily permitted emissions (DPE) for the case of existing and new sources, respectively. The variable is expressed in kg/day. The variable, identified as IDE, captures the maximum emission capacity permitted for each source.
8. *Average income*
   This variable is defined as the average income per month in the neighborhood where the source is located. This information was provided by the Chilean National Socioeconomic Characterization Survey (CASEN). This variable is defined in the econometric model as AVE_INC and in the model estimation is expressed in thousands of Chilean Pesos ($).
9. *Firm size*
   To determine a source's firm size, we could consider, among others, the following approximate variables: number of workers, annual sales, and number of sources owned. In this study, according to the available data, we used the number of sources owned by a plant. In the econometric estimation, firm size was represented by the variable FAC_SIZE.
10. *Population density*
    The impact of the location of the source on the compliance decision was captured by the population density in the area where the source is located. This variable is defined in the econometric model as POP_DEN and expressed as number of habitants/km$^2$.