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Trading quasi-emission permits

by

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Abstract

I study the design of environmental policies for a regulator that has incomplete information on firms' emissions and costs of production and abatement (e.g., air pollution in cities with numerous small polluting sources). Because of incomplete information on emissions, there is no policy that can implement the first-best. Since the regulator can observe firms' abatement technologies, however, it is possible to design a quasi-emissions trading program based on this information and show that it can provide higher welfare than command-and-control regulation such as technology or emission standards. I then empirically examine this claim using evidence from a particulate quasi-emissions trading program in Santiago, Chile.

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1 Introduction

In recent years, environmental policy makers are paying more attention to environmental markets (i.e., emissions trading programs) as an alternative to the traditional command-and-control (CAC) approach of setting emission and technology standards. A notable example is the 1990 U.S. acid rain program that implemented a nationwide market for electric utilities' sulfur dioxide (SO_2) emissions (Schmalensee et al., 1998; Ellerman et al., 2000). In order to have a precise estimate of the SO_2 emissions that are actually going to the atmosphere, the acid rain program requires each affected electric utility unit to install costly equipment that can continuously monitor emissions.[1]

This and other market experiences suggest that conventional emissions trading programs are likely to be implemented in those cases where emissions can be closely monitored, which almost exclusively occurs in large stationary sources like electric power plants and refineries. , it is not surprising that, among other reasons, environmental authorities continue relying on CAC instruments to regulate emissions from smaller sources because compliance with such instruments only requires the authority to ensure that the regulated source has installed the required abatement technology or that its emissions per unit of output are equal or lower than a certain emissions rate standard.[2] In addition, some regulators view that a trading program where emissions cannot be closely observed is likely to result in higher emissions than under an alternative CAC regulation because the former provides firms with more incentives to alter

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[1] Another example with similar monitoring requirements is the Southern California RECLAIM program that implemented separated markets for nitrogen oxide (NO_x) and SO_2 emissions from power plants, refineries and other large stationary sources. This program did not include a market for volatile organic compounds (VOC) in large part because of the difficulties with monitoring actual emissions from smaller and heterogeneous sources (Harrison, 1999).

[2] Note that there are some credit-based trading programs aimed at curbing air pollution in urban areas working in the US (Tietenberg, 1985). New sources (or expansion of existing ones) must acquire emission credits to cover their emissions through, for example, shutting down existing plants or scrapping old vehicles. Although these programs have the merit of involving small sources, they are very limited in scope in the sense that they are embedded within an existing CAC regulation and are particularly designed to prevent further deterioration of air quality from the entry of new sources.

their output and hence their actual emissions.[3]

Thus, it appears that environmental markets are not suitable for effectively reducing air pollution in cities such as Santiago-Chile or Mexico City where emissions come from many small (stationary and mobile) sources rather than a few large stationary sources. For example, it would be prohibitively costly to require operators of central heating systems in residential or commercial buildings to install continuous emission monitoring equipment. Through annual inspections, however, the regulator could monitor boilers' size, combustion technology, fuel type and emissions rate as he would precisely do under CAC regulation. But since the regulator does not observe the total number of hours boilers are operated during the year, he would certainly have imperfect estimates of boilers' actual emissions.

Rather than disregard environmental markets as a policy tool, I think the challenge faced by policy makers in cities suffering similar air quality problems is when and how to implement these markets using monitoring procedures that are similar to those under CAC regulation. While the literature provides little guidance on how to approach this challenge,[4] it is interesting to observe that despite its incomplete information on each source's actual emissions, Santiago-Chile's environmental agency has already implemented a market to control total suspended particulate (TSP) emissions from a group of about 600 stationary sources (Montero et al., 2002). Based on estimates from annual inspection for technology parameters such as source's size and fuel type, Santiago's environmental regulator approximates each source's actual emissions by the maximum amount of emissions that the source could potentially emit in a given year.[5]

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[3] Several conversations during 2000 and 2001 with some regulators at Chile's National Commission for the Environment.

[4] In his survey, Lewis (1996) briefly explains the implications of imperfect monitoring on instrument design. Lewis and Sappington (1992) study a similar situation in which a regulator cannot observe the quality of service (e.g., energy conservation) offered by a public utility. In addition, Fullerton and West (forthcoming) discuss the use of taxes on cars and on gasoline as an alternative to an unavailable tax on emissions.

[5] The authority incorrectly assumed that by using the source's maximum emissions as a proxy it would prevent perverse incentives that could result in higher emissions. As we shall see, the choice of proxy is an arbitrary matter because the number of permits being allocated can always be adjusted accordingly with no efficiency effects.

I believe that a close (theoretical and empirical) examination of this quasi-emissions trading program represents a unique case study of issues of instrument choice and design that can arise in the practical implementation of environmental markets in which regulators face important information asymmetries and have a limited number of policy instruments (e.g., cannot make transfers from or to firms).

Since affected sources under Santiago's quasi-emissions trading program (hereafter, the TSP program) were responsible for only 4.8% of TSP emissions in Santiago in 2000 (Cifuentes and Montero, 2000), the domestic policy question that motivates this paper is the following: Based on the experience from the TSP program, would it be economically sound and technically possible to design a comprehensive quasi-emissions trading program for the city of Santiago that can include other sources of TSP such as smaller stationary sources and industrial processes (both responsible for 27.0% of TSP in 2000), power diesel buses (36.7%), trucks (24.7%) and smaller commercial vehicles and cars (6.8%) and other pollutants such as NO_x?[6] The answer to this question becomes quite relevant when looking for amendments to the 1997 Air Pollution Control Plan for Santiago that seeks sharp emission reductions through the exclusive use of CAC instruments but for the TSP program (CONAMA, 1997; and Cifuentes and Montero, 2000).

In the next section (Section 2) I develop a theoretical model and start by showing that the regulator can only implement second-best policies when emissions are not directly monitored (I use the term second-best in a loosely way to refer to any policy that provides net benefits that are positive but lower than those provided by a first-best policy). In Section 3, I derive the optimal design for two of such second-best policies: emission standards and quasi-emission permits.

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[6] It may be also relevant to ask about the benefits of allowing interpollutant trading. See Montero (2001) for a discussion.

In Section 4, I discuss the conditions under which permits provides higher welfare than standards. I show that the permits policy not only provide firms with flexibility to reduce production and abatement costs (e.g., high cost abatement firms can buy permits instead of installing abatement technologies) but also may create perverse incentives for firms to choose socially suboptimal combinations of output and abatement ex-post (i.e., once the regulation is in place). There are two situations in which the latter effect can lead the permits policy to higher emissions, and hence, be potentially welfare dominated by the standards policy: (1) when firms with relatively large ex-ante levels of output are choosing low levels of abatement (i.e., when there is a negative correlation between production and abatement costs), and (2) when firms choosing higher levels of abatement find it optimal to reduce output ex-post. Because in theory it is not possible to rule out neither situation, in deciding whether or not to use a quasi-emissions trading program, the regulator will inevitably face a trade-off between cost savings and possible higher emissions.

In Section 5, I empirically examine the advantages of a quasi-emissions trading program using emissions and output data from the TSP program. I find strong evidence of cost savings and no increase in effective emissions relative to what would have been observed under an alternative standards policy. The main reason driving this result is that firms making larger reductions are, on average, increasing their utilization relative to other firms. This empirical finding seems to be more general than one may think. Firms choosing abatement investments with proportionally large fixed/sunk costs (e.g., installing end-of-pipe technologies) not only make larger reductions but also enjoy lower ex-post marginal abatement costs (ex-ante marginal abatement costs should be similar at the margin), so their ex-post marginal production costs is relatively lower, and hence, their utilization relatively higher.[7] Finally, in Section 6, I discuss

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[7] The SO_2 trading system of the 1990 US acid rain program provides strong evidence on this as well. Affected sources retrofitted with scrubbers (end-of-pipe technologies that can reduce up to 95% of the emissions coming

some policy implications and conclude by arguing that the results of this paper make a strong case for the wider use of tradeable permits even in those situations in which emissions are imperfectly observed. Furthermore, I suggest that permits should be adopted as a default, unless the available cost information indicates the opposite. In other words, the burden of proof should lie with the CAC policy and not with the permits policy.

2 The Model

Consider a competitive market for an homogeneous good supplied by a continuum of firms of mass 1. Each firm produces output q and emissions e of a uniform flow pollutant. To simplify notation, I assume that when the firm does not utilize any pollution abatement device $e = q$. Market inverse demand is given by $P = P(Q)$, where Q is total output and $P'(Q) < 0$. Total damage from pollution is given by $D(E)$, where E are total emissions and $D'(E) > 0$. Functions $P(Q)$ and $D(E)$ are known to the regulator.

A firm can abate pollution at a positive cost by installing technology x, which reduces emissions from q to $e = (1 - x)q$. Hence, the firm's emission rate is $e/q = 1 - x$. Each firm is represented by a pair of cost parameters (β, γ). A firm of type (β, γ) has a cost function $C(q, x, \beta, \gamma)$ where β and γ are unknown to the regulator. To keep the model mathematically tractable I assume that the cost function has the following quadratic form

$$C(q, x, \beta, \gamma) = \frac{c}{2}q^2 + \beta q + \frac{k}{2}x^2 + \gamma x + vxq \tag{1}$$

where c, k and v are known parameters common to all firms satisfying $c \geq 0$, $k \geq 0$, $\Lambda \equiv kc - v^2 > 0$ and $v \gtreqless 0$.[8] The interaction term in (1), vxq, has an essential role in the model

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out of the stack) experienced a noticeably increase in utilization relative to affected sources that switched to lower sulfur coals or simply did not abate emissions (Ellerman et al., 2000, pp. 334-341).

[8] The parameter v can be negative, for example, if switching to a cleaner fuel saves on fuel costs but involves

since it captures the effect of abatement on ex-post (i.e., after the regulation) output. Since we have constrained v to be the same for all firms, a negative value of v would indicate, for example, that, on average, the larger the x the larger the q, ceteris paribus.[9] Thus, our cost function satisfies $C_q > 0$, $C_{qq} \geq 0$, $C_x > 0$, $C_{xx} \geq 0$, and $C_{qx} \gtreqless 0$ in the relevant range (recall that $C_y \equiv \partial C / \partial y$).

Although the regulator does not observe firms' individual values for β and γ, we assume that he knows that they are distributed according to the cumulative joint distribution $F(\beta, \gamma)$ on $\beta \in [\underline{\beta}, \overline{\beta}]$ and $\gamma \in [\underline{\gamma}, \overline{\gamma}]$. Without any loss of generality I let

$$\mathrm{E}[\beta] \equiv \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \beta f(\beta, \gamma) d\beta d\gamma = \mathrm{E}[\gamma] \equiv \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \gamma f(\beta, \gamma) d\beta d\gamma = 0 \tag{2}$$

where $\mathrm{E}[\cdot]$ is the expected value operator and $f(\beta, \gamma) \equiv d^2 F(\beta, \gamma)/d\beta d\gamma$ is the joint probability distribution.[10] In addition, I let $\mathrm{Var}[\beta] \equiv \sigma_\beta^2$, $\mathrm{Var}[\gamma] \equiv \sigma_\gamma^2$ and $\mathrm{Cov}[\beta, \gamma] \equiv \rho_{\beta\gamma}\sigma_\beta\sigma_\gamma$. Note that when production and abatement costs are positively correlated (i.e., $\rho_{\beta\gamma} > 0$), firms with relatively large ex-ante levels of output (i.e., firms with low β) are more likely to choose high levels of abatement, so the possibility of higher emissions under the permits policy is reduced. In addition, when firms are rather heterogeneous (i.e., large values of σ_β^2 and σ_γ^2) cost savings under permits are likely to be significant.

Firms behave competitively, taking the output clearing price P as given. Hence, in the absence of any environmental regulation, each firm will produce to the point where its marginal

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such a large retrofitting cost (i.e., high k) that no firm switches to the cleaner and cheaper fuel unless regulated.

[9] Ideally, one would like a richer model in which $v = \delta$ can vary across firms, where $\delta > 0$ is the firm's private information drawn over some known interval $[\underline{\delta}, \overline{\delta}]$ and according to some known cumulative distribution. Then, a positive correlation between γ and δ would produce that a higher x leads to an ex-post higher q. Solving that model, however, requires numerical techniques. Although my simpler formulation can produce a peculiar intermediate result (average utilization may go up with the regulation if $v < 0$), it does not biased the results of the paper in any particular way. This situation can be avoided by simply re-writing the interaction term vxq as $(w + vx)q$ where $w = 0$ if $x = 0$ and $w + v \geq 0$ if $x > 0$.

[10] Because β and γ take negative values for some firms, I work with parameter values (including parameters in demand and damage functions) such that marginal costs are always positive, that is $\partial C/\partial q > 0$ and $\partial C/\partial x > 0$ for all β and γ.

production cost equals the product price (i.e., $C_q(q, x, \beta, \gamma) = P$), and install no abatement technology (i.e., $x = 0$). Because production involves some pollution, this market equilibrium is not socially optimal. The regulator's problem is then to design a regulation that maximizes social welfare.

I let the regulator's social welfare function be

$$W = \int_0^Q P(z)dz - \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} C(q, x, \beta, \gamma) f(\beta, \gamma) d\beta d\gamma - D(E) \tag{3}$$

where $Q = \int_\beta \int_\gamma q(\beta, \gamma) f d\beta d\gamma$ is total output and $E = \int_\beta \int_\gamma (1 - x(\beta, \gamma)) q(\cdot) f d\beta d\gamma$ is total emissions. In this welfare function, the regulator does not differentiate between consumer and producer surplus and transfers from or to firms are lump-sum transfers between consumers and firms with no welfare effects.[11]

The firms' outputs and abatement technologies that implement the social optimum or first-best outcome are given by the following two first-order conditions

$$q : P(Q) - C_q(q, x, \beta, \gamma) - D'(E) \cdot (1 - x) = 0 \tag{4}$$

$$x : -C_x(q, x, \beta, \gamma) - D'(E) \cdot (-q) = 0 \tag{5}$$

If rearranged, eq. (4) says that the benefits from consuming an additional (small) unit of output is equal to its cost of production and environmental effects. Eq (5), on the other hand, says that emissions should be reduced to the point where the marginal cost of emissions abatement (i.e., C_x/q) is equal to marginal damages (i.e., $D'(E)$).

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[11] The model can be generalized by allowing the regulator to consider a weight $\alpha \neq 1$ for firm profits and a shadow cost $\lambda > 0$ for public funds. However, this would not add much to our discussion.

However, because of various information asymmetries between firms and the regulator, it is not clear that the latter can design an environmental policy that can attain the first-best outcome. The regulator's problem then becomes to maximize (3) subject to information constraints (and sometimes administrative and political constraints as well). From the various possible type of information constraints, it is useful to discuss briefly the case where the regulator knows little or nothing about firms' costs (i.e., he may or may not have any prior about the joint distribution of β and γ) but can costlessly monitor each firm's actual emissions e. This is the case that have attracted most attention in the literature (Lewis, 1996). When the regulator can estimate e either directly from continuous monitoring equipment or indirectly from observations of both x and q, it is not difficult to show that despite the fact that he knows nothing about firms' costs he can still implement the first-best by announcing a (non-linear) emissions tax schedule $\tau(E)$ equal to $D'(E)$.[12]

This regulatory mechanism is simpler than those proposed by Kwerel (1977), Dasgupta et al. (1980) and Spulber (1988) in the sense that does not require incentive compatibility and transfers to firms. In fact, Kwerel's (1977) mechanism considers two instruments: grandfathered permits and subsidies to firms holding permits in excess of their emissions. Dasgupta et al. (1980) and Spulber (1988), on the other hand, designs consider non-linear transfer to firms based upon the firms' (truthful) revelation of their costs parameters.[13] In case the regulator has some aggregate information about firms' costs (i.e., he knows that β and γ are jointly distributed according to F on $\beta \in [\underline{\beta}, \overline{\beta}]$ and $\gamma \in [\underline{\gamma}, \overline{\gamma}]$), the policy design becomes even simpler

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[12] I must say that this assertion is not new and its proof is quite straightforward. A competitive firm (β, γ) takes the price $P(Q)$ and tax rate $\tau(E) = D'(E)$ as given and maximize $\pi(q, x, \beta, \gamma) = P(Q)q - C(q, x, \beta, \gamma) - D'(E) \cdot (1 - x)q$ with respect to q and x. The firm's first order conditions for q and x are those given by (4) and (5).

[13] One difference with Dasgupta et al. (1980) is that in their design telling the truth is a dominant strategy. In this non-linear price design $\tau(E)$, the first-best outcome is a Bayesian-Nash equilibrium (i.e., it will be attained if each firm acts rationally and believes that the other firms are doing so). In addition, Dasgupta et al.'s (1980) mechanism does not rely on perfect competition as $\tau(E)$ does.

because aggregate uncertainty is eliminated. The regulator can either levy an emissions tax $\tau = D'(E^*)$ or distribute a total of E^* tradeable emissions permits, where E^* is equal to the total number of emissions at the social optimum.

In this paper, however, I am interested in the regulatory problem where the regulator cannot directly observe firms' actual emissions $e = (1-x)q$; although he can costlessly monitor firms' abatement technologies or emissions rates x. As in Santiago's quasi-emissions trading program, this information asymmetry will be present when both continuous monitoring equipment is prohibitively costly (or technically unfeasible) and individual output q is not observable.[14] Thus, if the regulator asks for an output report from the firm, we anticipate that the firm would misreport its output whenever this was to its advantage. In this case, the regulator cannot implement the social optimum regardless of the information he or she has about firm's costs.[15]

Even if the regulator has perfect knowledge of firm's costs and, therefore, can ex-post deduce firm's output based on this information and the observation of x, the fact that he cannot make the policy contingent on either emissions or output prevents him from implementing the first best. In other words, the regulator cannot induce the optimal amounts of output and emissions with only one instrument (i.e., x).[16] Consequently, the regulator must necessarily content himself with "second-best" policies. In the next two sections I discuss how to design and chose among some of those policies.

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[14] The regulator can nevertheless estimate total output Q from the observation of the market clearing price P.

[15] Consider the extreme situation in which regulator knows both β and γ. His optimal policy will be some function $T(x;\beta,\gamma)$ in the form of either a transfer from the firm or to the firm. Then, firm (β,γ) takes $P(Q)$ and $T(x;\beta,\gamma)$ as given and maximizes $\pi(q,x,\beta,\gamma) = P(Q)q - C(q,x,\beta,\gamma) - T(x;\beta,\gamma)$ with respect to q and x. It is not difficult to see that firm's first order conditions for q and x will always differ from (4) and (5) for any function $T(x;\beta,\gamma)$.

[16] See Proposition 2 of Lewis and Sappington (1992) for the same conclusion in a related problem. On the other hand, since the regulator can have a good idea of total emissions E from air quality measures, one might argue that Holmström's (1982) approach to solving moral hazard problems in teams may apply here as well. However, in our context this approach is unfeasible because the large number of agents would require too big transfers; either from firms as penalties or to firms as bonuses.

3 Second-best policy designs

Rather than consider all possible "second-best" policies, I focus on those policies that are either currently implemented or have drawn some degree of attention from policy makers in the context of urban air pollution control. I first study the optimal design of a traditional technology (or emission) standard and then the optimal design of a quasi-emissions trading system.[17] To keep the model mathematically tractable, I make two further simplifications regarding the demand curve and the damage function. I let $P(Q) = P$ (constant) and $D(E) = hE$, where $h > v$.[18]

To visualize how the two policy designs depart from the social optimum, it is useful to compute the first-best and keep it as a benchmark. Plugging the above assumptions in (4) and (5), the first-best outcome is given by

$$x^* = \frac{(P - h - \beta)(h - v) - \gamma c}{ck - (h - v)^2} \tag{6}$$

$$q^* = \frac{P - h - \beta + (h - v)x^*}{c} \tag{7}$$

It is immediate that $\partial x^*/\partial \beta < 0$, $\partial x^*/\partial \gamma < 0$, $\partial q^*/\partial \beta < 0$ and $\partial q^*/\partial \gamma < 0$. As expected, higher production and abatement costs lead to lower output and abatement levels.

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[17] Note that a tax on quasi-emissions is equivalent (in terms of efficiency) to a quasi-emissions trading program. There are other policies (involving non-linear transfer to firms) that can provide higher welfare than the two policies I consider here. Given the general information structure of our model, however, the solution can be very involved as illustrated by Laffont et al. (1987). The conventional second-best solution can be obtained assuming, as in Lewis (1996), a simple information structure where $\gamma = \beta$ and $F(\cdot)$ satisfies the usual regularity conditions.

[18] These assumptions tend to offset each other, and if anything, they tend to favor the standards policy. Because costs are always lower under the permits policy, a backward sloping demand would lead to higher output, and hence, to higher surplus under such policy. On the other hand, because if not clear a priory whether emissions are higher or lower under the permits policy, a convex damage function may or may not lead to higher environmental damages under such policy.

3.1 Standards

The regulator's problem here is to find the technology (or performance) standard x_s to be required to all firms that maximizes social welfare (subscript "s" denotes standards policy).[19] The regulator knows that for any given x_s, firm (β, γ) will maximize $\pi(q, x_s, \beta, \gamma) = Pq - C(q, x_s, \beta, \gamma)$. Hence, firm's (β, γ) output decision will solve the first-order condition

$$P - cq - \beta - vx_s = 0$$

which provides the regulator with firm's output q as a function of the standard x_s

$$q_s(x_s) \equiv q_s = \frac{P - \beta - vx_s}{c} \tag{8}$$

Since x_s will be the same across firms, it is clear that production under a standard will also be suboptimal relative to the first-best q^* as q_s does not adapt to changes in γ.

Based on the welfare function (3), the regulator now solves

$$\max_{x_s} \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[Pq_s - C(q_s, x_s) - h \cdot (1 - x_s) q_s\right] f d\beta d\gamma$$

By the envelope theorem, the first-order condition is

$$\int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[-kx_s - \gamma - vq_s - h \cdot (1 - x_s) \frac{\partial q_s}{\partial x_s} + hq_s\right] f d\beta d\gamma = 0 \tag{9}$$

By replacing (8) and $\partial q_s / \partial x_s = -v/c$ into (9) and using (2), the first-order condition (9) reduces

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[19] Although in practice the regulator sets the emission standards $s = 1 - x_s$, it is simpler to solve for x_s than $1 - x_s$.

to

$$-kx_s - \frac{v \cdot (P - vx_s)}{c} + h \cdot (1 - x^s)v + h \cdot (P - vx_s) = 0$$

Thus, the optimal technology standards becomes

$$x_s = \frac{P \cdot (h - v) + hv}{\Lambda + 2vh} \tag{10}$$

where $\Lambda \equiv ck - v^2 > 0$. Comparing this result to the first-best (6), it is interesting to observe that $x_s > x^*(\beta = 0, \gamma = 0)$. This indicates that even in the absence of production and abatement cost heterogeneity (i.e., $\beta = \gamma = 0$ for all firms), the standards policy still require firms to install more abatement technology than is socially optimal. Because $q_s(x^*) > q^*$, it is optimal to set x_s somewhat above x^* to bring output q_s closer to its optimal level q^*.

3.2 Tradeable quasi-emission permits

The regulator's problem now is to find the total number of quasi-emission permits $\widetilde{e}_0$ to be distributed among firms that maximizes social welfare. Let R denote the equilibrium price of permits, which will be determined shortly.[20] The regulator knows that firm (β, γ) will take R as given and solve

$$\max_{q,x} \pi(q, x, \beta, \gamma) = Pq - C(q, x, \beta, \gamma) - R \cdot (\widetilde{e} - \widetilde{e}_0)$$

where $\widetilde{e} = (1 - x)\widetilde{q}$ are $\widetilde{q}$ firm's quasi-emissions and $\widetilde{q}$ is some arbitrarily output or capacity level that is common to all firms. For example, $\widetilde{q}$ could be set equal to the maximum possible

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[20] Note that under a tax policy, the optimal price R will be the quasi-emissions tax. Because there is no aggregate uncertainty in this model, both policies will be equivalent from an efficiency standpoint.

output that could ever be observed, which would occur when $x = 0$ and $\beta = \underline{\beta}$. As we shall see later, the exact value of $\widetilde{q}$ turns out to be irrelevant because it simply works as a scaling factor. Note that if $\widetilde{e} < \widetilde{e}_0$ the firm will be a seller of permits.

From firms' first-order conditions

$$P - cq - \beta - vx = 0 \tag{11}$$

$$-kx - \gamma - vq + R\widetilde{q} = 0 \tag{12}$$

we have that firm's (β, γ) optimal abatement and output responses to R and $\widetilde{q}$ (or, more precisely, to $R\widetilde{q}$) are

$$x_p = \frac{R\widetilde{q}c - \gamma c - (P - \beta)v}{\Lambda} \tag{13}$$

$$q_p = \frac{P - \beta - vx_p}{c} \tag{14}$$

where the subscript "p" denotes permits policy. Comparing (13) and (14) with (6) and (7) illustrates the trade-off a regulator faces when implementing a quasi-emissions trading program. While $\partial q_p/\partial\beta$ and $\partial x_p/\partial\gamma$ are negative as in the first-best, $\partial q_p/\partial\gamma$ and $\partial x_p/\partial\beta$ are both positive when $v > 0$.[21]

Now we can solve the regulator's problem of finding the optimal $\widetilde{e}_0$. Since the market

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[21] Note that $\partial q_p/\partial\beta = -k/\Lambda$, $\partial x_p/\partial\beta = \partial q_p/\partial\gamma = v/\Lambda$ and $\partial x_p/\partial\gamma = -c/\Lambda$.

clearing condition is

$$\int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \widetilde{e} f(\beta, \gamma) d\beta d\gamma = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} (1 - x_p) \widetilde{q} f d\beta d\gamma = \widetilde{e}_0 \tag{15}$$

and x_p is a function of $R\widetilde{q}$ as indicated by (13), it is irrelevant whether we solve for $R\widetilde{q}$ or $\widetilde{e}_0/\widetilde{q}$. Hence, we let the regulator solve (permits purchases and sales are transfers with no net welfare effects)

$$\max_{R\widetilde{q}} \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[P q_p(x_p(R\widetilde{q})) - C(q_p(x_p(R\widetilde{q})), x_p(R\widetilde{q})) - h \cdot (1 - x_p(R\widetilde{q})) q_p(x_p(R\widetilde{q})) \right] f d\beta d\gamma$$

By the envelope theorem, the first-order condition can be written as

$$\int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[-(1 - x_p) h \frac{\partial q_p}{\partial (R\widetilde{q})} + h q_p \frac{\partial x_p}{\partial (R\widetilde{q})} - R\widetilde{q} \frac{\partial x_p}{\partial (R\widetilde{q})} \right] f d\beta d\gamma = 0 \tag{16}$$

By plugging $\partial q_p / \partial (R\widetilde{q}) = [\partial q_p / \partial x_p] / [\partial x_p / \partial (R\widetilde{q})]$, $\partial q_p / \partial x_p = -v/c$, (13) and (14) into (16) and using (2), the first-order condition can be rearranged to obtain the optimal permits price

$$R\widetilde{q} = \frac{Ph(kc + v^2) + hv\Lambda}{c \cdot (\Lambda + 2hv)} \tag{17}$$

which, in turn, allows us to obtain the optimal permits allocation $\widetilde{e}_0/\widetilde{q}$ by simply replacing (17) in (13) and that in (15).

More interesting, we can replace $R\widetilde{q}$ in (13) and (14) to obtain expressions for q_p and x_p that are more readily comparable to q_s and x_s (see eqs. (8) and (10)). After some algebra, the following expressions are obtained

$$x_p = x_s + \frac{v\beta - c\gamma}{\Lambda} \tag{18}$$

$$q_p = \frac{P - vx_s}{c} - \frac{k\beta - v\gamma}{\Lambda} = q_s - \frac{v(k\beta - v\gamma)}{c\Lambda} \tag{19}$$

If firms are homogeneous (i.e., $\beta = \gamma = 0$ for all firms), it is not surprising that $x_p = x_s$ and $q_p = q_s$ and that both regulations provide the same welfare. As firms become more heterogenous, x and q move in different directions depending on the regulatory regime. For example, as firms differentiate along their abatement costs (different γ's), firms' abatement decisions x tend to remain closer to the social optimum x^* under the permits regulation than under the CAC regulation since $\partial x^*/\partial\gamma$ and $\partial x_p/\partial\gamma$ are both negative.[22] However, as firms differentiate along their production costs (different β's) and v is assumed positive, firms' abatement decisions remain closer to x^* under the CAC regulation since $\partial x^*/\partial\gamma$ and $\partial x_p/\partial\gamma$ have opposite signs. A similar trade-off can be found analyzing firms' production decisions to changes in β and γ. Put differently, permits provide firms with abatement flexibility (e.g., firms with high abatement costs can buy permits instead of installing pollution control equipment) but may generate greater incentives to shift output and abatement (and hence emissions) further away form their first-best levels. Because this output/abatement "misalignment" may result in higher emissions under the permits policy, in deciding whether or not to use a quasi-emissions trading program, the regulator will inevitably face a trade-off between abatement flexibility and possible higher emissions. I study this trade-off more formally in the next section.

4 A second-best policy choice

To find which policy should be adopted by a welfare maximizing regulator, we start by writing the difference between the social welfare achieved by the permits policy and by the standards

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[22] Note that $\partial x^*/\partial\gamma = \partial x_p/\partial\gamma$ for $v = 0$.

policy

$$\Delta_{ps} = W_p(\widetilde{e}_0/\widetilde{q}) - W_s(x_s) \tag{20}$$

where $\widetilde{e}_0$ is the optimal number of quasi-emission permits normalized by some $\widetilde{q}$ and x_s is the optimal standard. The normative implication of (20) is that if $\Delta_{ps} > 0$, the regulator should implement the quasi-emissions trading policy.

To explore under which conditions this is the case, we write (20) as

$$\Delta_{ps} = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[Pq_p - C(q_p, x_p) - (1-x_p)q_p h - Pq_s + C(q_s, x_s) + (1-x_s)q_s h\right] f d\beta d\gamma \tag{21}$$

where q_p, x_p, q_s and x_s can be expressed according to (18) and (19). Since $Q_p = Q_s = (P - vx_s)/c$, eq. (21) can be re-written as

$$\Delta_{ps} = \int_{\underline{\beta}}^{\overline{\beta}} \int_{\underline{\gamma}}^{\overline{\gamma}} \left[\{C(q_s, x_s) - C(q_p, x_p)\} + \{(1-x_s)q_s - (1-x_p)q_p\}\, h\right] f d\beta d\gamma \tag{22}$$

Recalling that $e = (1-x)q$, the first curly bracket of the right hand side of (22) is the difference in costs between the two policies, whereas the second curly bracket is the difference in emissions that multiplied by h gives the difference in environmental damages.

Let us first examine the case in which $\text{Cov}[\beta, \gamma] \equiv \rho_{\beta\gamma}\sigma_\beta\sigma_\gamma = 0$. By plugging (2), (18) and (19) into (22), after some algebra (22) becomes

$$\Delta_{ps} = \frac{v^2\sigma_\beta^2 + c^2\sigma_\gamma^2}{2c\Lambda} - \frac{hv \cdot \left(k\sigma_\beta^2 + c\sigma_\gamma^2\right)}{\Lambda^2} \tag{23}$$

and after collecting terms, it reduces to

$$\Delta_{ps} = A_1\sigma_\beta^2 + A_2\sigma_\gamma^2 \tag{24}$$

where $A_1 = (v^2\Lambda - 2kcvh)/2c\Lambda^2$ and $A_2 = (c\Lambda - 2vch)/2\Lambda^2$. Since these coefficients can be either positive, negative or zero,[23] the sign of (24) will depend upon the value of the different parameters. As the heterogeneity across firms decreases (i.e., σ_β^2 and σ_γ^2), however, the welfare difference between the two policies tend to disappear.

The ambiguous sign of (24) should not be surprising given the trade-off between flexibility and higher emissions that we identified in the previous section. Expression (23) illustrates this trade-off more clearly. The first term is the difference in costs between the two policies, which is always positive. The second term is the difference in damages, which can either be positive, negative or zero depending on the value of v. Hence, a quasi-emissions trading policy will always lead to cost savings but it can also lead to higher emissions unless $v \leq 0$.

The simplest way to illustrate how Δ_{ps} varies with changes in the value of the different parameters is to focus on v. If v is zero (negative), A_1 is zero (positive) and A_2 is positive; hence, Δ_{ps} is always positive. If $v > 0$, however, A_1 is negative and A_2 can be either positive or negative; hence, the sign of Δ_{ps} remains ambiguous. Further, since $h > v$, it is possible to show that $\partial\Delta_{ps}/\partial v < 0$, so there is a critical value $v_c = v_c(c, k, h, \sigma_\beta, \sigma_\gamma) > 0$ for which $\Delta_{ps} = 0$.[24]

To interpret this result one must recognized that a quasi-emissions trading program can create "perverse" incentives for shifting output from cleaner to dirtier firms resulting in higher total emissions. A low value of v, however, reduces both the effect of the environmental regulation on the firm's output under either policy (see (8) and (14)) and the effect of production

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[23] Recall that for interior solutions in all cases we must have $kc > (h - v)^2$, $kc > v^2$, and $h > v$.

[24] Note from second order conditions that if $v_c > \sqrt{kc}$ or $v_c > h$, Δ_{ps} will be always positive. On the other hand, if $v_c < h - \sqrt{kc}$ and $h - \sqrt{kc} > 0$, Δ_{ps} will be always negative.

cost heterogeneity (i.e., β) on firms' abatement decisions under the permits policy (see (13)). In fact, when $v = 0$ the regulation has no effect on utilization and total emissions are equal under either policy.[25] Hence, total savings from trading are based exclusively on abatement cost heterogeneity and equal to $\Delta_{ps} = \sigma_\gamma^2/2k$.

A comparative statics analysis for $v_c(c, k, h, \sigma_\beta, \sigma_\gamma)$ yields ambiguous signs for all parameters but for h and σ_β, in which case we have $\partial v_c/\partial h < 0$ and $\partial v_c/\partial \sigma_\beta < 0$.[26] While it is immediate from (23) that a higher marginal damage reduces v_c, it is not so immediate that higher production cost heterogeneity also reduces v_c.[27] The reason is that when $v > 0$ higher production cost heterogeneity (i.e., higher σ_β) leads to higher output misalignment (i.e., further away from the first-best) and hence higher emissions under permits than under standards (i.e., q_s closer to q^* than q_p). When $v < 0$, conversely, production cost heterogeneity leads to less output misalignment under the permits policy. In addition, it is interesting to notice that because $\partial v_c/\partial \sigma_\gamma$ is of ambiguous sign, higher abatement cost heterogeneity (i.e., higher σ_γ) does not necessarily lead to higher Δ_{ps} when $v > 0$. This is because higher abatement heterogeneity may exacerbate the shifting of output from cleaner to dirtier firms.

Let us now relax the assumption that $\rho_{\beta\gamma} = 0$. In this case (24) expands to

$$\Delta_{ps} = A_1\sigma_\beta^2 + A_2\sigma_\gamma^2 + A_3\rho_{\beta\gamma}\sigma_\beta\sigma_\gamma \tag{25}$$

where $A_3 = (2hkc + 2hv^2 - 2v\Lambda)/2\Lambda^2 > 0$. Thus, the advantage of quasi-emission permits increases when β and γ are positively correlated (i.e., $\rho_{\beta\gamma} > 0$). This occurs because when

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[25] Note that under a conventional emissions trading program output is affected by the regulation even if $v = 0$ because actual emissions depend on output.

[26] To find $\partial v_c/\partial h$, for example, we make $\Delta_{ps} = 0$ and implicitely differentiate with respect to h to obtain

$$\frac{\partial v_c}{\partial h} = \frac{v_c kc\sigma_\beta^2 + v_c c^2\sigma_\gamma^2}{(v_c kc - 2v_c^3 - hkc)\sigma_\beta^2 - (v_c c^2 + hc^2)\sigma_\gamma^2}$$

which is obviously negative since $h > v_c$ for an interior solution.

[27] Note that if $v < 0$, $\partial\Delta_{ps}/\partial\sigma_\beta > 0$.

both cost parameters (β and γ) are either simultaneously high or low, output and abatement remain closer to the first-best. For example, we know that a high γ leads to too much output q_p ($\partial q_p/\partial\gamma > 0$) but because β is also high, q_p does not increase as much as if β were, on average, zero. Similarly, we know that a high β leads to too much abatement ($\partial x_p/\partial\beta > 0$) but because γ is also high, x_p does not go up as much. Note that if $\rho_{\beta\gamma} < 0$, Δ_{ps} can still be positive provided that $v < v_c$. As before, it is possible to find a critical value $\rho^c_{\beta\gamma} < 0$ for which $\Delta_{ps} = 0$ when $v = 0$. These results can be summarized in the following proposition

Proposition 1 *The permits policy can lead to either higher or lower social welfare than the standards policy depending on the values of* v *and* $\rho_{\beta\gamma}$. Δ_{ps} *will be unambiguously positive if either (i)* $v \leq 0$ *and* $\rho_{\beta\gamma} \geq 0$*, (ii)* $v_c > v > 0$ *and* $\rho_{\beta\gamma} = 0$*, or (iii)* $v = 0$ *and* $\rho^c_{\beta\gamma} < \rho_{\beta\gamma} < 0$.

As v and $\rho_{\beta\gamma}$ are likely to vary from case to case,[28] there may be cases in which standards are the correct policy choice. However, if we believe that in the absence of any cost information the reasonable values to assume for v and $\rho_{\beta\gamma}$ should be around zero (or centered around zero), Proposition 1 suggests that the permits policy should be adopted as a default, unless relevant cost data could be gathered to indicate the opposite. In other words, the burden of proof should lie with the standards policy and not with the permits policy.

5 An Empirical Evaluation

The theoretical analysis indicates that whether an quasi-emissions trading program provides higher welfare than a traditional command-and-control approach is an empirical question. I use the experience from Santiago's total suspended particulate emissions (TSP) trading program to answer such question for at least one particular case and draw, if possible, more general

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[28] For example, $\rho_{\beta\gamma}$ seems to be positive in the US acid rain program where baseload electric units have, on average, lower production costs and lower abatement costs than peaking units. Spulber (1988) and Lewis (1996) also assume $\rho_{\beta\gamma} > 0$. As we shall see next, I found evidence of $\rho_{\beta\gamma} < 0$ for the TSP program.

policy lessons. Because firms are not required to provide the regulator with information on production and abatement costs, to test the advantages of the TSP program I apply the theoretical framework previously developed to information other than cost such as emission rates and utilization.

5.1 The TSP program

The city of Santiago has constantly presented air pollution problems since the early 1980s. The TSP trading program, established in March of 1992, was designed to curb TSP emissions from the largest stationary sources in Santiago (industrial boilers, industrial ovens, and large residential and commercial heaters) whose emissions are discharged through a duct or stack at a maximum flow rate greater than or equal to 1,000 m^3/hr. Because sources were too small to require sophisticated monitoring procedures, the authority did not design the program based on sources' actual emissions but on a proxy variable equal to the maximum emissions that a source could emit in a given period of time if it operates without interruption.

The quasi-emissions variable (expressed in kg of TSP per day) used by the authority in this particular program was defined as the product of emissions concentration (in mg/m^3) and maximum flow rate (in m^3/hrs) of the gas exiting the source's stack (multiplied by 24 hrs and 10^{-6} kg/mg to obtain kg/day).[29] Although the regulatory authority monitors each affected source's concentration and maximum flow rate once a year, quasi-emissions and permits are expressed in daily terms to be compatible with the daily TSP air quality standards. Thus, a source that holds one quasi-emissions permit has the right to emit a maximum of 1 kg of TSP per day indefinitely over the lifetime of the program.

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[29] In terms of our model, this is equivalent as to make $\widetilde{q}$ equal to the maximum possible output, which in our case is $(P - \underline{\beta})/c$. But note that the program would have worked equally well with an either higher or lower $\widetilde{q}$. The use of a different $\widetilde{q}$ only requires to adjust the number of quasi-permits $\widetilde{e}_0$ to be distributed such that $R\widetilde{q}$ remains at its optimal level.

Sources registered and operating by March 1992 were designated as existing sources and received grandfathered permits equal to the product of an emissions rate of 56 mg/m^3 and their maximum flow rate at the moment of registration. New sources, on the other hand, receive no permits, so must cover all their quasi-emissions with permits bought from existing sources. The total number of permits distributed (i.e., the emissions cap) was 64% of aggregate quasi-emissions from existing sources prior to the program. After each annual inspection, the authority proceeds to reconcile the estimated quasi-emissions with the number of permits held by each source (all permits are traded at a 1:1 ratio). Note that despite permits are expressed in daily terms, the monitoring frequency restricts sources to trade permits only on an annual or permanent basis.[30]

5.2 The data

The data for the study was obtained from PROCEFF's databases for the years 1993 through 1999.[31] Each database includes information on the number of sources and their dates of registration, maximum flow rates, fuel types, emissions rates and utilization (i.e., days and hours of operation during the year). While information on maximum flow rates, fuel types and emissions rates is directly obtained by the authority during its annual inspections, information on utilization is obtained from firms' own reports.[32] The 1993 database contains all the information, including the flow rate used to calculate each source's allocation of permits, before the program became effective in 1994. Table 1 presents a summary of the data. The first two rows show that the exit and entry of sources has been quite significant. By 1999 36% of the affected sources were new sources despite the fact they did not receive any permits.

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[30] For a full description of the program, see Montero et al. (2002).

[31] PROCEFF is the government office responsible for enforcing the TSP program.

[32] Since utilization has no effect at all on the source's compliance status, there is no reason to beleive that firms have incentives to misreport their true utilization. For the same reason, this information is available for most but not all sources.

In order to comply with the TSP trading program, affected sources can hold permits, reduce emissions or do both. They can reduce emissions by either decreasing their size (i.e., maximum flow rate) or their emissions rates, through either fuel switching (for example, from wood, coal, or heavy oil to light oil, liquid gas, or natural gas) or the installation of end-of-pipe technology such as filters, electrostatic precipitators, cyclones, and scrubbers. Sources do not gain anything, in terms of emissions reduction, by changing their utilization level (i.e., days and hrs of operation), because by definition it is assumed to be at 100%. Given that the authority controls for the size of the source at the moment of permits allocation and emissions monitoring, in terms of our theoretical model changes in emission rates would be captured by the variable x_p and utilization by the variable q_p.

The next rows of Table 1 show data on flow rates, emission rates and utilization. The large standard deviations show that these three variables vary widely across sources in all years.[33] As the 1993 numbers indicate, sources' utilization was quite heterogeneous before the implementation of the program (a clear indication of a large σ_β), indicating the potential for higher emissions under a permits policy. Table 1 also indicates that the emissions rates of affected sources has remained quite different across sources after the program became effective (indication of a large σ_γ). This compliance heterogeneity confirms that, contrary to what occurs under CAC regulation where all firms must either install the same abatement technology or comply with the same emissions rate x_s, emissions-trading regulation provides enough flexibility for sources to comply in very different ways.

The last two rows of Table 1 show data on total quasi-emissions and quasi-emissions permits.[34] Although 1994 was in principle the first year of compliance with the program, trading

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[33] It may seem strange to observe some flow rates below the 1,000 (m^3/hr) mark. In general, these are existing sources for which their flow rates were wrongly estimated above 1,000 (m^3/h) at the time of registration. Nevertheless, these sources chose to remain in the program to keep the permits they had already received.

[34] A few permits were retired from the market in 1997 as the authority revised the eligibility of some sources to receiving permits (Montero et al., 2002).

activity did not occur until the end of 1996 because of evident enforcement problems. The emissions goal of the TSP program was only achieved by 1997 (total quasi-emissions below total permits); year after which natural gas became available from Argentina at unexpectedly attractive prices that many affected sources switched to this cleaner fuel leaving the quasi-emissions cap of 4,087.5 permits largely unbinding. This is consistent with the fact that all TSP trading activity took place from end of 1996 to middle of 1998 with prices steadily declining from 17,000 to 3,000 US$/permit.[35] In the next section we take a closer look at these data and test whether an equivalent command-and-control approach would have provided higher welfare.

5.3 Model implementation

According to Proposition 1, a quasi-trading program is likely to provide higher benefits than a equivalent CAC program when both v and $\rho_{\beta\gamma}$ are small or negative and positive respectively. In an attempt to determined the sign of Δ_{ps}, I start with an econometric estimation of the sign and magnitude of v and offer some hints about the sign of $\rho_{\beta\gamma}$. I leave for the following subsection a fuller estimation of Δ_{ps}.

Based on first order conditions (11) and (12), v can be computed by estimating the following simultaneous-equation system

$$x_p^i = a_0 + a_1 q_p^i + a_2 z^i + \varepsilon^i \tag{26}$$

$$q_p^i = b_0 + b_1 x_p^i + b_2 q_0^i + u^i \tag{27}$$

where x_p^i is source i's the level of abatement (under the permits policy), q_p^i is output, z^i is a

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[35] Obviously, intra-firm trading has continued as new sources come into operation.

variable (or group of variables) that captures abatement costs so that $a_0 + a_2 z^i = R\widetilde{q}/k - \gamma^i/k$, $q_0^i = (P - \beta^i)/c$ is output before the permits policy (i.e., TSP program) was implemented, and ε^i and u^i are error terms. Note that in the absence of other exogenous shocks to firms' behavior, we should expect $b_0 = 0$ and $b_2 = 1$. The sign of v can be inferred from either $a_1 = -v/k$ or $b_1 = -v/c$. So, if a_1, $b_1 \geq 0$ we will learn that $v \leq 0$ and that Δ_{ps} is more likely to be positive than otherwise.

Since I have information on x_p^i and q_p^i for a few years, I estimate the system (26)-(27) using panel data regressions. I use 1995 as a reference year, that is a year before the TSP became effective. I use 1995 instead of 1993 because I have more complete information for 1995 and because effective enforcement with the TSP program did not begin until the end of 1996.[36] The basic specification model is the following

$$REDUC_{it} = a_0 + a_1 UTIL_{it} + a_2 FLOWRTE_{it} + a_3 EMRTE95_i + a_4 ENDPIPE_i + a_5 INDUST_i + a_6 STATE_i + \varepsilon_{it} \quad (28)$$

$$UTIL_{it} = b_0 + b_1 REDUC_{it} + b_2 UTIL95_i + b_3 NATGAS_{it} + u_{it} \quad (29)$$

where i indexes sources; t indexes years; ε_{it} and u_{it} are error terms whose characteristics will be discussed shortly; and the chosen variables relate to those in (26)-(27) as follows. The variable x_p is captured by $REDUC$ which is equal to the percentage reduction of a source's emissions rate, $EMRTE$, from its emissions rate in 1995, $EMRTE95$. Thus, source i's reduction in period t is given by $REDUC_{it} = (EMRTE95_i - EMRTE_{it})/EMRTE95_i$. Because I am

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[36] See Montero et al. (2002). In any case, results do not qualitatively change when I use 1993 as the reference year.

taking $EMRTE95$ as a proxy for the rate that would have been observed in the absence of the level TSP program (i.e., counterfactual rate), $REDUC$ must be equal or greater than zero (by construction cannot be greater than one as well) if input prices are assumed unchanged as in our theoretical model. However, in a more general equilibrium setting where the relative price of some dirtier inputs may go down after the introduction of the TSP program, it is possible to observe a few sources for which $REDUC_{it} < 0$.[37]

The variable q_p is captured by $UTIL$ which is a source's utilization rate. As in the theoretical model, TSP program's authority does not observe $UTIL$, and therefore, she cannot use it for monitoring and enforcement purposes. Put it differently, because the regulator only observes source's flow rate, $FLOWRTE$, and emissions rate, $EMRTE$, she has only control over changes in emissions due to changes in source's size (i.e., $FLOWRTE$) and emission rates but not over changes in emissions due to changes in utilization.

$FLOWRTE$ and the time-invariant variables $EMRTE95$, $ENDPIPE$, $INDUST$ and $STATE$ and are intended to capture differences in abatement costs across sources. If there are any scale economies associated with pollution abatement we should expect more abatement from bigger sources (i.e., larger $FLOWRTE$), other things equal.[38] Similarly, I expect that a source that starts from a high emission rate (i.e., high $EMRTE95$) should face more abatement possibilities and hence lower costs. Conversely, I expect a source already equipped with some end-of-pipe abatement technology required by previous regulation to be less likely to reduce emissions. Hence, I introduce the dummy variable $ENDPIPE$ that equals 1 if the

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[37] In cases of either lacking or obviously incorrect information on $EMRTE95$, I proceed as follows: I use $EMRTE93$ instead of $EMRTE95$ for 10 sources, $EMRTE96$ instead of $EMRTE95$ for 3 sources and eliminated 7 sources for which their $EMRTE$ have increased more than 50% relative to their counterfactual rate (i.e., $EMRTE95$). Note that results do not change when I include 3 additional firms for which $EMRTE$ have increase between 50 and 100%. Results do substantially change when I include the 4 additional sources for which their $EMRTE$'s have increased somewhere between 100 and 2500% times relative to their counterfactuals.

[38] To address any endogeneity concerns about $FLOWRTE$, I run the same regressions with $FLOWRTE_{it} = FLOWRTE95_i$ for all t and obtain virtually identical results.

source has any type of end-of-pipe abatement technology by 1995. I also introduce the dummy variables $INDUST$ and $STATE$ to see whether there is any difference in abatement costs (or abatement behavior) between industrial sources ($INDUST = 1$) and residential/commercial sources, and between state or municipality owned sources ($STATE = 1$) and privately owned sources.[39] Since it is reasonable to think that privately owned and industrial sources should be more responsive to changes in factor prices after the introduction of the TSP program than other sources, I expect the coefficients of $INDUST$ and $STATE$ to be positive and negative, respectively.

The variable $UTIL95$ in (29) is the source's utilization in 1995 and serves as a proxy for the level of utilization that would have been observed in the absence of the TSP program and other exogenous factors. Although it does not follow directly from the theoretical formulation, I also include $UTIL95$ in (28) for some regressions as a first attempt to explore the sign of $\rho_{\beta\gamma}$. Because high levels of ex-ante output and ex-post abatement would tend to suggest a positive correlation between production and abatement costs, the sign of the coefficient of $UTIL95$ in (28) should serve as a first indication of the sign of $\rho_{\beta\gamma}$.[40] Finally, $NATGAS$ is a time-variant dummy variable that equals 1 if the source is burning natural gas. Based on Montero et al. (2002), who showed that the TSP program has had virtually no effect on firms' decisions to switch to natural gas, I include this variable to control for the lower production costs that sources may enjoy after switching to this fuel. Since these lower costs should lead to higher utilization, I expect the coefficient of $NATGAS$ to be positive.

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[39] For example, $INDUST = 0$ and $STATE = 1$ for the boiler of the central heating system of a public hospital.

[40] Later I will determine the sign of $\rho_{\beta\gamma}$ following an approach consistent with the theoretical formulation.

5.4 Econometric results

To estimate the coefficients in (28)-(29), I use a random-effects model.[41] Further, since $UTIL$ and $REDUC$ enter as endogenous variables in (28) and (29), respectively, their correlations with the error terms ε_{it} and u_{it} would produce biased OLS estimators. Therefore, I employ a generalized two stage least squares estimation procedure (G2SLS) to obtain unbiased estimates.[42] Based on the data presented in Table 1, I construct a panel of 407 firms for years 1996 through 1999.[43] Since I do not have complete information for all firms in all years the total number of observations reduces to 1253. Summary statistics are reported in Table 2.

G2SLS results for both equations (28) and (29) are presented in Table 3a and 3b, respectively (first-stage results are omitted). Results in column (1) show that the coefficients of $UTIL$ and $REDUC$ (i.e., a_1 and b_1, respectively) are both positive and significantly different from zero indicating not only that $v < 0$ but also that v is of important magnitude; about 22% of k and 15% of c. Remaining coefficients in the utilization equation, $UTIL95$ and $NATGAS$, have the expected sign but only $UTIL95$ is significantly different from zero. In addition, abatement cost coefficients in the reduction equation (i.e., $FLOWRTE$, $EMRTE95$, $ENDPIPE$, $INDUST$, $STATE$) are significantly different from zero and with the expected signs except for $FLOWRTE$. Because there are a few sources with disproportionately large values of $FLOWRTE$, in column (2) I replace $FLOWRTE$ by its natural log, $LOGFLOW$, and in column (3) I include the dummy $LARGEFLOW$ that equals one for 15 observations in which $FLOWRTE_{it} > 50,000$ (bigger than more than three standard deviations from the mean). Since results barely change, in what follows I use $LOGFLOW$.

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[41] Note that using a fixed-effects model it is not possible to estimate coefficients on time-invariant dummy variables (e.g., $STATE$, $INDUST$).

[42] To obtain more efficient estimates I use Baltagi's error-component two-stage least-squares (EC2SLS) method (see Hsiao, 1986, pp. 97-127).

[43] Note that I do not include new firms that entered the market after 1995. Since I have 48 new firms in the sample, however, I was able to run regressions controlling for this characteristic and I found no effects in the results presented below.

In column (4), I include year dummies to control for exogenous factors that can affect all sources throughout the years (e.g., demand shocks, increase in enforcement capabilities, etc.). While the coefficients of $UTIL$ and $REDUC$ remain positive and significantly different from zero, the coefficients of the year dummies in the reduction equation show a rather unilateral reduction of emission rates overtime which can be attributed to a combination of more effective enforcement, availability of natural gas at low prices and the increase of emergency episodes of bad air quality during which most polluting sources (i.e., those with higher emission rates) must shut down operations momentarily.

In a further effort to control for the evident increase in compliance after 1996, in column (5) I present results for a panel of a subset of 360 firms for years 1997 through 1999. Results are similar to those in column (4) but for the size of coefficients of $UTIL$ and $REDUC$ that now are much larger. Because trading activity did not take place until December of 1996 (Montero et al., 2002), I think these latter numbers are better estimates of a_1 and b_1 in (28) and (29), respectively.

Because our theoretical model assumes that all firms are expected to produce, on average, the same amount of output, $\mathrm{E}[q_p] = (P - vx_s)/c$, one can argue that our previous results either underestimate or overestimate the true value of v by not taking into account the fact that firms are of different sizes (i.e., different $FLOWRTE$). One could further argue that the true value of v is likely be smaller (in absolute terms) and perhaps positive because of the negative sign of $FLOWRTE$ (or $LOGFLOW$). To explore this possibility, I treat each source with $FLOWRTE \geq 1500$ as a group of identical smaller sources of size $FLOWRTE = 1000$. Accordingly, I replicate each observation in the 97-99 panel by the closest integer resulting from the fraction $FLOWRTE_{it}/1000$.[44] The G2SLS results for this new panel of 4355 observations

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[44] Each of the 12 observations for which $FLOWRTE < 500$ were retained as a single observation.

are in column (6).[45]

Finally, I provide a first approximation for the sign of $\rho_{\beta\gamma}$ by including $UTIL95$ in (28). Results are in column (7). The sign of $UTIL95$ shows that sources with large ex-ante utilization are less likely to adopt high levels of abatement, suggesting a possible negative correlation between production and abatement costs.

5.5 The value of Δ_{ps}

The above results provide strong evidence that $v < 0$ and suggest that $\rho_{\beta\gamma}$ may be negative. Based on these results and Proposition 1 we cannot conclude whether Δ_{ps} is positive or negative yet. Nevertheless, I will use the econometric results below to estimate the magnitude of Δ_{ps}. From (18) and (19) it is immediate that

$$\mathrm{Var}[x_p] = \frac{1}{\Lambda^2}(v^2\sigma_\beta^2 + c^2\sigma_\gamma^2 - 2vc\rho_{\beta\gamma}\sigma_\beta\sigma_\gamma) \tag{30}$$

$$\mathrm{Var}[q_p] = \frac{1}{\Lambda^2}(k^2\sigma_\beta^2 + v^2\sigma_\gamma^2 - 2kv\rho_{\beta\gamma}\sigma_\beta\sigma_\gamma) \tag{31}$$

$$\mathrm{Cov}[x_p, q_p] \equiv \mathrm{E}[x_p q_p] - \mathrm{E}[x_p]\mathrm{E}[q_p] = \frac{1}{\Lambda^2}[(kc + v^2)\rho_{\beta\gamma}\sigma_\beta\sigma_\gamma - kv\sigma_\beta^2 - vc\sigma_\gamma^2] \tag{32}$$

Note that (32) is the negative value of the difference in total emissions, E, between the permits and the standards policy, that is $E_p - E_s = -\mathrm{Cov}[x_p, q_p]$. In turn, eqs. (30) and (32) allow us

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[45] I also tried weighted 2SLS estimation methods (the weights are based on $FLOWRTE$'s) for different cross-sections with similar results.

to re-write $\Delta_{ps} = A_1\sigma_\beta^2 + A_2\sigma_\gamma^2 + A_3\rho_{\beta\gamma}\sigma_\beta\sigma_\gamma$ as

$$\Delta_{ps} = \frac{\Lambda}{2c}\text{Var}[x_p] + h\text{Cov}[x_p, q_p] \tag{33}$$

As in (23), the first term in (33) is the difference in costs savings between the permits and the standards policies, which is always positive, while the second term, $h\text{Cov}[x_p, q_p]$, is the difference in environmental benefits.

The of sign of (33) the can be readily estimated by looking at the covariance matrix for $REDUC$ and $UTIL$. Using $FLOWRTE_{it}$ as a weight to control for size differences across sources, the weighted statistics for the 96-99 sample (1253 obs.) are $\text{Var}[x_p] = 0.115$, $\text{Var}[q_p] = 0.110$ and $\text{Cov}[x_p, q_p] = 0.004$, and the weighted statistics for the 97-99 sample (886 obs.) are $\text{Var}[x_p] = 0.117$, $\text{Var}[q_p] = 0.121$ and $\text{Cov}[x_p, q_p] = 0$.[46]

Based on $\text{Cov}[x_p, q_p] \approx 0$ and $v < 0$, we can immediately infer that $\rho_{\beta\gamma} < 0$ (see (32)). More importantly, however, $\text{Cov}[x_p, q_p] \approx 0$ allows us to conclude that $E_p = E_s$ and that $\Delta_{ps} = (\Lambda/2c)\text{Var}[x_p] > 0$. Thus, we can argue that the permits policy would unambiguously provide higher welfare than the standards policy for any group of sources with a cost structure similar to that of sources affected by the TSP program. Furthermore, because $\text{Cov}[x_p, q_p] = 0$ the superiority of the permits policy would be independent of the aggregate emissions goal.

To understand why $\Delta_{ps} > 0$ requires to recognize the presence of two competing effects. While $v < 0$ increases the advantage of the permits policy by bringing output and abatement closer to the first-best, $\rho_{\beta\gamma} < 0$ reduces such advantage by doing exactly the opposite. In the case of the TSP program both effects tend to cancel out so emissions would be similar under either policy and $\Delta_{ps} > 0$.

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[46] Unweighted statistics for the 96-99 sample are $\text{Var}[x_p] = 0.135$, $\text{Var}[q_p] = 0.106$ and $\text{Cov}[x_p, q_p] = 0.021$. While these figures lead to a larger (and positive) Δ_{ps}, they provide somehow baised estimates since bigger units are making relatively smaller reductions as indicated by the previous econometrics results.

The second effect, however, has still the adverse effect of reducing some welfare under the permits policy. This effect can be empirically estimated by solving the system of equations (30)–(32) for σ_β^2, σ_γ^2 and $\rho_{\beta\gamma}$ and sorting out the relative contribution of each of these three terms to (30), and hence, to $(\Lambda/2c)\text{Var}[x_p]$. Using the results of column (6) in Tables 3a and 3b, I let $a_1 = -v/k = 0.5$ and $b_1 - v/c = 0.25$. Further, I let $\text{Var}[x_p] = \text{Var}[q_p] = 0.12$ and $\text{Cov}[x_p, q_p] = 0$. Normalizing v to -1, the solution of the system is $\sigma_\beta^2 = 2.04$, $\sigma_\gamma^2 = 0.6$ and $\rho_{\beta\gamma} = -0.72$ and the advantage of the permits policy becomes $\Delta_{ps} = (2.04 + 9.6 - 5.76)/56 = 0.105$. If $v = 0$ and $\rho_{\beta\gamma} = 0$, Δ_{ps} would be 0.171, so the first effect, i.e., $v < 0$, increases welfare by 21% but the second effect, i.e., $\rho_{\beta\gamma} < 0$, decreases welfare by 60% adding to a net welfare reduction of 39%.

6 Conclusions and Policy Implications

I have studied the optimal design of second-best environmental policies for a regulator that has incomplete information on firms' emissions and costs of production and abatement (e.g., air pollution in cities with many small polluting sources). I have considered two of such policies: tradeable quasi-emission permits and emission standards. I first developed a model to show that an optimal permits policy not only provide firms with abatement flexibility but also may create perverse incentives that can shift firms' output and abatement further away from the first-best levels. Thus, in deciding whether or not to implement a permits policy, the regulator will inevitably face a trade-off between abatement flexibility and output and abatement misallocation. Because the latter can lead to higher emissions, I do find situations in which an optimal standards policy can be welfare superior. However, when I used emissions and output data from Santiago-Chile's TSP quasi-emissions trading program to test for this possibility I found no evidence.

Conversely, I found conclusive evidence that the production and abatement cost characteristics of the sources affected by the TSP program are such that the permits policy is unambiguously welfare superior because not only leads to cost savings but also to the same emissions level than the standards policy. Furthermore, given the significant heterogeneity in compliance behavior across sources, it is reasonable to think that the cost savings has been substantial. The superiority of the permits policy is due in large part to the fact that sources making larger emission reductions are also increasing their utilization relative to other sources. This behavior seems to be more common than one may think because firms making larger reductions are generally those choosing abatement alternatives with proportionally large fixed/sunk costs (e.g., installing end-of-pipe technologies) and lower ex-post marginal abatement costs. Therefore, their ex-post total marginal production costs become relatively lower. The empirical analysis also showed a negative correlation between production and abatement cost which has reduced the welfare advantage of the permits policy by approximately 40%.

If we now go back to the question that motivated this paper, I would argue that the theoretical and empirical results presented in the paper make a strong case for the wider use of environmental markets even in those situations in which emissions are imperfectly observed. In the particular case of Santiago, we would still need to work out the technical details of how to optimally integrate different type sources under a comprehensive trading scheme so that all trades are done on a one-by-one basis. As shown in the Appendix, it may be optimal to use different utilization factors for different type of sources. I leave this and related design issues for future research.

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Appendix: Optimal design for two groups of firms

Consider that firms' production costs c can be either c_1 or c_2 with $c_1 < c_2$, which the regulator can observe. To simplify notation, I assume firms are in the same proportion. Following the derivation of (10) it can be shown that the optimal standards policy design is x_{s1} and x_{s2}, where $x_{sj} = [P \cdot (h - v) + hv]/[\Lambda_j + 2vh]$, $\Lambda_j = kc_j - v^2$ and $j = 1, 2$. Similarly, from (8) we can obtain expressions for q_{s1} and q_{s2} where $q_{sj} = (P - \beta - vx_{sj})/c_j$.

Deriving the optimal permits policy design, on the other hand, is a bit more involved as it requires to solve for R, $\widetilde{q}_1$ and $\widetilde{q}_2$ because now it is optimal for the regulator to use different utilization factors to estimate quasi-emissions of each type of firm. Note that firms continue exchanging permits on a 1 by 1 basis at the market price R. The regulator is simply using additional information in an effort to bring quasi-emissions closer to actual emissions. Since the optimal design would satisfy the first-order condition (12), condition that must hold for all firms, we have for $\beta = \gamma = 0$ that $R\widetilde{q}_j = kx_{sj} + vq_{sj}$, and therefore

$$\frac{\widetilde{q}_1}{\widetilde{q}_2} = \frac{kx_{s1} + vq_{s1}}{kx_{s2} + vq_{s2}} \tag{A1}$$

The optimal design requires that after the regulator has "arbitrarily" chosen some value for $\widetilde{q}_1$, the value of $\widetilde{q}_2$ becomes automatically determined by (A1). Since expected output (or utilization) before the regulation is P/c_j for a firm of type j, it is reasonable to ask whether $\widetilde{q}_1/\widetilde{q}_2 \approx (P/c_1)/(P/c_2) = c_2/c_1 > 1$? By looking at (A1) and expressions for x_{sj} and q_{sj}, it unlikely to be the case.

Because $c_1 < c_2$ the intuition would still be that $\widetilde{q}_1/\widetilde{q}_2 > 1$. While $\partial x_s/\partial c < 0$, $\partial q_s/\partial c$ is of ambiguous sign, so to find out whether $\widetilde{q}_1/\widetilde{q}_2 > 1$, we take the derivative of $kx_s + vq_s$ with respect to c, which is given by

$$\frac{\partial(kx_s + vq_s)}{\partial c} = k\frac{\partial x_s}{\partial c} + v\frac{\partial q_s}{\partial x_s}\frac{\partial x_s}{\partial c} = \frac{\Lambda}{c}\frac{\partial x_s}{\partial c} < 0 \tag{A2}$$

which implies that $\widetilde{q}_1/\widetilde{q}_2 > 1$.

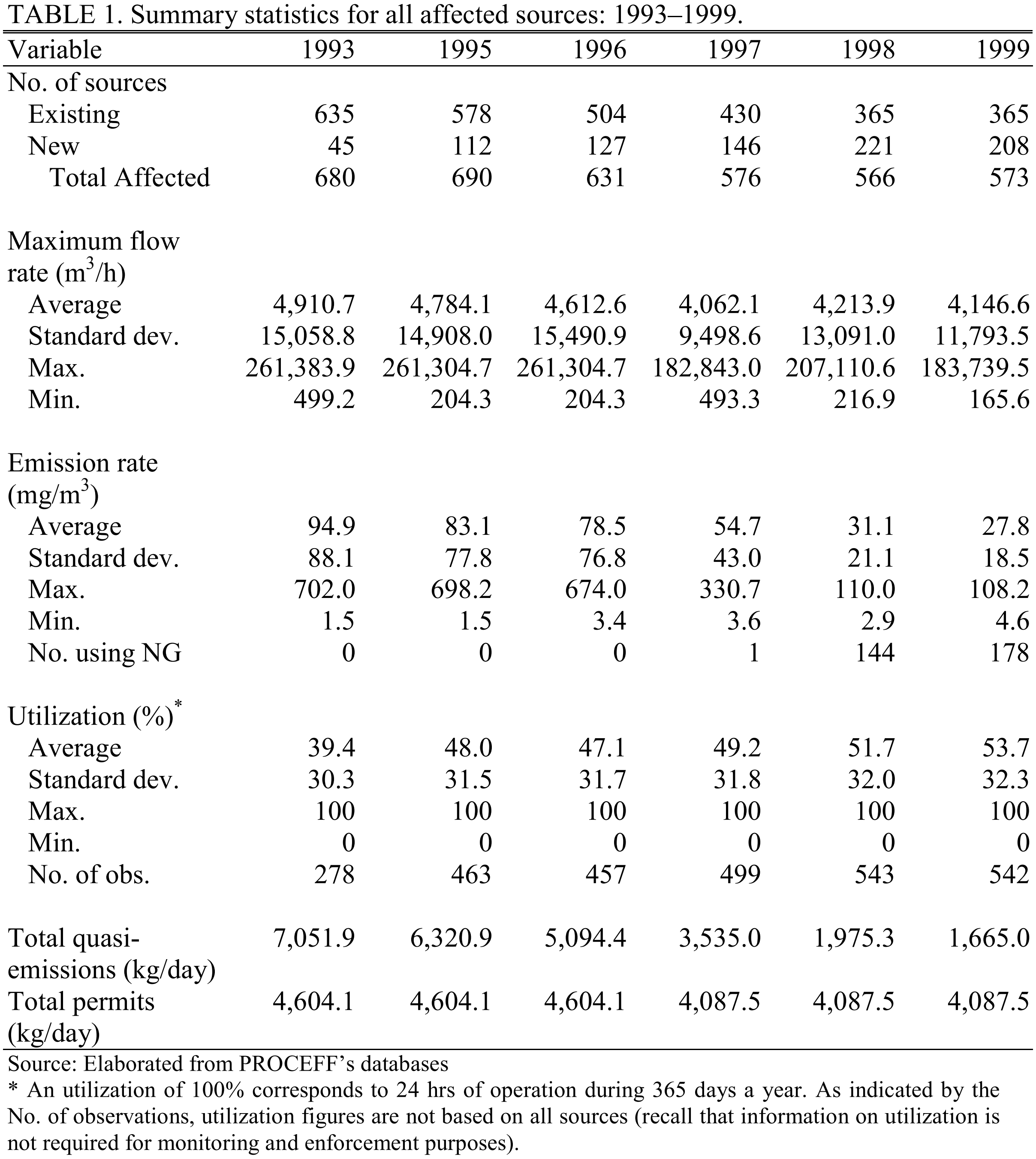

TABLE 1. Summary statistics for all affected sources: 1993–1999.

Variable	1993	1995	1996	1997	1998	1999
No. of sources						
Existing	635	578	504	430	365	365
New	45	112	127	146	221	208
Total Affected	680	690	631	576	566	573
Maximum flow rate (m^3/h)						
Average	4,910.7	4,784.1	4,612.6	4,062.1	4,213.9	4,146.6
Standard dev.	15,058.8	14,908.0	15,490.9	9,498.6	13,091.0	11,793.5
Max.	261,383.9	261,304.7	261,304.7	182,843.0	207,110.6	183,739.5
Min.	499.2	204.3	204.3	493.3	216.9	165.6
Emission rate (mg/m^3)						
Average	94.9	83.1	78.5	54.7	31.1	27.8
Standard dev.	88.1	77.8	76.8	43.0	21.1	18.5
Max.	702.0	698.2	674.0	330.7	110.0	108.2
Min.	1.5	1.5	3.4	3.6	2.9	4.6
No. using NG	0	0	0	1	144	178
Utilization (%)*						
Average	39.4	48.0	47.1	49.2	51.7	53.7
Standard dev.	30.3	31.5	31.7	31.8	32.0	32.3
Max.	100	100	100	100	100	100
Min.	0	0	0	0	0	0
No. of obs.	278	463	457	499	543	542
Total quasi-emissions (kg/day)	7,051.9	6,320.9	5,094.4	3,535.0	1,975.3	1,665.0
Total permits (kg/day)	4,604.1	4,604.1	4,604.1	4,087.5	4,087.5	4,087.5

Source: Elaborated from PROCEFF's databases

* An utilization of 100% corresponds to 24 hrs of operation during 365 days a year. As indicated by the No. of observations, utilization figures are not based on all sources (recall that information on utilization is not required for monitoring and enforcement purposes).

Figure 1: Table 1

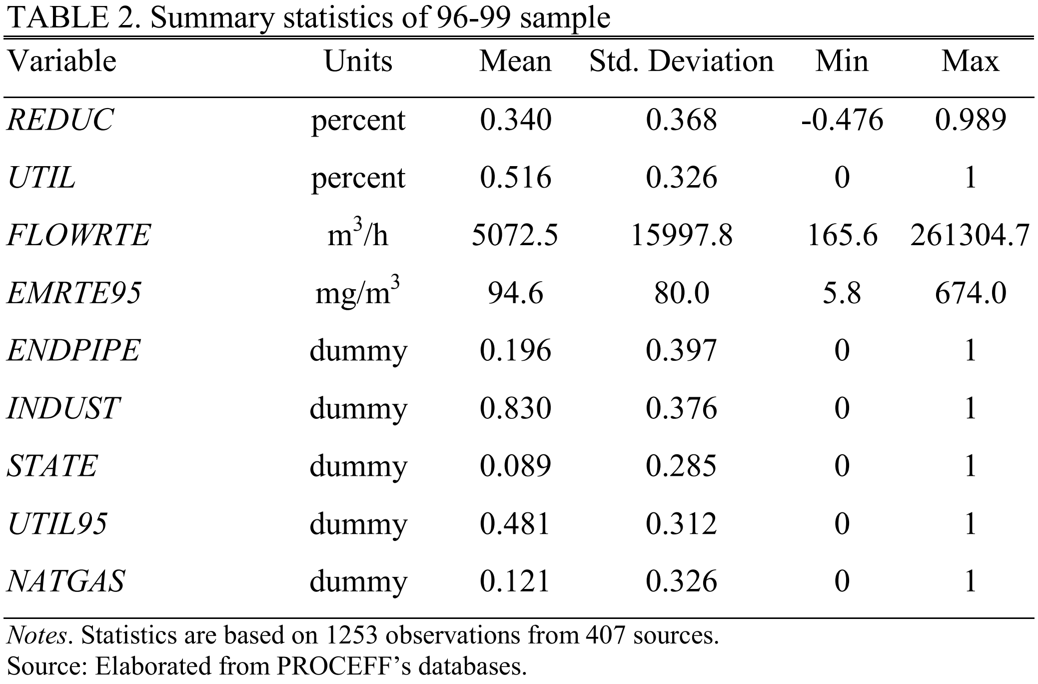

TABLE 2. Summary statistics of 96-99 sample

Variable	Units	Mean	Std. Deviation	Min	Max
REDUC	percent	0.340	0.368	-0.476	0.989
UTIL	percent	0.516	0.326	0	1
FLOWRTE	m^3/h	5072.5	15997.8	165.6	261304.7
EMRTE95	mg/m^3	94.6	80.0	5.8	674.0
ENDPIPE	dummy	0.196	0.397	0	1
INDUST	dummy	0.830	0.376	0	1
STATE	dummy	0.089	0.285	0	1
UTIL95	dummy	0.481	0.312	0	1
NATGAS	dummy	0.121	0.326	0	1

Notes. Statistics are based on 1253 observations from 407 sources.
Source: Elaborated from PROCEFF's databases.

Figure 2: Table 2

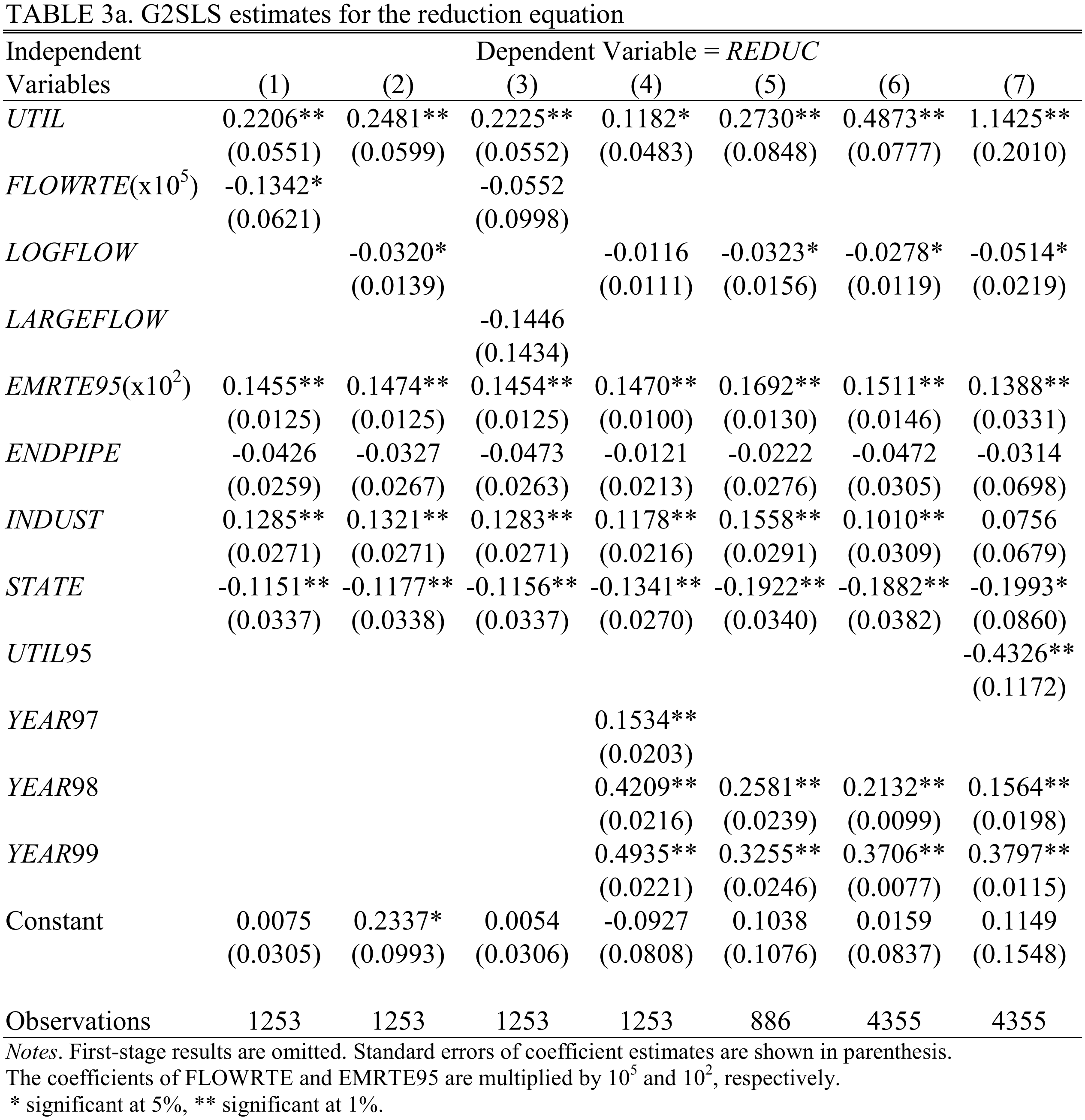

TABLE 3a. G2SLS estimates for the reduction equation

Independent Variables	Dependent Variable = *REDUC* (1)	(2)	(3)	(4)	(5)	(6)	(7)
UTIL	0.2206**	0.2481**	0.2225**	0.1182*	0.2730**	0.4873**	1.1425**
	(0.0551)	(0.0599)	(0.0552)	(0.0483)	(0.0848)	(0.0777)	(0.2010)
FLOWRTE(x10^5)	-0.1342*		-0.0552				
	(0.0621)		(0.0998)				
LOGFLOW		-0.0320*		-0.0116	-0.0323*	-0.0278*	-0.0514*
		(0.0139)		(0.0111)	(0.0156)	(0.0119)	(0.0219)
LARGEFLOW			-0.1446				
			(0.1434)				
EMRTE95(x10^2)	0.1455**	0.1474**	0.1454**	0.1470**	0.1692**	0.1511**	0.1388**
	(0.0125)	(0.0125)	(0.0125)	(0.0100)	(0.0130)	(0.0146)	(0.0331)
ENDPIPE	-0.0426	-0.0327	-0.0473	-0.0121	-0.0222	-0.0472	-0.0314
	(0.0259)	(0.0267)	(0.0263)	(0.0213)	(0.0276)	(0.0305)	(0.0698)
INDUST	0.1285**	0.1321**	0.1283**	0.1178**	0.1558**	0.1010**	0.0756
	(0.0271)	(0.0271)	(0.0271)	(0.0216)	(0.0291)	(0.0309)	(0.0679)
STATE	-0.1151**	-0.1177**	-0.1156**	-0.1341**	-0.1922**	-0.1882**	-0.1993*
	(0.0337)	(0.0338)	(0.0337)	(0.0270)	(0.0340)	(0.0382)	(0.0860)
*UTIL*95							-0.4326**
							(0.1172)
*YEAR*97				0.1534**			
				(0.0203)			
*YEAR*98				0.4209**	0.2581**	0.2132**	0.1564**
				(0.0216)	(0.0239)	(0.0099)	(0.0198)
*YEAR*99				0.4935**	0.3255**	0.3706**	0.3797**
				(0.0221)	(0.0246)	(0.0077)	(0.0115)
Constant	0.0075	0.2337*	0.0054	-0.0927	0.1038	0.0159	0.1149
	(0.0305)	(0.0993)	(0.0306)	(0.0808)	(0.1076)	(0.0837)	(0.1548)
Observations	1253	1253	1253	1253	886	4355	4355

Notes. First-stage results are omitted. Standard errors of coefficient estimates are shown in parenthesis.
The coefficients of FLOWRTE and EMRTE95 are multiplied by 10^5 and 10^2, respectively.
* significant at 5%, ** significant at 1%.

Figure 3: Table 3a

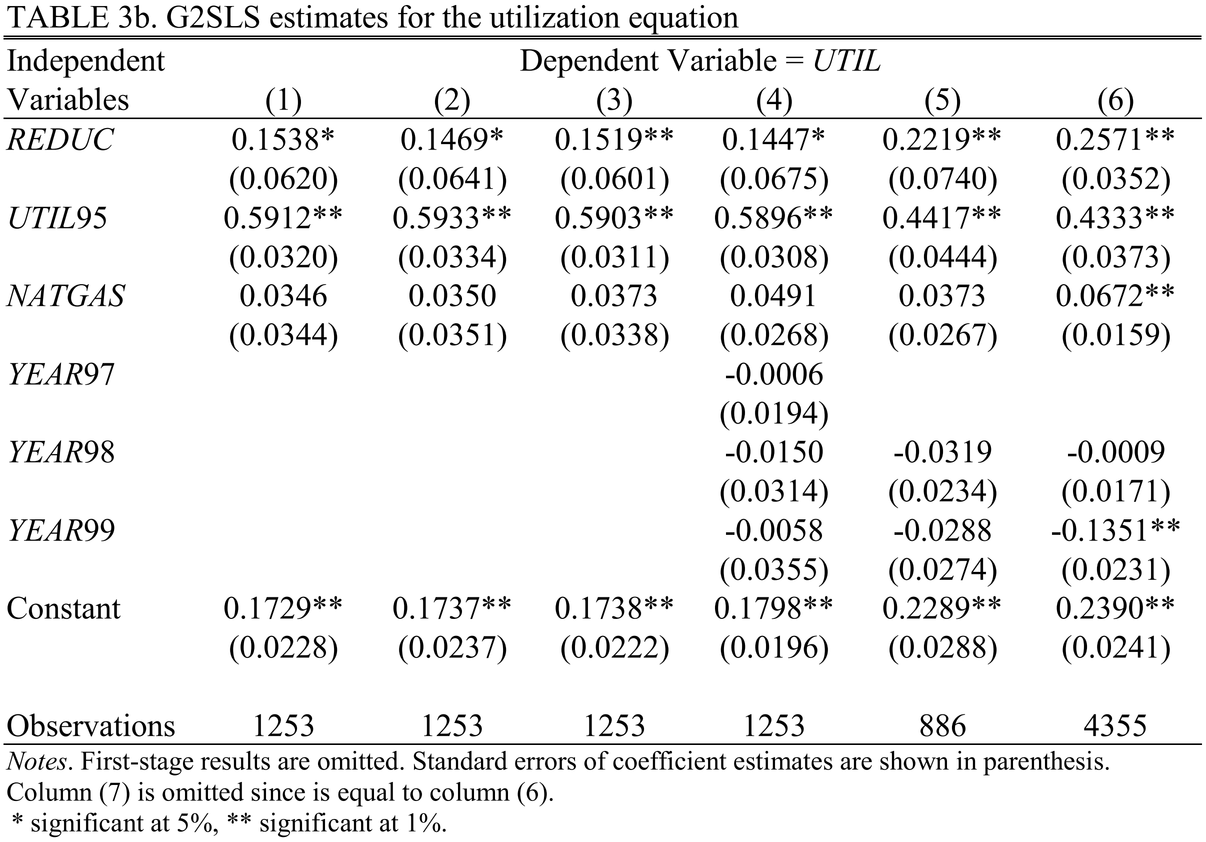

TABLE 3b. G2SLS estimates for the utilization equation

Independent Variables	Dependent Variable = *UTIL* (1)	(2)	(3)	(4)	(5)	(6)
REDUC	0.1538*	0.1469*	0.1519**	0.1447*	0.2219**	0.2571**
	(0.0620)	(0.0641)	(0.0601)	(0.0675)	(0.0740)	(0.0352)
*UTIL*95	0.5912**	0.5933**	0.5903**	0.5896**	0.4417**	0.4333**
	(0.0320)	(0.0334)	(0.0311)	(0.0308)	(0.0444)	(0.0373)
NATGAS	0.0346	0.0350	0.0373	0.0491	0.0373	0.0672**
	(0.0344)	(0.0351)	(0.0338)	(0.0268)	(0.0267)	(0.0159)
*YEAR*97				-0.0006		
				(0.0194)		
*YEAR*98				-0.0150	-0.0319	-0.0009
				(0.0314)	(0.0234)	(0.0171)
*YEAR*99				-0.0058	-0.0288	-0.1351**
				(0.0355)	(0.0274)	(0.0231)
Constant	0.1729**	0.1737**	0.1738**	0.1798**	0.2289**	0.2390**
	(0.0228)	(0.0237)	(0.0222)	(0.0196)	(0.0288)	(0.0241)
Observations	1253	1253	1253	1253	886	4355

Notes. First-stage results are omitted. Standard errors of coefficient estimates are shown in parenthesis. Column (7) is omitted since is equal to column (6).
* significant at 5%, ** significant at 1%.

Figure 4: Table 3b