A MARKET-BASED ENVIRONMENTAL POLICY EXPERIMENT IN CHILE*

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Abstract

We evaluate the performance of an environmental market in a less developed country on the basis of the experiences of the particulate matter control program of Santiago, Chile. We find that grandfathering the permits has created economic incentives for incumbent sources to more readily declare their (historic) emissions in order to claim any permits. In addition, the market has not fully developed because of transaction costs, regulatory uncertainty, and incomplete enforcement. Nonetheless, it has provided sources with the flexibility to adapt to new market conditions. Our analysis of this particular experience indicates that market-based policies can provide important advantages over traditional command-and-control policies even under limited institutional capabilities.

I. Introduction and Summary

RECENT years have seen a widespread interest in the use of market-based instruments—particularly emissions-trading or tradeable permits systems—to

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deal with air pollution, rather than the traditional command-and-control approach of setting emission and technology standards. While almost all experience with tradeable permit systems has been confined to the United States,[1] a few less developed countries (LDCs) are also beginning to experiment in different forms with emissions trading.[2] A close examination of these experiences is particularly interesting at this time since a global emissions-trading system with some type of voluntary participation from LDCs is at the center of current negotiations to curb emissions of carbon dioxide and other greenhouse gases.

This paper is an attempt to evaluate the performance of such environmental markets under the rules and institutions of an LDC. The analysis is based on the experience of the tradeable emission permits program established by Supreme Decree No. 4 (SD 4) in March 1992 to control total suspended particulate (TSP) emissions from stationary sources in Santiago, Chile.[3]

The analysis of the TSP-emissions-trading program offers several lessons for a broader design and implementation of environmental markets. Because sources were relatively small for the purpose of implementing sophisticated monitoring procedures,[4] the program was not designed on the basis of a source's actual emissions but on a proxy variable equal to the maximum emissions that a source could potentially emit in a given period of time. We refer to this variable as Emissions Capacity, which corresponds to the product of emissions concentration (in mg/m^3) and maximum flow rate (in m^3/hour) of the gas exiting the source's stack.[5] By using this simpler monitoring procedure, the monitoring task was reduced to the measurement of technology parameters only, such as the source's size and fuel type.[6]

We also find that grandfathering the permits, instead of auctioning them off, for example, has created economic incentives for incumbent sources

[1] See Thomas H. Tietenberg, Emissions Trading: An Exercise in Reforming Pollution Policy (1985); Robert W. Hahn, Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders, 3 J. Econ. Persp. 95 (1989); Vivian Foster & Robert W. Hahn, Designing More Efficient Markets: Lessons from Los Angeles Smog Control, 38 J. Law & Econ. 19 (1995); and Richard Schmalensee *et al*., An Interim Evaluation of Sulfur Dioxide Emissions Trading, 12 J. Econ Persp. 53 (1998).

[2] See World Bank, Five Years after Rio: Innovations in Environmental Policy (1997).

[3] Technically, SD 4 does not use the term "emissions permits" because that would require legislation that has not yet been approved by Congress. Instead, SD 4 uses the term "emissions offsets."

[4] It becomes economically unfeasible to require continuous monitoring equipment in sources that are relatively small compared, for example, with affected sources in the U.S. acid rain program. For more on this particular program, see A. Denny Ellerman *et al*., Markets for Clean Air: The U.S. Acid Rain Program (2000).

[5] We will use the terms "emissions capacity," "emissions," and "capacity" interchangeably throughout the rest of the paper. Note also that emissions concentration and emissions rate are the same concepts if we define flow rate as output.

[6] Note that this simple monitoring procedure should be very similar, if not the same, to one used under an emissions or technology standard approach.

(which some thought were nonexistent at the time SD 4 was promulgated) to more readily declare their emissions and claim the corresponding permits. We argue that this rent-seeking behavior has proved very effective in helping the authority complete its inventory of sources and emissions during the early stages of the program.[7] In this particular context of institutional limitations, it is hard to imagine that alternative regulatory instruments such as emissions standards or taxes would have induced a similar response among affected sources.

As one might expect in a context of partial institutional development, the TSP program has experienced enforcement problems. Its environmental objectives were not accomplished until 1997. Despite the fact that enforcement seems to be gradually improving over the years, the sharp decline in TSP emissions from industrial sources that began in 1997 and subsequently accelerated was mainly due to the arrival of low-price natural gas from Argentina, which has been displacing alternative (and dirtier) fuels such as coal and oil in all sectors of Chile's economy.[8]

These enforcement problems together with transaction costs and regulatory uncertainty have hindered the development of the TSP market. Observed prices and trading volume differ significantly from those predicted by a numerical model of a frictionless market. Some firms have tended to rely on autarkic compliance, paying less attention to the permits market. Nonetheless, many firms did take advantage of the market by buying permits instead of making irreversible investments that would have proved uneconomical ex post facto, that is, after the arrival of natural gas.

Under a traditional command-and-control regulatory approach, more sources would have made these irreversible (and ex post facto uneconomical) investments. Even if both types of regulations were equally costly ex ante, the permits regulation would be less costly ex post facto because it allows sources to more easily accommodate their compliance strategies to the new factor prices. Thus, our analysis of this particular market experience indicates that market-based policies can provide important advantages over traditional command-and-control policies even where there are limited institutional capabilities such as those that usually exist in LDCs.

[7] This is entirely consistent with the rent seeking observed during the initial allocation of (grandfathering) permits under the U.S. acid rain program, as documented by Paul L. Joskow & Richard Schmalensee, The Political Economy of Market-Based Environmental Policy: The U.S. Acid Rain Program, 41 J. Law & Econ. 37 (1998). The Environmental Protection Agency's open-market trading rules are also based on this rent-seeking behavior principle: firms that voluntarily declare their (baseline) emissions and emissions reductions can receive emissions credits that can be sold through the open market to regulated firms.

[8] In many ways, the effect of the arrival of natural gas at (unexpectedly) low prices on the TSP market resembles that of the unexpected expansion of cleaner, cheaper Powder River Basin coal on the SO_2 market of the U.S. acid rain program, as discussed in A. Denny Ellerman & Juan-Pablo Montero, The Declining Trend in Sulfur Dioxide Emissions: Implications for Allowance Prices, 36 J. Envtl. Econ. & Mgmt. 26 (1998).

This paper is organized as follows. Section II briefly describes Santiago's air pollution problem and outlines the basic regulatory elements of the TSP-emissions-trading program. Section III discusses the effect of the program on the evolution of emissions and emissions reductions from its implementation up to 1999. Section IV presents a numerical model of a frictionless TSP emissions market and compares its results to actual prices and trading activity. It then compares firms' actual compliance behavior with that under an alternative but hypothetical command-and-control regulation. Section V concludes with a discussion of overall market performance and policy implications.

II. Air Pollution in Santiago and the TSP-Emissions-Trading Program

The city of Santiago has constantly presented air pollution problems since the early 1980s. In fact, in June 1996 it was officially declared a saturated (or nonattainment) zone for four atmospheric pollutants: TSP, breathable particulate matter (PM10), carbon monoxide, and ozone. The declaration was based primarily on the fact that the daily air quality standards for these urban pollutants had been repeatedly exceeded at one or more air-quality-monitoring stations during the fall and winter seasons. While high concentrations of all four pollutants have adversely affected the health of people in Santiago, high concentrations of PM10 have caused the worst problems.[9]

The emissions-trading program created by SD 4 regulates TSP emissions from relatively large stationary sources (industrial boilers and ovens and large residential and commercial heaters), the emissions of which are discharged through a duct or stack at a maximum flow rate $\geq$1,000 m^3/hour.[10] Although it was signed in March 1992, compliance with the TSP program became mandatory in 1994. In principle, SD 4 provided the regulatory authority, PROCEFF,[11] with almost 2 years—from March 1992 to December 1993—to collect information on the characteristics of emissions sources and proceed with the allocation of permits.

As mentioned above, the emissions of each source are not measured directly. Rather, the emissions capacity is measured, which is the maximum amount of emissions that the source could potentially emit in a given period of time. Although the regulatory authority monitors each affected source's

[9] See Bart D. Ostro *et al*., Air Pollution and Mortality: Results from a Study of Santiago, Chile, 6 J. Exposure Analysis & Envtl. Epidemiology 97 (1996); and Bart D. Ostro *et al*., Air Pollution and Health Effects: A Study of Medical Visits among Children in Santiago, Chile, 107 Envtl. Health Persp. 69 (1999).

[10] Most of the TSP emissions of these sources are PM10 emissions. The measure of TSP under this particular program includes only direct particulate and excludes other pollutants such as sulfur dioxide and nitrogen oxide that could transform into secondary particulate.

[11] The Fixed Sources Emissions Control Program (PROCEFF) is the government office responsible for implementing and enforcing SD 4.

concentration and maximum flow once a year, emissions capacity is expressed in daily terms (kg TSP/day) to be compatible with the daily TSP air quality standards. Thus, a source that holds a permit has the right to emit a maximum of 1 kg of TSP per day indefinitely over the lifetime of the program.[12]

Sources registered and operating at the time SD 4 was promulgated are called existing sources and receive grandfathered emissions capacity permits equal to the product of an emissions concentration level of 56 mg/m^3 and its maximum flow rate at the time of registration in 1992.[13] New sources, on the other hand, receive no capacity permits and so must cover or "offset" all their emissions capacities by buying permits from existing sources. The amount of offset was phased in from 25 percent in 1994 to 100 percent in 1997 in increments of 25 percent annually. For new sources entering the program during or after 1998, 120 percent must be offset.[14] In addition, both existing and new sources (and other smaller stationary sources not regulated under the TSP program) must comply with an emissions concentration standard of 112 mg/m^3.

On the basis of the permits allocation procedure, it becomes clear that the TSP program does not impose an explicit cap on emissions (or emissions capacities) but rather an implicit cap equal to the sum of the capacity permits to be distributed. After measuring maximum flow rates and calculating capacity permits for each existing source, the total number of permits to be distributed was estimated to be 64 percent of the aggregate emissions capacity prior to the program.

After each annual inspection, the regulator proceeds to reconcile the estimated emissions capacity with the number of capacity permits held by each source.[15] An existing source can be either a seller or buyer of permits depending on whether its estimated emissions capacity is below or above its

[12] According to the 1997 atmospheric decontamination plan for Santiago, the program is expected to continue at least until 2011. For more, see CONAMA, Plan de Prevención y Descontaminación Atmosférica de la Región Metropolitana (1997).

[13] It is beyond the scope of this paper to estimate the efficiency implications of grandfathering the permits to existing sources instead of auctioning them off (or charging Pigouvian taxes, for that matter). One implication may be to retard the entrance of more efficient new sources. There are also implications from the presence of distortionary taxes (such as income tax). For a complete discussion on these issues, see Charles D. Kolstad, Environmental Economics (2000).

[14] Note that a 120 percent rule simply means that these new sources must hold 1.2 permits for each unit of emissions capacity.

[15] A source that fails to procur permits to cover its emissions capacity incurs serious penalties and a possible temporary shutdown. In practice, however, the regulatory agency has aimed its enforcement efforts to first assure compliance with the 112 mg/m^3 standard by both existing and new sources. In fact, during the first 3 years of compliance (1994–96), the regulator did not pay much attention to the trading activity and, consequently, to the reconciliation of permits and emissions capacity.

grandfathered permits.[16] Although permits are traded at a 1 : 1 ratio, all trades require approval by the regulatory agency, even a trade between two existing sources sharing common ownership.[17] It is important to note that although the caps on the emissions permits are expressed in daily terms, the monitoring frequency restricts sources to trade permits on either an annual or permanent basis.[18]

Finally, the TSP program interacts closely with Supreme Decree No. 32 of 1990, which controls emissions from stationary sources during declared states of "pre-emergency" and "emergency" episodes of bad air quality in Santiago.[19] Sources that are affected and nonaffected by the TSP program can be forced to shut down during an emergency (pre-emergency) episode if they are among those sources held responsible for 50 percent (30 percent) of the total mass emissions from stationary sources. Thus, one important reason for switching to cleaner fuels such as natural gas may be to be deleted from the list of most-polluting sources, which are subject to sudden interruption during bad air quality episodes. Because these episodes are not so rare,[20] exclusion from this list may be an important reason for switching to cleaner fuels.[21]

III. Evolution of Emissions

This section evaluates the effect of the TSP program on the evolution of emissions since program implementation. We first describe the process of data collection and explore evidence of rent-seeking behavior by incumbent sources. Then we analyze the emissions trend and attempt to disentangle the effect of enforcement and exogenous factors such as the arrival of natural gas on such a trend. In particular, we develop an econometric test to see whether the TSP program has had any effect on firms' decisions to switch

[16] An existing source that is shut down or retired can lose its permits if they are not traded within a period of 2 years. If that is the case, the aggregate capacity cap decreases because these unused permits are not redistributed among the remaining affected sources.

[17] PROCEFF goes through trade approvals mainly to assure a permit's validity and keep record of permits held by retired sources. This reduces the need for establishing any kind of liability rules.

[18] Because permits are given away in perpetuity, banking (and borrowing) of permits is virtually impossible. It would have been possible had permits been distributed on an annual basis (where each permit can be used to cover emissions in just one particular year), as in the U.S. acid rain program or in the Southern California RECLAIM program.

[19] A pre-emergency is declared when the air quality index for particulate matter (ICAP) reaches a level of 300 (equivalent to an ambient PM10 concentration of 240 $\mu g/m^3$). An emergency is declared when the ICAP reaches 500 (equivalent to 330 $\mu g/m^3$).

[20] During 1997, for example, 13 pre-emergency episodes occurred between May and September. No emergency episodes were registered during that time.

[21] Victor Turpaud of Metrogas, personal interview, October 1999. Note that as firms switch to cleaner fuels, the concentration cutoff point also falls because the mass percentage remains fixed. Today, the cutoff point for an emergency episode is 31 mg/m^3, which in practice means that only sources using natural gas and some others using fuel oil no. 2 are unaffected.

to natural gas. Finally, we discuss to what extent the TSP market has affected the evolution of emissions.

A. Data and Rent Seeking

A common problem faced by environmental regulators (and regulators in general) in LDCs is the limited institutional capabilities to implement and enforce any new policy. The TSP-emissions-trading program is no exception. As we collected and processed data to construct our sample for the analysis of the program, we found that the inventory of sources and emissions that PROCEFF had at the moment of implementation and distribution of permits was far from complete.

Our sample was prepared using PROCEFF databases for the years 1993–99.[22] 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. Each database includes information on the number of sources and their dates of registration, maximum flow rates, fuels, emissions concentrations, and days and hours of operation. A summary of the sample we constructed is in Table 1.

During the construction of our sample, we found clear evidence of inventory problems and rent-seeking behavior.[23] As shown in the first two rows of Table 1, the PROCEFF 1993 database included 563 existing sources and 32 new sources. Using the permits allocation rule, we estimated that the total permits to be allocated to the 563 existing sources would be 4,604.1 kg/day, as shown in the Permits row. According to later databases, however, there were 85 undefined sources that did not appear in the 1993 database but were in operation sometime during 1992–93, which gives a total of 680 affected sources by 1993.[24] Most of these undefined sources approached the regulator claiming permits.[25] After a case-by-case review that took several years, 72 of these sources received the status of existing sources and the remaining 13 sources received the status of new source either because of important expansions after 1992 or because they began operating after March 1992.

While grandfathering the permits prompts a rent-seeking behavior that allows the regulator to more readily identify sources that are not in the original inventory, it may also create incentives for false reporting, particularly when the authority has a poor historic record of sources and emissions. Besides

[22] Unfortunately, information for 1994 (the first year of compliance) was not available.

[23] Rent-seeking behavior occurs because a source that is not currently registered but eligible to receive permits may have incentives to report itself now and claim its permits rather than remain temporarily unregulated and wait for PROCEFF to register it later on, in which case it would not be entitled to any permits.

[24] The number of affected sources dropped over the years as many existing sources were shut down.

[25] Marta Zamudio of PROCEFF, personal communications, 1997–99.

TABLE 1

Summary Statistics for Affected Sources: 1993–99

Variable	1993	1995	1996	1997	1998	1999
Number of sources:						
Existing	563	551	504	430	365	365
New	32	101	117	136	193	208
Undefined	85	38	10	10	8	0
Total affected	680	690	631	576	566	573
Permits (kg/day)	4,604.1	4,604.1	4,604.1	4,087.5	4,087.5	4,087.5
Maximum flow rate (m^3/hour):						
Average	4,910.7	4,784.1	4,612.6	4,062.1	4,213.9	4,146.6
Standard deviation	15,058.8	14,908.0	15,490.9	9,498.6	13,091.0	11,793.5
Maximum	261,383.9	261,304.7	261,304.7	182,843.0	207,110.6	183,739.5
Minimum	499.2	204.3	204.3	493.3	216.9	165.6
Concentration (mg/m^3):						
Average	94.9	83.1	78.5	54.7	31.1	27.8
Standard deviation	88.1	77.8	76.8	43.0	21.1	18.5
Maximum	702.0	698.2	674.0	330.7	110.0	108.2
Minimum	1.5	1.5	3.4	3.6	2.9	4.6
Number > 112	106	87	83	29	0	0
Number using NG	0	0	0	1	144	178
Aggregate emissions (kg/day):						
Actual	7,442.5	6,500.2	5,195.1	3,535.0	1,953.6	1,636.6
Corrected[a]	7,051.9	6,320.9	5,094.4	3,535.0	1,975.3	1,665.0
Counterfactual	6,158.6	5,954.5	5,062.4	4,203.1	3,258.4	2,830.6

Source.—Elaborated by the authors from PROCEFF databases.
[a] Actual emissions are corrected by the offsetting requirements of new sources.

the 72 undefined sources that later became existing sources and received their permits, only 415 of the 563 existing sources that should have received permits according to the 1993 database were found eligible to receive permits, which reduces the total number of permits actually allocated to 4,087.5 kg/day. The remaining sources were found to be doubly registered, shut down before March 1992, or incorrectly entered by PROCEFF.[26] While some false initial reporting is inevitable when firms are provided with incentives to report their existing and historic emissions, the regulator is still better off collecting some information from these sources, which will improve with subsequent revisions and inspections, than having no information at all.

B. *Declining Emissions*

To meet the aggregate goals of SD 4, sources can reduce their emissions by decreasing either their maximum flow rate or their emissions concentration, 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

[26] *Id*.

technology such as filters, electrostatic precipitators, cyclones, and scrubbers. Aggregate emissions change as the sizes and concentrations of sources evolve over time. Table 1 indicates that source size, as measured by flow rate, varies widely across sources (as suggested by the large standard deviations) but has remained, on average, relatively stable over the last 3 years of the program.[27] It may seem strange to observe some flow rates below the 1,000 m^3/hour mark. In general, these are existing sources, the flow rates of which were estimated to be above 1,000 m^3/hour by March 1992 but later were corrected; nevertheless, the owners of these sources chose to remain in the program to keep the permits they had already received.[28]

Table 1 also indicates that the emissions concentrations of affected sources likewise varied widely across sources before and after the program became effective. This compliance heterogeneity confirms that, contrary to what occurs under command-and-control regulation, for which all firms must either install the same abatement technology or comply with the same concentration level, emissions-trading regulation provides enough flexibility for sources to comply in very different ways. Concentration figures also show that while most affected sources have been in compliance with the (daily) standard of 112 mg/m^3 even before the program became effective, many others were above the standard until 1997 (see the row labeled "Number > 112" in Table 1). This clearly evidences the enforcement problems that were experienced during the first years of the program.

Adoption of cleaner fuels has led to an important and continuous decrease in emissions concentrations, particularly after the introduction of natural gas at the end of 1997, as indicated by the number of sources adopting natural gas (see the row labeled "Number using NG" in Table 1).[29] Imported from Argentina, natural gas has become available at such low prices that by July 1999, 178 of the 573 affected sources had adopted it. This emissions concentration decline has resulted in a sharp decline in aggregate emissions capacities after 1997. As indicated in Table 1, actual emissions have been more than halved since 1997.[30]

[27] Note that a large part of the fall of the total flow rate in 1997 is due to the correction in the number of affected sources. Since then, aggregate flow rate has slightly increased from 2,339,767 (m^3/hour) in 1997 to 2,375,989 (m^3/hour) in 1999.

[28] An existing source whose flow rate falls below the 1,000 m^3/hour mark by some noticeable amount (about 10 percent) can return all its permits and exit the program (but still remain subject to the 112 mg/m^3 standard that affects smaller sources as well), but if the flow rate increases in the future it must return to the program as a new source.

[29] The average concentration of sources switching to natural gas is around 20 mg/m^3.

[30] It is worth explaining that the arrival of natural gas was not totally unexpected, as indicated by an official agreement signed by the governments of Argentina and Chile back in 1991. The exact arrival date and delivered prices were more uncertain, however, which should provide further reasons for firms not to commit to irreversible abatement investments before the uncertainty was resolved. For details on the agreement, see Comisión Nacional de Energía, El Sector Energía en Chile (1993).

To see whether affected sources are, on aggregate, complying with the emissions limits imposed by SD 4, we need to correct actual emissions by the offsetting requirement for new sources, which varied from 25 percent in 1994 to 120 percent in 1998 and thereafter.[31] The lack of effective enforcement during the first years of the program becomes again evident as corrected (actual) emissions were above the total number of permits being allocated. However, by 1997, the declining trend in emissions concentrations led emissions capacities to fall below the aggregate limits imposed by the program.[32]

While it is not possible to discard higher enforcement efforts, we argue that the environmental goals of SD 4 have been accomplished by reasons exogenous to the trading program. On the one hand, we observe an important increase in the number of pre-emergency and emergency episodes from less than 5 per year during 1993–96 to 13 in 1997, which have created further incentives for affected and nonaffected sources to switch to cleaner fuels. On the other hand, the cost analyses of consultants and firms indicate that most, if not all, switches to natural gas have been made for economic reasons, independent of the TSP program.[33] In the next section, we econometrically test such claims.

C. The Decision to Switch to Natural Gas

To test more formally whether the TSP program has had any effect on the decision to adopt or switch to natural gas, we develop a simple discrete choice econometric model and compare the likelihood of switching between affected and nonaffected sources. The latter are smaller stationary sources with a maximum flow rate lower than 1,000 m^3/hour that are not affected by the TSP program but that still must comply with the 112 mg/m^3 standard and the pre-emergency and emergency episodes. As shown in Table 2, nonaffected sources also reduced their emissions concentrations during and after 1997, possibly as a response to more frequent preemergency and emergency episodes and the availability of natural gas.

The dependent variable in our logit model, NATGAS, is the source owner's decision to switch to natural gas by 1999. We do not observe the net benefits of switching, only whether the decision is made or not. Therefore, the ob-

[31] For example, corrected (actual) emissions in 1995 are equal to actual emissions from existing sources plus one-half of actual emissions from new sources. Further, corrected emissions in 1999 are equal to actual emissions from existing sources plus 1.2 times actual emissions from new sources.

[32] It is hard to attribute any decrease in emissions capacities to a downturn in the regional economy on the basis of the 8.4 percent average growth rate observed for the Santiago Metropolitan Region during 1992–97.

[33] Victor Turpaud of Metrogas, personal interview, October 1999.

TABLE 2

SUMMARY OF SELECTED VARIABLES FOR EACH SAMPLE

	Sample 1	Sample 2	Sample 3	Sample 4
NATGAS	155	180	213	247
INDUSTRIAL	642	684	695	747
ENDPIPE	23	28	25	30
OIL2	1,643	1,650	1,643	1,650
AFFECTED	379	427	437	492
Interactions:				
AFFECTED × NATGAS	96	121	127	161
AFFECTED × INDUSTRIAL	295	337	331	383
AFFECTED × ENDPIPE	11	16	12	17
AFFECTED × OIL2	239	246	239	246
N	2,050	2,098	2,318	2,376

servation is

$$\text{NATGAS} = \begin{cases} 1 & \text{if NATGAS*} > 0 \\ 0 & \text{if NATGAS*} \leq 0 \end{cases},$$

where NATGAS* is an index function that can be written as

$$\text{NATGAS*} = a_0 + \sum a_k x_k + u,$$

where x_k represents the k source's characteristics that affect the decision to switch to natural gas and u is an error term that is assumed to have a standard logistic distribution. The model predicts that a source will switch if the index function $a_0 + \sum a_k x_k + u$ is greater than zero or if $\Lambda(\text{NATGAS*}) > 0.5$, where $\Lambda(\cdot)$ is the logistic cumulative distribution function.

The k variables in the index function are chosen to capture the net benefits of switching. As indicated by some operators of affected and nonaffected sources, large industrial sources should be the sources that most benefit from switching because of technical and economies-of-scale considerations. Thus, we include the dummy INDUSTRIAL, which equals one for an industrial source, and the variable SIZE, which is equal to the maximum flow rate. Because the days and hours of operation vary significantly across sources,[34] we also include the variable UTILIZATION as the source's rate of utilization. We expect the three coefficients to be positive.

We should also expect that affected sources already equipped with end-of-pipe technologies or using relatively clean fuels such as fuel oil no. 2 are less likely to switch to natural gas, all else being equal. Hence, we include the dummy ENDPIPE, which equals one if the affected source has any type of end-of-pipe abatement technology installed by 1997, and the dummy OIL2

[34] Average and standard deviation values for affected sources' hours of operation in 1999 were 4,707 (54 percent of the time) and 2,831 hours, respectively. For nonaffected sources, these values were 2,719 and 2,168 hours, respectively.

TABLE 3

SUMMARY STATISTICS FOR NONAFFECTED SOURCES: 1993–99

Variable	1993	1997	1998	1999
Number of sources:				
Existing	1,617	1,602	1,587	1,514
New	0	259	376	482
Total	1,617	1,861	1,963	1,996
Maximum flow rate (m^3/hour):				
Average	478.9	462.7	394.4	395.2
Standard deviation	461.3	412.0	237.4	232.1
Maximum	6,654.0	5,318.6	1,220.0	1,065.6
Minimum	.0	.0	.0	.0
Concentration (mg/m^3):				
Average	39.4	37.1	35.3	33.2
Standard deviation	20.0	12.8	10.8	9.6
Maximum	469.9	189.3	107.8	89.8
Minimum	1.5	3.8	5.7	4.1
Number using NG	0	26	43	86
Aggregate emissions (kg/day)	789.5	809.5	646.4	621.6

SOURCE.—Elaborated by the authors from PROCEFF databases.
NOTE.—NG = natural gas.

if the affected source was burning fuel oil no. 2 by 1997. We expect both coefficients to be negative.

The effects of the TSP program on a source owner's decision is captured with the dummy AFFECTED, which equals one if the source is regulated under the program and zero otherwise. If the program has accelerated the adoption rate of natural gas by affected sources, the coefficient of AFFECTED should be positive.

Using PROCEFF's 1999 databases for both affected and nonaffected sources (as summarized in the last columns of Tables 1 and 3), we construct four different samples as follows.[35] To distinguish between (new and existing) sources that switched to natural gas from other fuels such as oil and coal from those new sources that began operation with natural gas, the first two samples include only sources operating by 1997, so these are sources that have the possibility to switch from their current fuel to natural gas. The third and fourth samples include all sources operating by 1999.[36] In addition, to have a more meaningful comparison between affected and nonaffected sources we did not consider extremely large sources. We use two thresholds—5,000 and 10,000 m^3/hour of flow rates—capturing 97 percent and 99 percent of the sources, respectively. Table 2 displays a summary of selected

[35] To control for the fact that by 1999 natural gas was still not available in some distant counties of Santiago's metropolitan area, we consider only sources located in counties where at least one source (either affected or nonaffected) has adopted natural gas.

[36] These two samples include 42 new sources that entered the program after 1997 with natural gas.

TABLE 4

MAXIMUM-LIKELIHOOD LOGIT ESTIMATES OF SWITCHING EQUATION

	Sample 1 (1)	Sample 2 (2)	Sample 3 (3)	Sample 4 (4)	Sample 4 (5)
SIZE	1.392**	.647**	1.260**	.640**	.828**
	(3.194)	(3.077)	(3.251)	(3.330)	(6.350)
$SIZE^2$	−.209*	−.054*	−.181*	−.054*	−.072**
	(2.558)	(2.312)	(2.500)	(2.524)	(4.288)
INDUSTRIAL	.867**	.978**	.751**	.837**	.899**
	(3.659)	(4.252)	(3.770)	(4.296)	(4.777)
UTILIZATION	2.008**	2.085**	1.947**	2.068**	2.082**
	(6.534)	(7.089)	(7.326)	(8.064)	(8.116)
ENDPIPE	−1.312	−2.357**	−1.749*	−2.693**	−2.730**
	(1.652)	(2.951)	(2.234)	(3.424)	(3.451)
OIL2	−1.106**	−1.048**	−1.387**	−1.347**	−1.353**
	(5.613)	(5.452)	(8.248)	(8.154)	(8.200)
AFFECTED	−.027	.342	.089	.403	
	(.066)	(1.001)	(.250)	(1.327)	
Constant	−4.052**	−3.870**	−3.638**	−3.496**	−3.543**
	(13.55)	(14.94)	(15.27)	(17.37)	(17.83)
Log likelihood	−403.5	−429.1	−516.4	−545.3	−546.2
% correctly classified	92.0	91.9	90.8	90.7	90.8

NOTE.—Asymptotic normal test statistics are in parentheses. The dependent variable is NATGAS.
* Statistically significant at the .05 level.
** Statistically significant at the .01 level.

variables for each of the four samples: (1) $0 < F_{97} \leq 5{,}000$, (2) $0 < F_{97} \leq 10{,}000$, (3) $0 < F_{99} \leq 5{,}000$, and (4) $0 < F_{99} \leq 10{,}000$, where F_{xx} is the maximum flow rate in year 19xx.

Table 4 presents the maximum-likelihood logit estimates for the different samples and specifications. Results indicate that most coefficients statistically differ from zero and have the expected signs. The coefficients of AFFECTED shown in the first four columns, however, indicate that the TSP program has virtually had no effect on an owner's decision to adopt natural gas, although the results in the fourth column (sample 4) show some positive, although not statistically different from zero, effect.[37] These latter results would predict that, on average, the program increased an affected source's probability of switching to natural gas from 25.5 percent to 31.6 percent.

D. Emissions Reductions by the TSP Program

In an effort to separate the effect of the TSP program on the observed emissions path from other factors, such as the introduction of natural gas, we develop a counterfactual emissions capacity path, that is, a hypothetical path that would have been observed in the absence of the program. To

[37] As shown in the last column of Table 4, if we omit AFFECTED, the value of the remaining coefficients barely changes.

construct such a counterfactual path, we first assume that each source complies with the concentration standard of 112 mg/m^3 but do not consider the effect of pre-emergency and emergency episodes on emissions. We further assume that the program does not affect a source's maximum flow rate[38] and that concentrations remain unchanged from their 1993 levels for sources that did not switch to natural gas.[39] For new sources entering in 1993, we use their own concentration for that year; for new sources entering after 1993, we use the average concentration for new sources entering in 1993.[40] For sources switching to natural gas, we take a conservative approach and use their observed emissions corrected by the econometric results of the fourth column of Table 4.[41]

Aggregate counterfactual emissions capacities for several years are presented at the bottom of Table 1. During the period 1993–96, either observed or corrected emissions capacities exceeded the counterfactual because of the assumption that all sources comply with the standard of 112 mg/m^3, which certainly has not been the case. In 1997, aggregate emissions capacities fell below the counterfactual, which suggests some influence of the program on the decline in emissions. However, aggregate emissions capacities were below even the total number of capacity permits, which seems to indicate instead some sort of market inefficiency.[42]

Conversely, if the market is working reasonably well, the low emissions capacity level observed would simply be an economic response to the emergency and natural gas factors, which are exogenous to the program. In this case, the difference between our counterfactual and actual emissions could

[38] We think this is a conservative assumption. As indicated by econometric tests (results not shown here for space considerations), the TSP program seems to have increased, rather than decreased, affected sources' maximum flow rates from 1993 to 1997 and from 1997 to 1999. In addition, the program does not seem to be affecting the entrance of new sources as we compare the evolution of new entries among affected and nonaffected sources.

[39] We use a concentration level of 112 mg/m^3 for all sources for which the concentration was above 112 in 1993. The average concentration then became 74.0 mg/m^3.

[40] An average concentration of 70.6 mg/m^3 was adopted for the 33 new sources in 1993 and the 13 undefined sources that after 1993 were classified as new sources.

[41] More precisely, we increase the counterfactual concentration of switching sources by the expected amount of concentration reduction prompted by the TSP program. The expected concentration reduction (CR) is calculated as follows: $\text{CR} = P_{\text{SNR}} \times C_S + (1 - P_{\text{SNR}}) \times C_{\text{NS}} - [P_{\text{SR}} \times C_S + (1 - P_{\text{SR}}) \times C_{\text{NS}}]$, where C_{S} is the concentration after switching to natural gas, C_{NS} is the counterfactual concentration when there is no switching, P_{SNR} is the probability of switching in the absence of regulation, and P_{SR} is the probability of switching when the source is regulated under the TSP program. These probabilities were predicted for each switching source using the logit estimates. Because the AFFECTED coefficient was not very significant, after the correction, aggregate counterfactual emissions capacities increased by only .9, 54.7, and 66.4 kg/day in 1997, 1998, and 1999, respectively.

[42] We do not need to find total emissions below the emissions cap to claim market inefficiency. We can have a trading system in which emissions are exactly equal to the cap and aggregate abatement costs are significantly above those expected under a well-functioning market. This could happen, for example, if each affected source decides to comply with its initial permits allocation without going to the market.

be attributable almost entirely to the emergency episodes. Because new sources do not receive any permits, we should still observe an emissions market with significant trading activity and reasonably low prices.

IV. The Market

In this section, we build a numerical model against which the actual performance of the TSP market (actual prices and trading activity) created under SD 4 is compared. We also develop a hypothetical command-and-control regulation to contrast firms' actual compliance behavior with that under an alternative and less flexible regulation.

A. A Numerical Model

We consider a frictionless market where new and existing affected sources trade permits until no further exchanges are mutually beneficial. Data on individual permits allocation and counterfactual emissions are those discussed in Section III. Data on individual marginal abatement costs were obtained by use of an engineering "bottom-up" approach based on information from domestic literature and in situ interviews with sources' operators and sellers of control equipment.[43,44]

To better understand the evolution of the program, we split our analysis into two parts. Since there is only one switch to natural gas in 1997, the first part of our analysis simulates a static "before NG" (before natural gas) market, using data from the 1997 database and assuming that natural gas was neither available nor expected to be available.[45] In the second part, we simulate a static "after NG" market, using data from the 1999 database.

Table 5 summarizes counterfactual emissions capacities, emissions capacity permits, and reduction requirements for both market simulations, followed by the frictionless market equilibrium results.[46] If we neglect expectations

[43] We gathered data for a subsample of 255 existing sources with an aggregate flow rate (F) equal to 64.1 percent of the aggregate F of 1,747,103 m^3/hour of all existing sources in 1997 and 47 new sources with an aggregate F equal to 54.9 percent of the aggregate F of 592,667 m^3/hour of all new sources in 1997. We then extrapolated from this for the whole sample according to F-values. Thus, the annual aggregate marginal cost curves for existing and new sources (in the relevant range) in 1997 are $360 + 1.05q$ and $23.73q$, respectively, where q is reduction in kg/day.

[44] Note that the effects of pre-emergency and emergency episodes on sources' marginal abatement costs are not included in this analysis. That would reduce both the counterfactual and equilibrium price.

[45] In reality, firms had some expectation about the arrival of natural gas (see *supra* note 30). Adding this uncertainty to the model would, on the one hand, make permits more attractive to avoid irreversible commitments but, on the other hand, reduce the present value of permits if counterfactual emissions are expected to decrease.

[46] The equilibrium price of permits (which give the right to emit 1 kg of TSP per day indefinitely during the program's life) were computed by assuming an infinite horizon and using an annual discount rate of 10 percent.

TABLE 5

NUMERICAL DATA AND RESULTS

Market	Counterfactual (kg/day)	Total Permits (kg/day)	Reduction (kg/day)	Equilibrium Price ($/kg/day)	Volume (kg/day)
Before NG	4,203.1	4,087.5	115.6	4,602	1,844.9
After NG	2,830.6	4,087.5	<0	0	1,112.3

NOTE.—NG = natural gas.

about the availability of natural gas, the before-NG market simulation indicates an equilibrium price of $4,602 and a large volume of trading (including inter- and intrafirm trades)[47] above 1,800 kg/day, which indicates that 45 percent of the total numbers of permits distributed must change hands from one source to another.[48] With the price-based adoption of natural gas, the after-NG market simulation yields an equilibrium price of zero (because there are no reduction requirements at the aggregate level) accompanied by a still-high volume of trading close to 30 percent of total permits. Even if the price falls to zero, 333 sources (including 208 new ones) must cover their (counterfactual) emissions with permits.

B. Actual Prices and Trading Activity

In this section, we examine whether actual prices and transaction volumes depart in any important way from those predicted by the above theoretical results. Tables 6 and 7 present information on actual prices and trading volumes, respectively, that we collected from various data sources.[49] Actual prices from December 1996–97 are three to four times higher than those predicted by the before-NG market simulation, and the actual trading volume is only 9 percent of the total trading activity predicted by the numerical model when we consider only the approved transactions among affected sources (159.7 kg/day) and 18 percent when we add transactions under review (337.1 kg/day).

The introduction of natural gas has had an important effect on actual prices, but these are still too high if counterfactual emissions are below the aggregate

[47] A firm can own more than one source, so intrafirm trading refers to permits exchange between sources of the same firm.

[48] Because we do not have detailed cost data for all affected sources, the trading volume figures presented in Table 5 are lower bounds. They are equal to the volume of trading for an equilibrium price of zero, that is, for an aggregate reduction equal to zero or "negative." When the reduction required is positive and relatively small, as in the first row, the volume of trading is a bit higher because according to the aggregate marginal cost curves for existing and new sources, the sources making most reductions would be the existing sources, which are also the ones selling permits.

[49] Note that the trading activity reported in Table 6 corresponds to interfirm trading and purchases/sales by brokerage houses; otherwise, there would be no reported price.

TABLE 6

PERMIT PRICES

	Price (1998 U.S.$)	Volume (kg/day)
December 1996	16,558	NA
December 1996	17,031	NA
December 1996	14,193	.9
April 1997[a]	11,158	NA
September 1997	12,274	1.2
March 1998	5,895	2
March 1998	11,579	1
June 1998	6,316	NA
June 1998	6,316	3.65
July 1998	8,421	7.3
August 1998	3,158	14.6

SOURCE.—Elaborated from information provided by Ambar (Alejandro Cofré), El Mercurio, Gestión Ambiental, Metrogas, PROCEFF, and SESMA.
NOTE.—NA: not applicable.
[a] This corresponds to a permits rental of 1 year at a price of $1,419 that we converted to a permanent permit transaction using a 10 percent real discount rate.

emissions limit, as shown in the after-NG market simulation.[50] These numbers provide a strong indication that the market has not fully developed, in the sense that some sources are not participating in the market and instead rely on autarkic compliance via some combination of abatement options and intrafirm trading.

In fact, using partial information on sources' ownership from PROCEFF databases, we found that around 80 percent of the trading activity reported in the numerical simulations of Table 5 would correspond to interfirm trading. This is in sharp contrast, however, with the little interfirm trading activity reported in Table 7 (less than 10 percent of the total volume). We leave a discussion of the possible reasons for this limited market participation for the final section of the paper.

C. An Alternative Regulatory Approach

It is important to understand that a permits market that does not fully develop can still provide firms with some flexibility to better adapt to market events than to alternative regulatory regimes. Here we ask about the effect that an alternative, less flexible regulatory approach such as emissions or technology standards would have had on a source's compliance decision, particularly under the changing market conditions of the TSP program.

To provide a fair comparison between the TSP program and an alternative

[50] According to an online broker at http://www.sustentable.cl, there have been no interfirm trades reported after those of Table 6 and only a few permit offers at prices varying from $3,700 to $4,600.

TABLE 7

Trading Activity Recorded by PROCEFF by July 1999

Type of Transaction	Number of Sources	Kilograms per Day
Approved transactions:		
Intrafirm	30	156.7
Interfirm	2	3.0
Total	32	159.7
Transactions under review:		
Intrafirm	22	87.5
Interfirm	5	17.0
Total	27	104.5
Other transactions approved[a]	10	72.9

Source.—Elaborated from data provided by PROCEFF.
[a] These are valid permits held by broker houses.

regulatory approach, we arbitrarily construct an emissions concentration standards regulation for 1997 that would yield an aggregate emissions capacity similar to the permits cap under the TSP program. We use 1997 because it best illustrates the compliance behavior of sources prior to the arrival of natural gas. As is typical in the design of command-and-control regulations, new sources face a stricter concentration standard (28 mg/m^3) than existing sources (88 mg/m^3).[51] If sources just comply with these standards at their flow rate of 1997, aggregate emissions capacity reaches 4,088.2 kg/day, virtually equal to the 1997 cap of the TSP program.[52]

Actual compliance data show that the average concentration of the 146 new sources entering the TSP program in 1997 was 45.30 mg/m^3, with a large standard deviation of 39.28 mg/m^3, which reveals significant compliance heterogeneity. Among these new sources, 86 sources had concentration rates above our new sources' hypothetical standard of 28 mg/m^3. Two years later and after the arrival of natural gas, 45 of these 86 sources had reduced their concentration rates below 28 mg/m^3 (most of them by switching to natural gas).

While it is very likely that some of the 60 new sources that entered the program with concentration rates below 28 mg/m^3 did not take full advantage of the permits market (considering only a combination of intrafirm trading and abatement technologies), it is most likely that under the hypothetical command-and-control regime, some of the remaining 86 new sources would have made irreversible abatement investments (for example, installing end-

[51] We arbitrarily chose 28 mg/m^3 because it is the average rate of all sources in 1999. Similar results would follow with either higher or lower numbers. Note also that the 28 mg/m^3 standard is technically feasible since by 1997 the concentration rate of 174 of the 576 affected sources was below that number.

[52] For simplicity, we can assume that the choice of flow rate is not affected by either type of regulation.

of-pipe technologies) to comply with the 28 mg/m^3 standard, investments that after the arrival of natural gas would have become unnecessary.

V. Discussion of Results and Policy Implications

Our results suggest that the market created under SD 4 has not fully developed. We argue that the main reason behind such an outcome is a combination of regulatory uncertainty, significant transaction costs, and incomplete enforcement. At the time the program was promulgated in March 1992, there were virtually no institutional capabilities to regulate stationary sources. Before permits could be allocated, it was necessary to develop a comprehensive inventory of sources and their historic emissions. In part because of limited resources, the completion of the inventory and the final allocation of permits ended up being an uncertain process lasting more than 5 years.

By concentrating all its regulatory activity on the quantification of sources and emissions (and on compliance with a concentration standard), the regulator, PROCEFF, did not track down trading activity during these years, so there was virtually no reconciliation of permits and emissions. As the market began to take off at the end of 1996, market participants faced significant transaction costs and lengthy, uncertain approval processes. Table 7 provides two pieces of evidence: the volume of intrafirm trading is much larger than the volume of interfirm trading, and a large number of transactions are still under review.

As the program moved forward, PROCEFF came to realize that its initial allocation of permits was too generous. In an effort to reverse this situation, new sources registered during and after 1998 were required to offset 120 percent of their emissions and new provisions are being added to the decontamination plan of Santiago, which will reduce the number of existing permits in a way yet to be defined. All this regulatory uncertainty has been increased by recently expressed intentions on the part of the regulator to study the possibility of increasing offset requirements for new sources beyond 150 percent, which has probably induced firms to hold many more permits than are currently needed.

A quite obvious recommendation to improve market performance in this particular permits program and more generally in any existing or future program is to look for ways to reduce regulatory uncertainty and transaction costs and improve enforcement.[53] Unfortunately, implementing such a rec-

[53] It is worth indicating that high transaction costs and uncertain approval processes are not unique to the TSP program. They have also been present in U.S. emissions markets as discussed in Hahn, *supra* note 1; Foster & Hahn, *supra* note 1; Robert N. Stavins, Transaction Costs and Tradeable Permits, 29 J. Envtl. Econ. 133 (1995); and Juan-Pablo Montero, Marketable Pollution Permits with Uncertainty and Transaction Costs, 20 Resource & Energy Econ. 27 (1998).

ommendation is in most cases beyond the capabilities of the authority in charge of the permits program because of limited resources, time constraints, or political constraints.

There are recommendations on instrument design, however, that can be more readily implemented by the program regulator. In particular, we argue that annual auctions and the use of a more liquid currency can help the market to take off and develop. Annual auctions of a small portion of the total number of permits help to start up a market by sending important price signals and, if necessary, giving new sources access to permits.[54] Although TSP emissions capacities are monitored annually, Table 6 shows that sources in the TSP-emissions-trading program are trading permits on a permanent rather than annual basis,[55] significantly reducing the liquidity of the market. The regulator should avoid defining permits on a perpetual basis and instead define them on an annual (or other time frame) basis, as has been done in permits markets in the United States.[56] In the case of the TSP program, annual permits, for example, would not compromise the environmental goals of SD 4 or impose any extra monitoring and inspection burden on the regulator.

Even if the market does not fully develop, it still can provide important advantages over traditional command-and-control regulations such as speeding up the completion of the inventory of sources and emissions and providing affected firms more flexibility to comply in different ways and to better adapt to new market conditions. Because the TSP program is an example of a market-based environmental policy for which a preexisting regulatory framework was not in place, our analysis of this particular market experience suggests that market-based policies can, and should, be introduced from the start in the regulatory agendas of those countries beginning to pass environmental legislation.

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[54] The first auction in the U.S. acid rain program provides good lessons on the importance of price signals. See Ellerman *et al*., *supra* note 4, for a discussion.

[55] The only exception is the April 1997 transaction in Table 6 that corresponds to a 1-year permits rental instead of a permits sale.

[56] This also gives the regulator more flexibility to design nonuniform emissions caps over time and to introduce borrowing and banking provisions.

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