JOURNAL OF ENVIRONMENTAL ECONOMICS AND MANAGEMENT **31,** 302–313 (1996)
ARTICLE NO. 0046

Cost-Effective Policies to Improve Urban Air Quality in Santiago, Chile

RAÚL E. O'RYAN*

Center for Applied Economics, Industrial Engineering Department, Universidad de Chile, Santiago, Chile

Received August 30, 1994; revised February 23, 1995

This paper examines the applicability of market-based incentives for controlling emissions of particulate matter from fixed sources, in a developing-country context. It uses Santiago, Chile as a case study. A linear programming model has been developed to establish the costs of achieving different air quality targets using marketable permits and command-and-control (CAC) policies. The main conclusion is that an ambient permit system (APS) substantially reduces compliance costs of achieving a given air quality target at each receptor location in the city. Consequently, the use of permits is warranted. However, spatial differentiation of permits is required, thus complicating the design and use of such an instrument. Moreover, the reduction in compliance costs under APS is significantly less when the air quality targets imposed for each receptor location are the same as those achieved by other CAC policies.

I. INTRODUCTION

The city of Santiago, Chile, like many large cities in developing countries, suffers critical air pollution problems. In particular, in winter the concentrations of total suspended particulates (TSP) and smaller PM-10 particulates constantly exceed the established ambient standards. Significant adverse health effects on the city's 4.8 million inhabitants, associated with the high levels of pollution by TSP, have been established [8, 23].

The city's policymakers are currently struggling to improve air quality, and they face the problem of defining the appropriate policies for the different sources responsible for TSP emissions. There are numerous studies based on simulation models for the United States, which establish the magnitude of the static efficiency gains made possible through the use of marketable permits for fixed sources [1, 5, 11, 12, 16, 17, 18, 20]. Unfortunately, no such studies are available for a developing-country context.

This paper evaluates the use of market-based incentives (MBIs) and CAC policies to control TSP emissions from fixed point sources in Santiago.[1] Using a linear programming model, the total costs of achieving a desired air quality standard have been established for each policy. The first relevant question addressed is whether the efficiency gains of using MBIs are significant when compared to CACs. If not, given the well known weaknesses in monitoring and

*This paper was developed while doing research at the University of California, Berkeley. I am grateful to Michael Hanemann, Albert Fishlow, Wade Martin, and two anonymous reviewers for valuable comments.

[1] Point sources are sources that emit a gas flow greater than 1000 m^3N per hour, through a chimney.

0095-0696/96 $18.00

enforcement typical in developing countries, it may be more efficient to implement direct regulation policies with which policymakers are more familiar.

A second issue—related to the fact that TSP is one of the most localized pollutants and that it is very common in developing countries—is whether considering the spatial dimension is important for cost-effectiveness. If it is, and as a result spatially differentiated permits are required, both the design and the use of the system become complicated. These complications, together with inadequate institutional capacities, may reduce the effectiveness of this instrument in developing countries.

A third issue, addressed using the model, is to determine where the gains mainly come from when using MBIs: from cost reductions due to the equalization of marginal costs of abatement, or from lower required reductions at each receptor location under the optimal flexible policy. It has been argued that under a cost-effectiveness approach an ambient permit system allows higher emissions than under CAC policies, and that the resulting ‘‘overcontrol’’ of emissions associated with the use of CAC policies are assumed to produce zero benefits [20–22]. This obviously overstates the cost advantage of an APS policy. However the magnitude of this overstatement has generally not been evaluated, except crudely [20].

Section II presents the compliance costs of four policies for different reduction goals. Section III examines how the compliance cost ratios change when an APS policy is required to meet the same air quality at every receptor location that percentage emission reduction (PER) and concentration standards (STD) obtain. The final section presents the main conclusions.

II. COMPLIANCE COSTS OF IMPROVING AIR QUALITY UNDER DIFFERENT POLICIES

To examine the abatement costs of TSP emissions from fixed point sources in Santiago, the city was divided into a 34×34 km grid. The grid comprises 289 (2×2 km) cells which contain the relevant sources of the air pollution problem in Santiago, as well as most of the exposed population. In this area there is a total of 1441 fixed point sources belonging to 742 establishments. Total TSP emissions in the city reach 8.9 tons/day. Figure 1 presents emissions, measured in kilograms per day, from each cell in the grid. Clearly, polluting sources are clustered in a few specific zones. The cell with highest emissions is located in the northwestern part of the city and emits 660 kg/day, 7.4% of the total emitted in the city. Of the 289 cells of the grid, only eight are highly polluting, and the sixteen most polluting cells emit 63% of total emissions. These emissions spread out smoothly to the rest of the city. Figure 2 presents the corresponding concentration levels in each cell.

Industrial boilers are the main emission sources, corresponding to 69% of total emissions, while furnaces account for 15% of the total.[2] Heaters are also significant contributors (12%). Finally, a diverse array of industrial processes and bakeries account for 3 and 1%, respectively. Wood and coal are important fuels for industrial boilers and heaters and account for over 50% of total emissions in the city.

[2] Furnaces which could clearly be assigned to aluminum, bronze, and copper foundries have been included in the category ‘‘industrial processes.’’

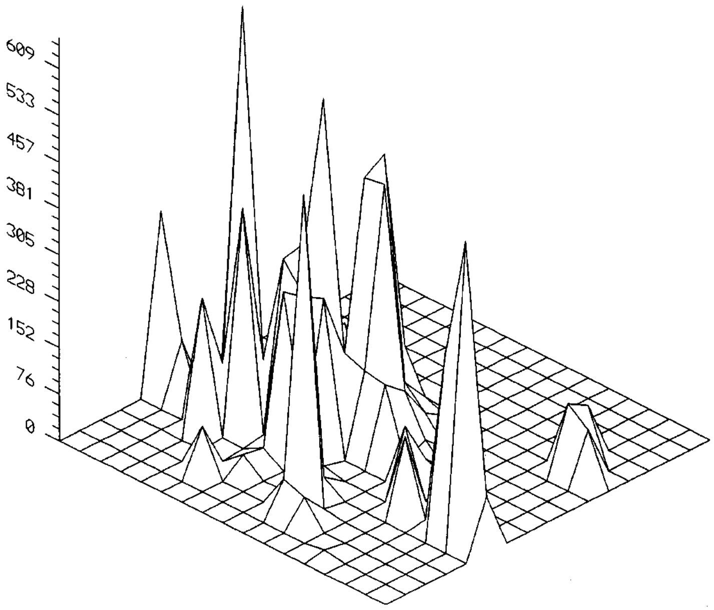

FIG. 1. Current emissions per cell (kg per day).

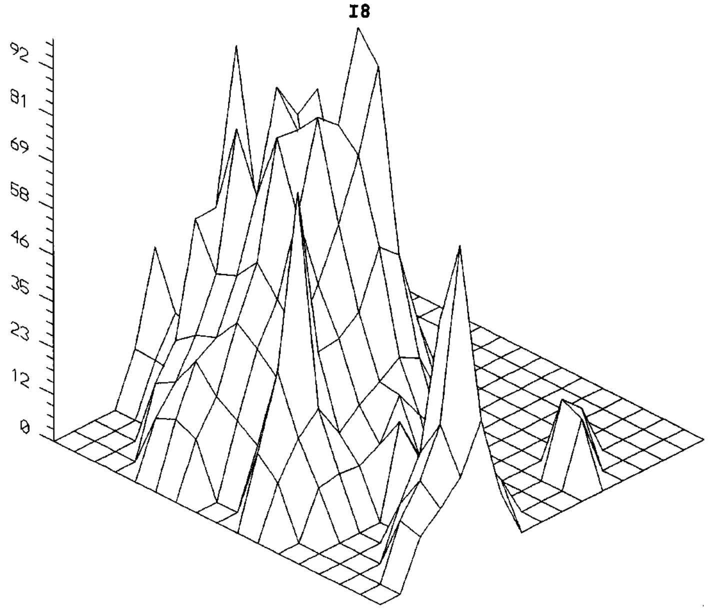

FIG. 2. Current concentration of particulates per cell (in percentage, I8 = 100).

The Problem

The regulator's problem is to obtain the desired air quality in each receptor location at a minimum cost. For the n (1441) polluting sources, K (289) zones in which emissions are generated, and the same number of receptor locations (say localized at the center of each zone), the problem to be solved is

$$\min \sum_{i=1}^{n} c^i(e^i) \tag{1}$$

subject to

$$Q = f(e^1, \ldots, e^n) \tag{2}$$

$$Q \leq Q^* \tag{3}$$

$$e^i \geq 0 \quad i = 1, \ldots, n, \tag{4}$$

where e^i is the emissions by source i after the policy is applied; $c^i(e^i)$ is the total abatement cost for source i from reducing to e^i; Q is a vector of ambient concentration standard at the K receptor locations; $f(e^1, \ldots, e^n)$ is a natural systems model relating emission levels by all sources to ambient concentrations at each receptor; and Q^* is a vector of desired ambient concentration levels.

To solve this problem, it is necessary to know both $c^i(e^i)$ and $f(e^1, \ldots, e^n)$, i.e., how abatement costs relate to different emission levels for each process, and the natural systems model relating the vector of concentrations at each of the K receptor locations to emissions from the n sources.

Abatement Costs and Transfer Coefficients

The costs of abatement for each source depends on the control alternatives that are applicable. Based on the literature [2, 21, 22] and expert opinions, two categories of abatement alternatives were identified for the main processes in Santiago: (i) collection devices such as cyclones, multicyclones, bag filters, and wet scrubbers, and (ii) for some sources, a change of fuel. To estimate the costs of collection devices, the net discounted cash flow of total capital investments and net annual operating costs incurred each year over the useful life of the equipment were estimated. To estimate the present value of switching to cleaner fuels, the cost of transformation and the cost differential associated with using a different fuel were estimated. Different sized control devices were costed. As a result, analytical cost relations were established for each control alternative. These costs depend on the size of the source (gas flow) and hours of operation. Each control alternative was also assigned an abatement efficiency.

The natural systems model can be substituted in this case by an environmental "transfer" coefficient, α_{ik}, relating changes in emissions by source i to changes in concentration at receptor k. To obtain these coefficients a simplified "cell" dispersion model, available for Santiago, was used. The wind fields had to be averaged over the day for this, and meteorological conditions had to be selected which reflected episode conditions. Twenty two episode days were used and the corresponding transfer coefficients averaged. As a result, the transfer coefficients obtained reflect the impact of a unit of emissions on concentration levels in each cell of the grid, for negative meteorological conditions. The results, which were surprising because it was previously thought that the main impacts were in a different direction, are presented in Appendix 1.

The Policies Evaluated

With information on emissions, location of each source, costs of abatement for each individual source, and the transfer coefficients, the overall costs of two MBI policies and two CAC policies were evaluated. The policies considered for this exercise were:

(i) The optimal spatially differentiated ambient permit system (APS). Under this policy permits, defined in units of concentration at each receptor, are distributed so as to achieve the desired air quality goal at each receptor.
(ii) A marketable emission permit system (EPS). Under EPS, total allowable emissions from fixed sources in the airshed are established. Permits, equivalent to these emissions, are distributed to polluters, who can then buy and sell the permits from any part of the city on a one-to-one basis.
(iii) An equal percentage emission reduction for all sources (PER). All point sources in the region are required to reduce emissions by an equal percentage of current daily emissions.
(iv) A uniform concentration standard for all sources (STD). All point sources are required to emit at concentrations lower than a single concentration standard.

To compare the costs of different policies, the most widely used criterion are the compliance costs, under each policy, of meeting a uniform concentration standard at all receptor locations in the city (each cell of the grid in this case). Any policy must at least reach this standard everywhere. This is the success criterion used in this section. Allowed concentrations ranging from as low as 5% of current concentration in the cell with highest concentration (I8) to as high as 95% were evaluated.

Compliance Costs under Different Policies

The reductions in allowed concentrations at the worst receptor location(s), under each of the four policies, resulting from different expenditure levels by fixed sources in Santiago are presented in Fig. 3. A first conclusion from this figure is that for low values of required abatement there is a win–win situation: some sources can reduce emissions and obtain net benefits while doing so![3] A fully operating APS policy would take full advantage of this win–win situation, obtaining net benefits from reductions of up to 50% of current concentration levels. The explanation for this is that at current prices, sources using wood (and in some cases coal) in combustion processes can switch to petroleum-6 (and 5 in some cases) and produce the same amount of energy at a lower cost. This lower operating cost (discounted over 20 years) covers the required transformation cost, and the source actually obtains net benefits.

From the policymaker's perspective, APS is clearly better than all other policies. With a total expenditure of only U.S. $20 million, a perfectly functioning APS

[3] This is not surprising if sources are assumed to be operating inefficiently, i.e., with inadequate operating and/or maintenance practices. However this has been ruled out.

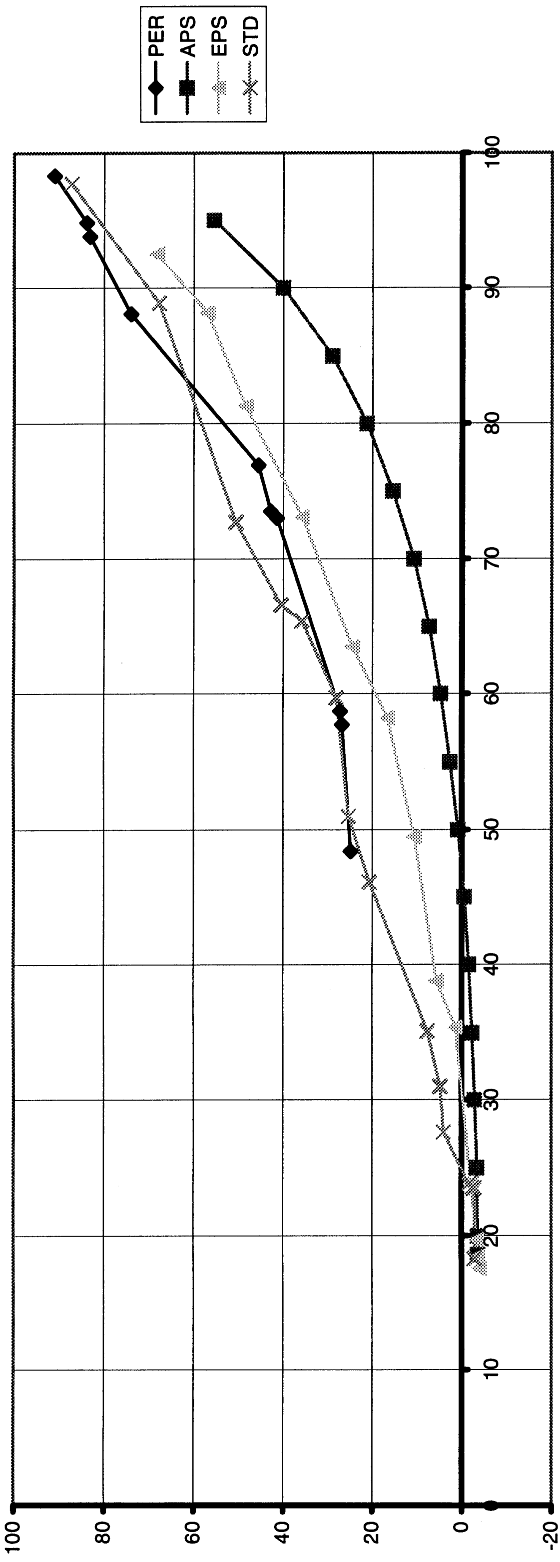

FIG. 3. Total abatement costs (U.S. $ Millions) vs percentage reduction for fixed point sources in Santiago under different policies.

policy could obtain a reduction of almost 80% in allowed concentrations at the worst receptor. With the same expenditure EPS would reduce 60%, and PER and STD would only reduce 46% of concentrations. If the regulator is willing to accept expenditures of up to U.S. $60 million, then APS reduces allowed concentrations by almost 95%, and PER and STD by 83%. These are substantial differences which could imply important cost reductions in emission control for individual sources.

However, from the figure it can be seen that when required reductions are small —below 35%—the absolute difference between compliance costs is small; i.e., all policies perform similarly. This results from the fact that required expenditures will also be small, since sources can install simple and cheap abatement alternatives, such as cyclones.

A spatially undifferentiated EPS policy performs substantially worse than APS. EPS requires overcontrol from sources that are not close to binding receptor locations, making it more costly than APS. However, it performs better than both PER and STD, in particular for expenditures between U.S. $1 million and U.S. $20 million. For expenditure levels between U.S. $30 million and U.S. $50 million, EPS and PER perform similarly. In this latter case, in view of the difficulties of setting up a market for permits, the regulator could choose to implement a CAC policy if the optimal APS is not feasible. PER and STD policies perform similarly for most expenditure levels.

Finally, as expected, as required reductions increase, the relative advantage of an APS policy decreases. For a 60% reduction in concentrations, APS is almost six times less costly than PER or STD and four times more efficient than EPS. For a required reduction of 90%, the cost ratio falls to 1.9 for PER, 1.7 for STD, and 1.5 for EPS.

III. COMPLIANCE COSTS WHEN SIMILAR CONCENTRATIONS ARE IMPOSED

What explains the lower compliance costs of the APS policy, when compared to suboptimal policies? It is the result of two components [22]. First is the "equal-marginal-cost component," which relates to the size of the cost difference due to the equalization of marginal control costs which occurs under APS and EPS.[4] As a result, sources with low abatement costs are allowed to trade emissions with high cost sources under both policies, generating a cost advantage with respect to STD and PER. The second component is the "degree-of-required-control component." It is derived from the fact that under APS the degree of required emission reductions are lower than under any of the other policies. As a result, under APS the allowed concentration limits in the most highly polluted cells are met exactly, while cells with low original concentrations do not reduce substantially. Cost gains relative to other policies are obtained in this case at the expense of worse air quality. This component makes APS more efficient than EPS and reinforces the advantages obtained by the first component over STD and PER.

Figure 4 presents air quality at each receptor location when a reduction of (approximately) 75% is required. It is clear that while APS results in meeting the

[4]Strictly speaking, in the absence of marginal costs, the model equates as closely as possible the average costs of reduction of each technology, for each process in the same zone.

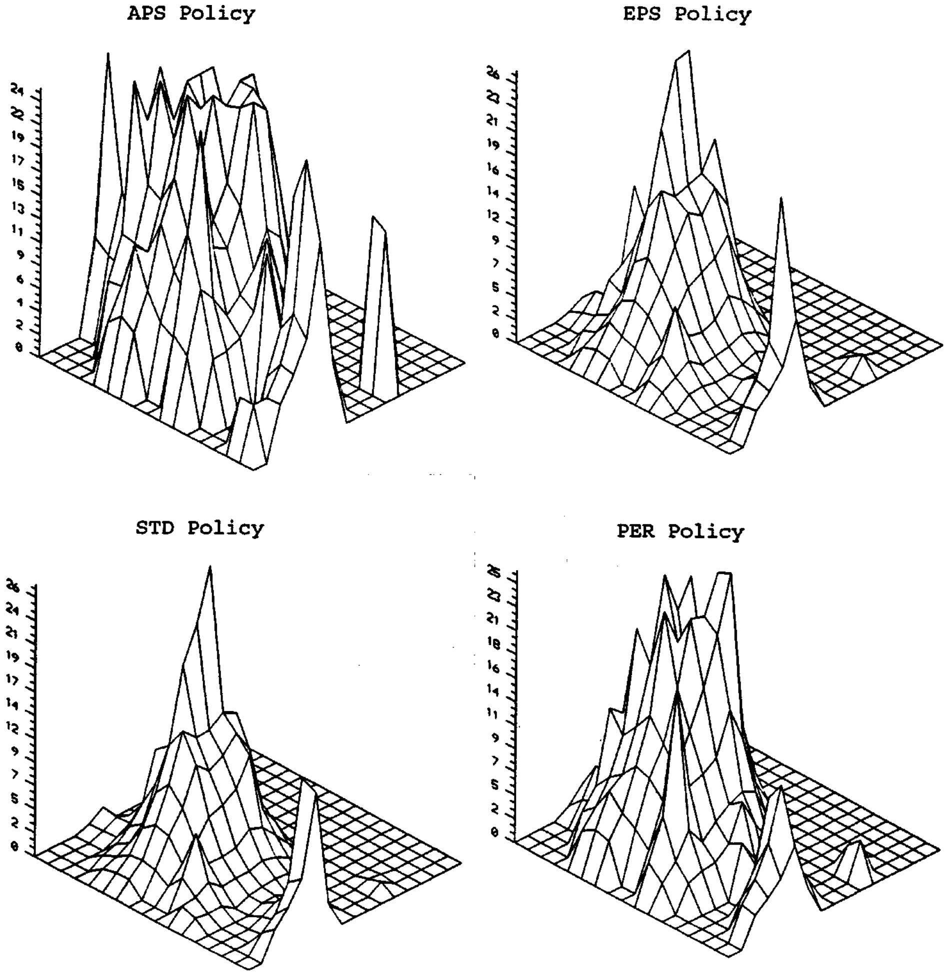

FIG. 4. Air quality at each receptor location for a 75% reduction requirement under APS, EPS, STD, and PER policies (percentage of original air quality in I8).

required restriction almost exactly in many receptor locations, all other policies imply significantly higher improvements in air quality, especially the STD policy.

To make policies comparable in terms of concentrations achieved at each receptor (not only the worst ones as in the previous case), the same concentrations achieved under the CAC policies have been used as goals for APS. This eliminates the second component as a source of cost advantage for APS and is thus a test of how important the equal-marginal-cost component is. Tables 1 and 2 present the resulting cost ratios for selected reductions.[5]

The results are extremely interesting: cost ratios fall significantly. For example, from Fig. 3 a 74% reduction in I8 would be four times more costly under PER than under APS in the original case. However, if corrections are made for air quality, the cost ratio falls to 1.31; i.e., PER is only 31% more expensive. Similarly, for a

[5] I am grateful to Professor Thomas Tietenberg for suggesting this exercise.

TABLE I
Cost Ratios for Selected Reductions Using Air Quality from PER Policy as Constraint for APS

Percentage reduction in cell I8	Costs under APS policy ($ Millions)	Costs under PER policy ($ Millions)	Cost ratio PER/APS
48%	10.6	24.8	2.34
74%	32.3	42.5	1.31
88%	56.5	73.9	1.30

TABLE II
Cost Ratios for Selected Reductions Using Air Quality from STD Policy as Constraint for APS

Percentage reduction in cell I8	Costs under APS policy ($ Millions)	Costs under STD policy ($ Millions)	Cost ratio STD/APS
28%	2.9	4.1	1.41
35%	5.9	7.7	1.32
60%	23.7	28.0	1.18
73%	43.8	50.6	1.15

73% reduction under STD, the cost ratio falls from 3.0 to 1.15. It follows that a substantial part of the cost advantage obtained from using APS is due to the degree-of-required-control component.

IV. CONCLUSIONS AND DISCUSSION

The results of this study confirm the cost-effectiveness of using flexible policies in Santiago, as opposed to uniform command and control policies. A fully operating ambient permit system would allow substantially higher reductions for the same expenditure to be achieved, in particular if reductions greater than 35% are required.

However, the permit system needed must consider the use of spatially differentiated permits; i.e., they should not be traded on a one-to-one basis. If a nondifferentiated EPS system is used, the full cost reduction is not obtained, due to the localized behavior of TSP. Moreover, EPS is not substantially more cost effective than CAC policies, even if all trades are consummated. If they are not consummated, EPS can turn out to be more expensive than CAC. This result is extremely interesting for policymakers in Santiago since the trading rule system that has been proposed does not consider the use of spatial differentiation. The above discussion suggests that this would either make the policy costly, if a specific air quality is desired, or that the target air quality would not be reached.

Significant cost reductions are not obtained under APS for all levels of allowed concentration reductions. For levels of required abatement of up to 35% the cost differential between APS and STD is less than U.S. $10 million. Given the difficulties associated with the implementation and operation of a marketable permit system, alternative policies may be used in this case. In particular, using an STD policy or simply banning the use of wood and coal in processes that can switch to other fuels are suitable alternatives, because most sources currently using these fuels would benefit from the switch.

Moreover, breaking the potential cost savings from using MBIs into its two components gives important insights as to the relative importance of each component. After correcting for differentials in air quality, an APS system is still significantly less costly than CAC policies, however not as much as is suggested when this correction is not made. This exercise allows one to avoid misleading exaggerations typical of the earlier literature in this field.

The final assessment of the use of marketable permits requires additional considerations. Transaction costs, in particular the search costs associated with the optimal APS policy, can be very high and may thus hamper achieving the cost-effective result. Moreover, it cannot be assumed that current sources will actually use the system actively once it is in place. Some important clues point against this possibility for Santiago. First, many sources currently using wood and coal as fuel could switch to fuel oil and obtain net benefits from doing so because of the fuel price differential. However, they have not switched. This suggests that the benefits of such actions are not a sufficient incentive to make these sources change their current (inefficient) behavior.[6] Second, for full cost-effectiveness most trades would have to be intra-firm due to the small size and number of sources per firm involved. This increases the transaction costs. Third, cost savings per source in Santiago will generally be in the tens of thousands, or at best, hundreds of thousands of dollars. Consequently, the incentives to trade will be low, and it can be expected that only large sources will actively engage in trading. Finally, judging by their current practices it would appear that entrepreneurs are not well informed for taking the most cost-effective actions.

In conclusion, a mix of policies including both banning wood and coal as boiler fuels, together with a simple trading procedure, would be an appropriate way to initiate a flexible system in Santiago. Even if few trades take place, this would be an improvement over the inflexible CAC. Moreover, the incorporation of new point sources would also be possible without damaging air quality. Both the regulator and the managers of sources would learn how to take advantage of a flexible system, on a step-by-step basis. This would strengthen the possibility of establishing an optimal permit system in the future.

Finally, the results obtained also inform the discussion on the goal-setting procedure for each source type: mobile sources, exhaust emissions from streets, fixed point sources, and household emissions. It is straightforward to obtain the cost per unit of emission-reduction by point sources, for each level of required reduction, and for each policy. These values can then be compared to the corresponding unit costs of reducing emissions by the other source types. As a result, reductions by each source type can be targeted on a more cost-effective basis.

[6] There may also be costs associated with stopping the source in order to make the corresponding improvements which have not been included in abatement costs. However, considering that most of these sources are boilers and heaters it is unlikely that stopping them for a short period would be too expensive for firms.

APPENDIX 1

Transfer Coefficients for Santiago during Episode Days
(% *referred to cell* = 100)

					6.16		
				5.39	12.71	5.93	
5.10	7.93	12.41	20.50	34.96	100.00	14.14	7.13
5.84	8.01	11.18	15.49	20.37	26.88	7.65	5.25
5.06	6.35	7.96	9.90	11.06	11.86	5.83	
		5.07	5.79	5.94	5.89		

Notes. (1) For an emission of 10 g/s for 12 hours for episode days in Santiago, in 1989. (2) 100% = 30.9 $\mu g/m^3$. (3) Only values greater than 5% have been included.

Level 100 (at the center) indicates that the maximum impact is on the cell where the emitter is located, and the other numbers represent the relative influence of this unit, over the day, on the surrounding cells. The results turned out to be surprising. The average influence of a unit emitted is stronger toward the southwest, whereas it was previously thought (based on yearly averages) that the major influence was toward the northeast.

REFERENCES

1. S. Atkinson and D. Lewis, A cost-effectiveness analysis of alternative air quality control strategies, *J. Environ. Econom. Management* **1** (3), 237–250 (1974).
2. B. Bretschneider and J. Kurfurst, Air pollution control technology, *in* "Fundamental Aspects of Pollution Control and Environmental Science: 8," Elsevier, Amsterdam (1987).
3. G. Eskeland and E. Jiménez, Policy instruments for pollution control in developing countries. *World Bank Res. Observer* **7** (2), 145–169 (1992).
4. R. Hahn, "A Primer on Environmental Policy Design, Fundamentals of Pure and Applied Economics." Harwood Academic, Reading, UK (1990).
5. R. Hahn and R. Noll, Designing a market for tradable emission permits, *in* "Reform of Environmental Regulation" (W. Magat, Ed.), Chap. 7, p. 119–146. Ballinger Pub. (1982).
6. R. Hahn and G. Hester, Where did all the markets go? An analysis of EPA's emission trading program, *Yale J. Reg.* **6** (1), 109–153 (1989a).
7. R. Hahn and G. Hester, Marketable permits: Lessons from theory and practice, *Ecology Law Quart.* **16** (36), 361–406 (1989b).
8. Intendencia Region Metropolitana, Estudio Epidemiológico sobre Efectos de la Contaminación Atmosférica, Final Report, Dec., 52 pp. (1989).
9. Intendencia Region Metropolitana, Sistema de Derechos de Emision de Contaminantes Atmosfericos, Final Report, Sept., 182 pp. + 4 annexes (1990).
10. A. Krupnick, Urban air pollution in developing countries: Problems and policies. Draft prepared for the World Institute for Development Economics Research Conference on The Environment and Emerging Development Issues (1990).
11. A. Krupnick, Costs of alternative policies for the control of nitrogen dioxide in Baltimore, *J. Environ. Econom. Management* **13**, 189–197 (1986).

12. A. McGartland and W. Oates, Marketable permits for the prevention of environmental degradation, *J. Environ. Econom. Management* **12**, 207–228 (1984).
13. A. McGartland, Marketable permit systems for air pollution control: An empirical study, Ph.D. dissertation, University of Maryland (1984).
14. W. Oates, P. Portney, and A. McGartland, The net benefits of incentive-based regulation: A case study of environmental standard setting, *Amer. Econom. Rev.* 1233–1242 (1989).
15. OECD (Organization for Economic Co-Operation and Development), ''The Application of Economic Instruments for Environmental Protection,'' Environment Committee, Paris (1989).
16. P. R. Portney, ''Public Policies for Environmental Protection,'' Resources for the Future, Washington, DC (1990).
17. E. Seskin, R. Anderson and R. Reid, An empirical analysis of economic strategies for controlling air pollution, *J. Environ. Econom. Management* **10**, 112–124 (1983).
18. W. Spofford and C. Paulsen, ''Efficiency Properties of Source Control Policies for Air Pollution Control: An Empirical Application to the Lower Delaware Valley,'' Resources for the Future Discussion Paper QE18-13, Washington, DC (1988).
19. T. Tietenberg, Market-based pollution control: What have we learned?, presented at the ''International Workshop on Solutions for the Problem of Air Pollution in Santiago, Chile, December 2–5, 1992'' (1992).
20. T. H. Tietenberg, ''Emissions Trading, an Exercise in Reforming Pollution Policy,'' Resources for the Future, Washington, DC (1985).
21. W. Vatavuk *et al.*, ''OAQPS (Office of Air Quality Planning and Standards) Control Cost Manual (Fourth Edition),'' Report No. EPA/450/3-90/006 (1990a).
22. W. Vatavuk *et al.*, ''Estimating Costs of Air Pollution Control,'' Lewis Publishers (1990b).
23. World Bank, ''Chile: Managing Environmental Problems: Economic Analysis of Selected Issues,'' Country Operations Division, Country Department IV, Latin America and the Caribbean Regional Office, Final Report (1994).