Comparison of Net Benefits of Incentive-Based and Command and Control Environmental Regulations: The Case of Santiago, Chile

Raúl O’Ryan and José Miguel Sánchez

The ambient permit system proposed in the literature for cost-effective pollution reduction is difficult to implement and may result in lower net benefits than using another instrument. The article develops a model for comparing the environmental net benefits of three policy instruments for Santiago, Chile, when the policy problem is to meet a given ambient quality standard. Two market-based instruments—the ambient permit system and a simpler emission permit system—are examined along with an emission standard, a command and control instrument usually favored by regulators. Both emission permit system and emission standard are costlier than the ambient permit system, sometimes in large part because they improve ambient emission concentrations beyond the required target in much of the city, but the ambient permit system requires a lower degree of control to comply with the standard. The somewhat costlier emission permit system and emission standard provide much higher net benefits than the ambient permit system when the health benefits of their “excessive” air quality improvements are taken into account. These benefits are different from the fact that an ambient permit system is administratively costlier to implement.

JEL code: Q25

Theory suggests that when a regulator wants to obtain a cost-effective (or minimum cost) solution for improving environmental quality in a given airshed or watershed, tradable permits or pollution taxes are the appropriate instrument. For the simple case of a uniformly distributed pollutant, the solution is a unique emission tax or an emission permit system that allows one-for-one emission trades among sources in different locations. This simplifies implementation, requiring only the total allocated emission permits that allow reaching...
the required air quality target. A unique price for each emission permit would result independent of the location of the emitting source.

However, when the pollutant is not uniformly distributed—as is the case for particulates and many other local pollutants—the optimal system requires that pollution permits be issued not for the amount of emissions at the source, as in an emission permit system, but for the deposition at each receptor point in the airshed, through an ambient permit system. The required overall air quality must be obtained when measured by depositions at each receptor point. As a result, different prices for each unit of concentration reduction emerge at each receptor location. The design and implementation of the instrument become quite complex, requiring multiple interactions among sources that are not based on one-for-one emission trades. To ease implementation, a simple—but not optimal—approximation is to define different trading zones within which sources can trade on a one-for-one basis. Any trading between zones, if allowed at all, must be based on transfer coefficients that consider how pollutants disperse. An example is the Regional Clean Air Management Program in Southern California (RECLAIM), which defines two different zones. Emission permits have been issued for each zone, but trading between these zones is not allowed.¹

Simulation studies for both developed and developing economies of the static efficiency gains from the use of incentive-based instruments, in particular of an ambient permit system, rather than of command and control instruments or an emission permit system, conclude that the cost reductions produced by an ambient permit system are significant in some cases and not very large in others (Atkinson and Lewis 1974; Hahn and Noll 1982; Seskin, Anderson, and Reid 1983; Krupnick 1986; McGartland and Oates 1985; Spofford and Paulsen 1988; Portney 1990; O’Ryan 1996).² An important caveat, however, is that ambient concentrations in many receptor locations are higher under the ambient permit system than under the emission permit system or command and control instruments, while still meeting the pollution reduction target. As a result, the magnitude of the cost reductions from an ambient permit system stems both from the efficiency gains related to equalizing the pollutant reduction marginal costs or cost per unit of pollutant concentration at the receptor location—a true efficiency gain—and from the lower degree of overall required pollution control (Tietenberg 1985).³

¹. This assumes that emissions from one zone do not affect the other zone, which is a simplification that allows implementing the system (www.aqmd.gov/reclaim).
². This ranking of instruments based on cost-effectiveness assumes no uncertainty of benefits and costs, perfectly monitored emissions, complete enforcement, and no asymmetric information. The magnitude of the efficiency gains depends on numerous factors, including dispersion characteristics of the pollutant, relative size and abatement costs of sources, and number of emitting sources (see Tietenberg 1985).
³. This result is true for a unique or dominant receptor location under the ambient permit system. Otherwise, with many receptors the marginal cost of emission reduction for each source is equal to the sum across all receptors of the shadow price of the pollutant concentration at each receptor times the impact of the source’s emissions on that receptor.
If no value is assigned to the higher overall level of pollution reduction achieved by the emission permit system and the command and control instruments, these instruments will be considered less desirable from a social perspective than the ambient permit system. The problem is that cost-effective approaches implicitly assign a shadow price of zero to improvements that exceed the target. If, “however, reduced concentrations below the level of the standards bring with them improvements in health or the environment, command and control instruments approaches will produce greater benefits than incentive based approaches” (Oates, Portney, and McGartland 1989, p. 1233). Consequently, comparison of instruments without correcting for these benefits is unfair and may be misleading. Two approaches can be used to overcome this problem. One is to eliminate the lower degree of required control component by requiring that all instruments comply with the same air quality standards in all receptor locations, as is done by O’Ryan (1996). The comparison in this case is still in a cost-effectiveness framework. A second approach is to determine the net benefits for each instrument, allowing for a more complete comparison using a cost–benefit analysis.

This article compares the net benefits of an ambient permit system, an emission permit system, and an emission standard, a command and control instrument, in Santiago, Chile, using cost–benefit analysis. Its contribution to the literature is to point out that regulatory schemes that are simpler to implement than the ambient permit system can also yield higher net benefits. Which pollution control system yields the highest net benefits is an empirical question. The authors are not aware of any of the study that answers this question in a developing economy, and there are few studies that address the question in developed economies. In a comparison of a uniform standard and an ambient permit system in Baltimore, Md, Oates, Portney, and McGartland (1989) conclude that the resulting net benefits of the uniform standard are only slightly lower (US$6 million).

In developing economies, where few pollution control efforts have been undertaken, abatement costs are usually not very high and the health benefits of improving air quality can be significant. As a result, the net benefits of improving air quality may favor the use of the emission permit system and command and control instruments. The health benefits of improved air quality under these instruments will outweigh their relative cost disadvantage compared with an ambient permit system. To examine this hypothesis, Santiago’s emission permit system, the Sistema de Compensaciones, is compared with an ambient permit system and an effluent concentration standard (a command and control instrument).

The next section presents an overview of the air pollution problem in Santiago. Section II addresses the compliance costs of reaching given air quality targets using market-based instruments and command and control instruments.

4. The additional benefits of reduced transaction costs from a simpler system are not evaluated in this analysis.
A linear programming model is used to establish the total costs of achieving a desired air quality standard for each instrument. The following sections present the population-based health benefits associated with each instrument, and then compare the net benefits of applying the ambient permit system and the two second-best policies. The last section presents the main policy conclusions and suggests future research lines.

I. Santiago’s Air Pollution Problem

Santiago, Chile, like many large cities in developing economies, suffers from severe air pollution. During winter, concentrations of particulate matter of ten micrometers in diameter (PM10) constantly exceed the established ambient standards. An extensive international epidemiologic literature reports illness and premature deaths due to exposure to airborne particulate matters. Studies have found that 5.2 million inhabitants were affected in the city because of these high levels of PM10 pollution. The city’s policy-makers have been struggling since the early 1990s to improve air quality, implementing Decontamination Plans in 1990 and 1997 (for details, see O’Ryan and Larraguibel 2000).

For particulate matter emissions from large stationary sources—industrial boilers and processes, and large residential and commercial heaters—a relatively stringent effluent concentration standard was established in 1992. To introduce flexibility, an emission permit system for particulates was introduced in March 1992, under which existing pollution sources can sell or buy permits, depending on whether their estimated emissions are below or above their grandfathered permits. The system does not consider emission banking. Permits are expressed in kilograms per day and are traded at a one-for-one ratio. All trades require approval by the regulatory agency. Annual compliance inspections reconcile emissions with the number of permits held by each source. A source that fails to cover its emissions with permits incurs heavy penalties, including the possibility of a temporary shutdown. While an emission permit system was known to be suboptimal from a cost-effectiveness perspective, a more complicated ambient permit system was rejected because the required models for implementing it were not available and trades were believed to be unnecessarily complicated. However, there was no explicit evaluation of this decision or of its impacts.

5. Ostro and others (1996) found a strong association between PM10 and daily mortality rates among Santiago residents after controlling for several potential other factors. Ostro and others (1999) found a statistically significant association between PM10 and medical visits for lower respiratory tract illness in children.


7. Ambient permit systems are difficult to implement because of information and model requirements. In particular, implementing such a system would require knowing the contribution to concentrations at different receptor locations of each of the sources included in the system. Additionally, the acceptability of the instrument by sources is negatively affected since two otherwise similar sources would face different trading rules simply because they are in different locations.
To examine the spatial configuration of emissions from fixed-point sources in Santiago, the city can be divided into a $34 \times 34$ kilometer grids of $289 (2 \times 2$ kilometers) cells that contain the relevant sources of air pollution in Santiago, as well as most of the exposed population. This area of the city contains 1,098 fixed-point sources. Total PM10 emissions in the city from these sources reached 2.55 tons a day in 1998 (CONAMA 2000). Figure 1 presents average daily PM10 emissions from each cell in the grid, for that year. Point sources are clustered in a few zones. The cell with highest emissions is in the northwestern part of the city and emits 594 kilograms per day, 23 percent of the total PM10 emitted by point sources in the city. Of the 289 cells of the grid, only 7 are highly polluting (emit more than three percent of total emissions) and the 14 most polluting cells account for 65 percent of total emissions. These emissions spread over the rest of the city, affecting air quality in each cell.

8. Even though this value seems low, together with emissions by mobile sources (roughly double those by fixed point sources) and the serious thermal inversion problem in Santiago, air quality concentrations exceed the standards discussed previously.

9. This cell includes a power plant with both natural gas- and diesel-powered generators, the largest single emitting source in the city and the only power plant in Santiago. Despite the magnitude of the source, it is included in this analysis since no strategic behavior should be observed. Additionally, there does not seem to be any important incentive for the power plant to hoard permits since it is the only power plant in the city and there is no possibility that another one will be authorized to operate in the city. As a result, the plant has been included in the current tradable permit program.
II. Costs of Improving Air Quality under Alternative Regulatory Instruments

The general setting is that there are \( n \) sources of pollution spatially distributed in the city. Air quality is measured at \( K \) receptor points, and a ton of pollution emitted by the firm \( i \) has a different impact on air quality at receptor \( k \) than a ton emitted by the firm \( j \). Generally, the regulator wants to reach a vector \( \mathbf{Q}^* = (q_1^*, \ldots q_k^*, \ldots q_K^*) \) of maximum permitted ambient pollution concentrations. As is usual in policy formulation, the same standard is imposed on all locations—for all \( k \), \( q_k^* = q^* \).\(^{10}\)

The Policy Instruments

Three policies are evaluated for Santiago: two market-based instruments (ambient permit system and emission permit system) and one command and control instrument (an effluent concentration or emission standard).

For the spatially differentiated ambient permit system, it is assumed that permits, defined in units of concentration at each receptor, are distributed to achieve the desired unique air quality goal at each receptor. Trades are not undertaken on a one-for-one emissions basis. This is the traditional cost-effective benchmark policy.

Under the marketable emission permits system, total allowable emissions are established for fixed sources in the airshed. Permits in an amount equal to these emissions are distributed to polluters, who can then buy and sell them on a one-for-one emissions basis. The number of permits each source buys or sells is the result of the cost minimization of compliance costs by each source.

Under the uniform effluent concentration standard, all point sources are required to emit at concentrations lower or equal to a unique stack concentration standard. Total compliance costs are then the sum of the compliance costs for each source needed to at least meet the stack concentration standard.

Conceptual Framework for Comparing the Compliance Costs of Each Instrument

To compare policy instruments, it is necessary to impose the condition that they reach the desired air quality goal at all receptor locations. However, different policy instruments typically result in different concentrations at each receptor location. To stay as close to reality as possible, it is usually accepted that the target has been reached when at least one receptor location has a concentration of \( q^* \)—the binding receptor—and the others are the same or lower. For this reason, to compare compliance costs, the command and control scheme and emission permit system will be defined so as to achieve the same air quality standard at their binding receptors as the ambient permit system.

10. Primary standards that are established to protect health are usually required by law to be the same everywhere in the country.
Formally, the cost-effective ambient permit system instrument is used to obtain the least cost solution to achieve a maximum permitted ambient concentration of $q^*$ at $K$ receptor points in the city. This can be expressed as the following problem (Montgomery 1972):

\[
\min_{\{e_i\}} \sum_{i=1}^{n} C_i(e_i) \quad \text{s.t.} \quad Q^* \geq ED; \quad E \geq 0
\]

where $D$ is an $n \times K$ dispersion matrix ($d_{ik}$ is the impact of a ton of pollution emitted by source $i$ on concentrations at receptor $k$), $E$ is a $1 \times n$ vector of emissions by $n$ firms in the city, $C_i(e_i)$ is the cost to firm $i$ of emitting $e_i$, and $Q^*$ the $K$-component vector of target concentrations.

Under the ambient permit system, there are $K$ types of permits (one for each receptor) that give firms the right to increase ambient concentrations at each receptor. It is well known that as long as permits totaling $q^*$ are given out for each receptor and the $K$ sets of permits are traded in competitive markets, the ambient permit system minimizes the cost of achieving $Q^*$ (Montgomery 1972).

Under an emission permit system, permits equal to $E^*$ tons of emissions are distributed to the $n$ firms, and firms trade emission permits one-for-one basis. If the permit market is competitive, the emission permit system is a solution to the following problem:

\[
\min_{\{e_i\}} \sum_{i=1}^{n} C_i(e_i) \quad \text{s.t.} \quad E^* \geq \sum_{i} e_i.
\]

The emission vector that solves problem (2), $E^*$, implies a vector $Q^* = E^*D$. Plotting total costs against the largest element of $Q^*$ ($q_{\text{max}}$) gives the cost of achieving $q^* = q_{\text{max}}$ under the emission permit system. If problem (1) has been solved for a given $q^*$, then $E^*$ has to be varied until the largest elements of $Q^*$ coincide with $q^*$.

Under the emission standard, each source’s emissions depend on the size of the source (gas flow) and hours of operation per day. The resulting emissions vector after the standard is applied, $E^c$, will imply a vector of ambient concentrations, $Q^c = E^cD$. The standard that would make the largest elements of $Q^c$ coincide with $q^*$ is the standard to be compared with the ambient permit system and emission permit system.

**Empirical Estimation of Abatement Costs and Concentrations**

To estimate the abatement costs under each instrument required to reach the concentration target, it is necessary to know both the abatement cost function, $C_i(e_i)$, and the matrix $D$ relating the vector of emissions to concentrations. The cost of abatement for each source depends on the applicable control
alternatives. On the basis of the literature (Bretscheider and Kurfurst 1987; Vatavuk 1990; Aranda 1996; Bravo 2000) and expert opinion, two categories of abatement alternatives were identified for the main processes in Santiago: collection devices such as cyclones, multicyclones, bag filters, and wet scrubbers, and for some sources, a change of fuel. Each control option was also assigned an abatement efficiency value.\textsuperscript{11}

The costs of collection devices were estimated based on estimates of the net discounted cash flow of total capital investments and net annual operating costs incurred each year over the useful life of the equipment. The present value of switching to cleaner fuels was estimated based on estimates of the cost of transformation and the cost differential associated with using a different fuel. Control devices of different sizes were costed. Analytical cost relations were established for each control alternative (see supplemental Appendix S.1). For each option, the minimum cost required to reach the required standard was used. However, the lack of flexibility may impose a high cost on some point sources, resulting in overall costs that are higher than that under an ambient permit system.

To relate concentrations to emissions, the natural systems model is represented by the environmental “transfer” coefficient, $d_{ik}$, of the dispersion matrix $D$. A tool that simulates the dispersion process for Santiago was used to obtain these coefficients, based on a multiple cell model that is solved using mass conservation equations.\textsuperscript{12} The wind fields had to be averaged over the day, and meteorological conditions reflecting episode conditions (days in which the air quality standard is exceeded) had to be selected.\textsuperscript{13} A total of 28 episode days were used, and the corresponding transfer coefficients were averaged. As a result, the transfer coefficients reflect the impact of a unit of emissions on concentration levels in each cell of the grid for adverse meteorological conditions.\textsuperscript{14}

\textit{The Simulation Model}

Each policy instrument is defined using different policy targets: air quality at each receptor location for the ambient permit system, total emissions for the emission permit system, and a uniform stack concentration target for the emission standard. To compare the compliance costs of these policy instruments,

\textsuperscript{11} These are presented in supplemental Appendix S.1. For the model each source was assigned only the options applicable to it. It is not assumed that existing abatement technologies are dismantled when there is a fuel switch, and the conservative assumption is made that no extra reductions are obtained when control equipment exists. Mixtures of more abatement and fuel switching were not considered, based on expert opinion that suggested that the technical options that were economically feasible are those considered in table S.1 of supplemental Appendix S.1.

\textsuperscript{12} The coefficients are derived in Muñoz (1993).

\textsuperscript{13} The results are presented in supplemental Appendix S.2, “Transfer Coefficients,” and discussed in detail in Muñoz (1993).

\textsuperscript{14} These concentrations do not include secondary particulate matter generated by nitrogen dioxide and sulfur dioxide emissions, as there are no models available for this for Santiago. However, efforts are being initiated to estimate the impact of these emissions in the city.
the ambient concentration reached in the binding receptor under each instrument is used as a common target.\textsuperscript{15} Specifically, different reductions in pollution concentrations relative to the binding receptor are used as targets for each policy instrument. Table 1 presents the level of application of each instrument required to reach the same concentration target as defined by the ambient permit system.

For the simulation exercise, the problem for each instrument is specified as a linear programming model with binary variables. For the ambient permit system, the model considers the objective function and environmental constraint—a concentration target at each receptor location—presented above. The solution determines which control option was used by each of the sources considered to comply at minimum cost. Summing individual compliance costs over all sources results in total compliance costs.

To simulate the other two policy instruments, only the environmental constraint has to be modified. The emission permit system is similar to the ambient permit system, but must comply with an overall emission target—total emissions must be lower than a predetermined target. Under the emission standard, each emitting source must comply with a target effluent concentration.\textsuperscript{16} Once each source has made its cost-minimizing decision, the resulting emissions in each cell are added to obtain the aggregate emissions on an average episode day. These emissions are then transformed into concentrations at each point of the grid using transfer coefficients, making it possible to compare the average daily concentration reductions in episode days under each instrument and the costs of reaching these reductions.

Specifically, the compliance costs under each policy instrument are estimated using the following model that considers an objective function and two constraints: a technological constraint common to all instruments and an environmental constraint specific to each one. The model considers a total of 1,098

### Table 1. Level of Application of Emission Permit System and Emission Standard to Reach Target Concentration

<table>
<thead>
<tr>
<th>Ambient permit system concentration target (micrograms per cubic meter)</th>
<th>Emission permit system (kilograms per day)</th>
<th>Required emission standard (micrograms per cubic meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.1</td>
<td>1,832</td>
<td>90.0</td>
</tr>
<tr>
<td>27.8</td>
<td>1,556</td>
<td>37.0</td>
</tr>
<tr>
<td>26.5</td>
<td>1,324</td>
<td>13.0</td>
</tr>
<tr>
<td>25.2</td>
<td>1,063</td>
<td>8.0</td>
</tr>
<tr>
<td>22.9</td>
<td>955</td>
<td>2.3</td>
</tr>
</tbody>
</table>

\textit{Source:} Authors’ analysis based on data from Bravo (2000).

\textsuperscript{15} This guarantees that in all other receptor locations, air quality is the same or better.

\textsuperscript{16} The result of global minimization of costs is identical in the case of the emission standard to the individual cost minimization problem and for this reason the same model can be applied. In both cases, the source will choose the unique technology that enables complying at minimum cost.
emission sources and a maximum of 10 abatement options for each source. Each of the 289 cells of the Santiago grid is a receptor location. The simulation is carried out for a linear programming model with a binary variable. The model is formulated using the GAMS software and results are obtained with CPLEX solver.

The general model is as follows:

Objective function: \( \text{Min} \sum_{i=1}^{1089} \sum_{t=1}^{10} CT_{i,t} X_{i,t} \)

where \( CT_{i,t} \) is the annual cost of applying technology \( t \) to source \( I \), and \( X_{i,t} \) is the binary variable that determines whether technology \( t \) is applied to source \( i \).

Technological constraint: \( \sum_{t=1}^{10} X_{i,t} = 1 \quad \forall i = 1, \ldots, 1,098 \)

Environmental constraint: specific to each instrument.

For the *ambient permit system*, the specific environmental constraints are

\[
\sum_{i=1}^{1089} \sum_{t=1}^{10} \sum_{k=1}^{289} E_i \text{HO}_i \alpha_{k',k} \text{UB}_{i,k'} (1 - \text{EFF}_{i,t}) X_{i,t} \\
\leq Q_k \quad \forall k = 1, \ldots, 289
\]

where \( \alpha_{k',k} \) is the transfer coefficient representing the effect emissions in zone \( k \) have on concentrations at location \( k' \), \( \text{HO}_i \) is the hours of operation of source \( i \) per day, \( \text{UB}_{i,k} \) is a dummy variable taking a value of one if source \( i \) is located in cell \( k \) and zero otherwise, \( \text{EFF}_{i,t} \) is the efficiency in emission reductions of technology \( t \) being applied to source \( i \), and \( Q_k \) is the air quality target for location \( k \) (and for all receptor locations).

For the *emission permit system*, the specific environmental constraints are

\[
\sum_{i=1}^{1089} \sum_{t=1}^{10} E_i \text{HO}_i (1 - \text{EFF}_{i,t}) X_{i,t} \leq E
\]

where \( E_i \) is the total emission of source \( i \) (in kilograms per hour), and \( E \) is the aggregate emission target.
For the emission standard, the specific environmental constraints are

\[
\sum_{t=1}^{10} \Omega_i (1 - \text{EFF}_{it}) X_{it} \leq \Omega \quad \forall i = 1, \ldots, 1,098
\]

where \( \Omega_i \) is the effluent concentration level (in milligrams per cubic meter) of source \( i \) obtained as emissions divided by flow, and \( \Omega \) is the effluent concentration standard (milligrams per cubic meter).

For programming purposes, the targets defined by each instrument are set through \( Q_k \), \( E \), and \( \Omega \). Targets implying concentrations at each receptor location ranging from 29.1 to 22.9 micrograms per cubic meter were evaluated. Lower targets are not possible in the worst receptor location without reducing activity at some sources or closing them down, options not considered in this study.\(^{17}\)

**Compliance Costs under Alternative Policies**

The model yields both costs and concentrations per cell of the grid. Before presenting the results, it is necessary to make a correction to current emissions. Natural gas had only been introduced in 1998 in Santiago, and many sources that could profitably switch to this fuel had not done so yet. To eliminate any distortionary effect on source decisions, it is assumed that all sources that can profit from switching to natural gas do so at the start of the program. Consequently, only the costs and benefits from additional reductions are considered.

As expected, the ambient permit system is clearly the most cost-effective instrument. The maximum reduction can be obtained with an annual cost for participating sources of almost US$20 million, less than half the cost for the other policy instruments.

The annualized compliance costs and resulting reductions in concentrations for each policy for fixed-point sources in Santiago are presented in table 2.\(^{18}\) The reduction in compliance costs for the ambient permit system is considerable. The emission permit system is particularly expensive when small reductions are required, for example, for a 29.1 micrograms per cubic meter concentration, the target emission permit system costs are 45 times those of ambient permit system. However, over the range of reduction options for concentration targets lower than 28.7 micrograms per cubic meter, the costs for similar reductions are only 3–20 times higher with an emission permit system than with an ambient permit system. Compliance costs under the emission standard are even more expensive, between 3 and 35 times higher than the ambient permit system for most of the reduction range. The emission standard

\(^{17}\) Even with the best available control technology, concentrations cannot be reduced more for the thermoelectric megasource.

\(^{18}\) Concentrations consider only fixed-point sources. When mobile sources are included, concentrations increase about 50 percent.
is also more expensive than the emission permit system for most of the reduction range except for extremely small or large reductions.

For very low and very high values of the target, the emission permit system is more costly than the command and control instrument. This is not an unexpected result, because the emission permit system is not cost-effective and so can be more costly than a command and control instrument for some specific reduction goals. This type of result, documented in other studies (Tietenberg 1985), depends on the target, the relative compliance cost functions, and the relative size and number of sources (O’Ryan 2006).

**Air Quality at Each Receptor Location and Population–Weighted Concentrations**

A key result is that concentration reductions are different in each receptor location—for the same target—under each policy instrument. This shows that part of the cost reductions from the ambient permit system is not related to efficiency gains, but is because of the lower degree of required control. Since health effects are related both to pollutant concentrations and to the size of the exposed population in each cell, estimation of pollution exposure under each instrument for each target requires estimation of population-weighted concentrations in each cell and summation of them across all cells. For the four receptors with the highest pollutant concentrations, population-weighted

<table>
<thead>
<tr>
<th>Concentration target (micrograms per cubic meter)</th>
<th>Ambient permit system</th>
<th>Emission permit system</th>
<th>Emission standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.3a</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>29.1</td>
<td>0.01</td>
<td>0.45</td>
<td>0.07</td>
</tr>
<tr>
<td>28.7</td>
<td>0.06</td>
<td>0.96</td>
<td>0.56</td>
</tr>
<tr>
<td>28.2</td>
<td>0.1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>27.8</td>
<td>0.2</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>27.4</td>
<td>0.2</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>26.9</td>
<td>0.3</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>26.5</td>
<td>0.5</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>26.1</td>
<td>1.1</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>25.6</td>
<td>2</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>25.2</td>
<td>2</td>
<td>14</td>
<td>21</td>
</tr>
<tr>
<td>24.8</td>
<td>3</td>
<td>14</td>
<td>30</td>
</tr>
<tr>
<td>24.3</td>
<td>6</td>
<td>24</td>
<td>31</td>
</tr>
<tr>
<td>23.9</td>
<td>10</td>
<td>27</td>
<td>34</td>
</tr>
<tr>
<td>23.4</td>
<td>13</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>23.0</td>
<td>19</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>22.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*aCurrent concentration level in the binding receptor.

Source: Authors’ analysis based on data from Bravo (2000).
concentrations are higher under the ambient permit system than under the other two instruments, reflecting the lower degree of abatement required under the ambient permit system (Figure 2).

As a consequence, the health benefits from applying each instrument will be different. In particular, the emission permit system, which imposes larger improvements in population–weighted air quality, would be expected to result in higher health benefits than the other instruments. The following section estimates these health benefits.

III. The Health Benefits of Improved Air Quality

The damage function approach, frequently used in environmental cost–benefit analysis, is used to estimate the health-related benefits of improved air quality (see, for example, Ostro 1996; Environment Canada 1997; European Commission 1998; USEPA 2000). The methodology involves four steps. First, the change in emissions is determined for each policy instrument. Second, the resulting impact on concentrations is estimated. Third, the effects of the reductions in pollutant concentration on various health outcomes are estimated. The changes in health outcomes are quantified using dose–response functions for a set of health effects for which there are well-established statistical relations in the environmental epidemiologic literature. These dose–response functions are applied to the exposed population to determine the population-weighted health effects. Forth, these health effects are valued in monetary units and summed over the different effects, the individuals exposed, and time.

Dose–Response Functions

The dose–response functions used were obtained from the environmental epidemiologic literature. For mortality the dose–response function used was
<table>
<thead>
<tr>
<th>Source</th>
<th>Health effect category</th>
<th>Concentration response parameter</th>
<th>Unit cost in 1998 (in U.S. dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ostro and others (1996)</td>
<td>Acute mortality (ICD 460) (percent increase per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>0.1%</td>
<td>700,000</td>
</tr>
<tr>
<td>Burnett and others (1995)</td>
<td>Hospital admissions for respiratory illness (ICD 480–86) (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>$6.73 \times 10^{-4}$</td>
<td>1,600</td>
</tr>
<tr>
<td>Burnett and others (1995)</td>
<td>Hospital admissions for cardiac illness (ICD 410, 413, 427, and 428) (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>$6.4 \times 10^{-4}$</td>
<td>3,500</td>
</tr>
<tr>
<td></td>
<td>Emergency room visits for respiratory illness (a parameter that relates total emergency room visits to the total number of hospital admissions in 1995 is used instead of a dose–response function. Emergency room visits were six times the number of hospital admissions)</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>Ostro (1990)</td>
<td>Restricted activity days, adult population (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>0.0168</td>
<td>16</td>
</tr>
<tr>
<td>Dockery and others (1996)</td>
<td>Lower respiratory illness in children (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>0.0011</td>
<td>170</td>
</tr>
<tr>
<td>Abbey and others (1993)</td>
<td>Chronic bronchitis, population over age 25 (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>$6.1 \times 10^{-5}$</td>
<td>140,000</td>
</tr>
<tr>
<td>Krupnick, Harrington, and Ostro (1990)</td>
<td>Acute respiratory symptoms (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>0.1679</td>
<td>9</td>
</tr>
<tr>
<td>Whittemore and Korn (1980)</td>
<td>Asthma attacks, among asthmatic population (individual risk factor per one microgram per cubic meter change in annual average PM10 concentration)</td>
<td>0.059</td>
<td>170</td>
</tr>
</tbody>
</table>

**Note:** ICD is international classification of diseases.

*Numbers have been rounded up to avoid giving a sense of false precision.

**Source:** Authors’ analyses based on data sources shown in table 3 and Holz and Sánchez (2000) for unit costs.
estimated for Santiago (Ostro and others 1996). For the other health effects, the functions were obtained from epidemiologic studies estimated for other populations, although the selection criteria used followed Ostro and others (1996).

A large body of literature relates adverse health effects with ambient concentrations of PM10. The concentration response parameters reported in table 3 are typically obtained as the mean value reported by epidemiologic studies selected as providing the most reliable results. Most of the studies estimated linear and log-linear models, which imply a continuum of effects even at low concentration levels. This is justified by the fact that studies have failed to find thresholds for effects associated with particulate matter. In addition, many recent epidemiologic studies have found an association between particulate matter and health effects throughout the whole range of concentrations, even for levels under the primary air quality standards of the U.S. Environmental Protection Agency. There is also little evidence that the slopes of the dose–response functions diminish significantly at lower concentrations (Ostro 1996, p. 4). As a consequence, the functions used in this study assume that the slope of the dose–response function is the same regardless of the concentration level.  

Finally, since these dose–response functions consider average annual PM10 concentrations, the average daily episode concentrations estimated previously had to be converted to annual values. For this, the factors estimated by Jorquera (2002a, b) were used, which represent average dispersion conditions for each month in Santiago at four different receptor locations. Since his results do not vary much by location, the average results for the four locations were used. Average dispersion conditions in the worst winter month (June) are more than four times as bad as in the best month (January) (table 4). To estimate the average annual reduction in PM10 concentrations, these factors are assumed to represent the average dispersion conditions for each month relative to the episode conditions (which has a factor of 1). Consequently, the average is a weighted average, where the weights are the number of days in the month relative to the total annual number of days times the relative dispersion factor.

Monetary Valuation of Health Effects

For valuing a reduction in mortality from lowering pollution levels, the concept of the value of a statistical life is used, estimated from willingness to pay studies. The value of a statistical life is the average of 13 studies selected  

19. See also European Commission (1998, vol. 7, pp. 133–134): “for many of these pollutants, there is clearly a threshold at the individual level, in the sense that most people are not realistically at risk of severe acute health effects at current background levels of air pollution. There is however no good evidence of a threshold at the population level; i.e., it appears that, for a large population even at low background concentrations, some vulnerable people are exposed some of the time to concentrations which do have an adverse effect. This understanding first grew in the context of ambient particles, where the no threshold concept is now well established as a basis for understanding and for policy.”
by the U.S. Environmental Protection Agency that report the lowest values. The values were deflated using the gross national product (GNP) per capita in purchasing power parity terms estimated for 1999 by the World Bank to account for differences in GNP per capita between the United States and Chile. For reductions in illnesses, no willingness to pay studies are available; therefore, the cost of illness estimates from Holz and Sánchez (2000) was used. This approach considers direct treatment costs plus lost income as a measure of productivity loss during illness. This method is simple, but it has several limitations. It is a lower bound estimate of the true willingness to pay for reductions in illness because it does not consider other costs, such as pain and inconvenience. In addition, it does not consider the fact that people can take defensive actions. The third column of table 3 presents the unit values for each health effect used for the monetary valuation in this analysis.

Table 4. Relative Dispersion Factors for Each Month

<table>
<thead>
<tr>
<th>Month</th>
<th>Relative dispersion factor</th>
<th>Number of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.239</td>
<td>31</td>
</tr>
<tr>
<td>February</td>
<td>0.279</td>
<td>28</td>
</tr>
<tr>
<td>March</td>
<td>0.366</td>
<td>31</td>
</tr>
<tr>
<td>April</td>
<td>0.579</td>
<td>30</td>
</tr>
<tr>
<td>May</td>
<td>0.805</td>
<td>31</td>
</tr>
<tr>
<td>June</td>
<td>1.000</td>
<td>30</td>
</tr>
<tr>
<td>July</td>
<td>0.859</td>
<td>31</td>
</tr>
<tr>
<td>August</td>
<td>0.646</td>
<td>31</td>
</tr>
<tr>
<td>September</td>
<td>0.431</td>
<td>30</td>
</tr>
<tr>
<td>October</td>
<td>0.279</td>
<td>31</td>
</tr>
<tr>
<td>November</td>
<td>0.251</td>
<td>30</td>
</tr>
<tr>
<td>December</td>
<td>0.251</td>
<td>31</td>
</tr>
</tbody>
</table>

Source: Authors’ analysis based on data from Jorquera (2002a, b).

Health Benefits

The ambient permit system results in substantially lower health benefits than the emission permit system and the emission standard (figure 3). The differences are largely because each policy imposes different reductions in each cell. The annual benefits obtained are on the order of tens of millions of dollars a year, similar to the annualized costs of reducing emissions.

20. The value of a statistical life estimate used in this study is lower than that estimated by Rizzi and Ortuzar (2003) for Chile using a stated choice approach in which individuals are asked to choose among alternatives. Their estimation adjusted to the 1998 U.S. dollars is approximately $800,000. However, in a recent paper by Rizzi (2005), also using stated-choice surveys, estimated a value of a statistical life for Chile of between US$200,000 and US$300,000.
IV. Comparing Costs and Benefits

Subtracting the annual costs of each policy instrument from the annual benefits yields the net annual benefits to be expected from each policy instrument (figure 4). The net benefits are significantly higher for the emission permit.

**Figure 3.** Annual Population-Weighted Health Benefits Associated with Ambient Particulate Matter (PM10) Concentration Targets, by Pollution Control Instrument

![Graph showing health benefits](image)

*Source: Authors’ analysis based on data from Chilean National Institute of Statistics.*

**Figure 4.** Annual Net Benefits Associated with Ambient Particulate Matter (PM10) Concentration Targets, by Pollution Control Instrument

![Graph showing net benefits](image)

*Source: Authors’ analysis based on data from Bravo (2000) and Chilean National Institute of Statistics.*
system and the emission standard than that for the ambient permit system. The maximum net benefit is obtained at a PM10 concentration of 25.2 micrograms per cubic meter using the emission permit system. These net benefits are approximately US$32 million per year, almost four times higher than the maximum net benefits under the ambient permit system.

On average, net benefits are ten times higher under the emission permit system and almost six times higher under the emission standard than under the ambient permit system, with the difference even higher in many cases. For example, for a 28.2 micrograms per cubic meter concentration target, the net benefits of the emission permit system are 22 times higher than those from the ambient permit system, and 12 times higher than those of the emission standard. In other cases, the difference is small. For example, for a PM10 concentration level of 24.3 micrograms per cubic meter, net benefits from the emission permit system are only 3.4 higher and those from the emission standard are only 2.7 times higher than those from the ambient permit system.

Requirements to achieve concentration levels below 23 micrograms per cubic meter have negative net benefits because of the sharp increases in cost, even when using flexible instruments. The implication is that the regulatory authority must determine the reduction targets carefully to capture most of the net benefits. A difference as small as three micrograms per cubic meter in the required reduction target can result in significantly lower net benefits.

For mortality, different values of a statistical life do not change the ranking of instruments and the net benefit-maximizing concentration target. For example, with a lower value of a statistical life of US$300,000 the maximum net benefits are achieved with an emission permit system at a concentration level of 25.6 micrograms per cubic meter. The net benefits are, of course, lower, reaching only US$19 million a year.

As conjectured, in a developing country such as Chile, where little effort has previously been undertaken to reduce air pollution, the benefits of better air quality associated with an emission permit system or an emission standard outweigh the relatively small compliance cost reductions obtained with the more cost-effective ambient permit system. Clearly, the decision to apply an emission permit system for Santiago is correct when both costs and benefits are taken into account.

V. Conclusions

The choice of instrument to regulate PM10 pollution that yields the highest net benefit is an empirical matter. For Santiago, a simulation model was used to rank policy instruments using given transfer coefficients, emission coefficients, cost estimates, coefficients for health effects, and unit costs of health effects. The analysis assumed away some of the issues currently being discussed in the theoretical literature on instrument choice, such as imperfect emission
monitoring, information asymmetries, dynamic incentives for innovation, and incomplete enforcement of regulation.

Correcting for the difference in benefits associated with each instrument makes a significant difference in the choice of policy instrument to be used when the air quality goal is fixed and uniform across the airshed, as is usually the case. When only a cost-effectiveness criterion is used, the ambient permit system is clearly the preferred option for Santiago, reducing costs significantly compared with the emission permit system and the emission standard over a relevant range of pollution concentration levels. However, when the benefits associated with the overcontrol achieved using these two instruments are included, the emission permit system has the highest net benefits and the ambient permit system has the lowest net benefits over a wide range of plausible reduction possibilities.

In this latter case one of the main advantages of an ambient permit system plays against it. Since it is able to impose reductions that closely match the uniform standard in different parts of the city, it does not take advantage of the significant health benefits from reducing concentrations more than required by the standard. The efficiency gains of the ambient permit system are much smaller than the economic losses from the health impacts resulting from the higher pollutant concentrations allowed by this instrument. While in principle an ambient permit system could be designed to exactly emulate the concentrations reached by the other two instruments, and this would then clearly be the best option, in practice regulators set up a uniform air quality standard within an airshed rather than a system of differentiated standards.

The emission permit system and the emission standard have higher net benefits than the ambient permit system. An emission permit system is a particularly good policy choice for Santiago. Even though there are efficiency losses compared with an ambient permit system, these are more than compensated for by the health benefits obtained as a result of the reductions in pollutant concentrations in excess of the required standard. An emission permit system is also much simpler to implement than a trading system that involves spatial complexities in each trade.

These results may be applicable to other developing economies where control costs are not extremely high because emissions control is at an early stage. The health benefits from an emission permit system or an emission standard may outweigh the lower abatement costs from an ambient permit system. For developed economies, which do not face the same initial conditions (Oates, Portney, and McGartland 1989), the significant reductions in control costs associated with an ambient permit system might outweigh the losses in health benefits compared with other policies.

VI. Supplementary Material

Supplementary material is available online at http://wber.oxfordjournals.org/


