Fondazione Eni Enrico Mattei

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NOTA DI LAVORO 55.2002

JULY 2002

ETA – Economic Theory and Applications

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Summary

Policy makers and analysts are often faced with situations where it is unclear whether market-based instruments hold real promise of reducing costs, relative to conventional uniform standards. We develop analytic expressions that can be employed with modest amounts of information to estimate the potential cost savings associated with market-based policies, with an application to the environmental policy realm. These simple formulae can help increase intuition and understanding of the sources of cost savings, and help identify and design instruments that merit more detailed investigation. We illustrate the use of these results with an application to nitrogen oxides control by electric utilities in the United States.

Key Words: Environmental policy, market-based instruments, cost heterogeneity, cost effectiveness

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1. Introduction

Over the past decade, policy makers in many parts of the world have given increasing attention to the use of markets to address a variety of social problems. This has been particularly true in the case of environmental protection efforts, where various types of tradeable permit and charge systems have begun to be employed (Stavins 2001). Indeed, market-based environmental policy instruments, which were controversial just ten years ago, have now evolved in political circles to the point of becoming conventional wisdom, at least in the United States (Keohane, Revesz, and Stavins 1998). This change may please most economists, but it also highlights the importance of identifying the appropriate policy instrument for each environmental problem that is faced in its particular socio-economic context. In some cases, market-based instruments may be highly desirable, but in other cases their advantages may be small. We provide some relatively simple formulae for exploring the costs of alternative policy instruments, with the intention of increasing intuition and understanding of the sources of cost savings, and to help identify instruments that merit more detailed investigation.

While we focus here on policymaking for environmental problems, the basic issue we explore is quite general. Namely, what is the relationship between potential gains from trade and heterogeneity in technology and/or preferences? There are many areas where this generic issue arises, including: international trade and cross-country heterogeneity in technology, tastes, and endowments; gains from localized regulatory control and heterogeneity across regional jurisdictions; welfare effects of tax and public spending harmonization across a set of countries, such as the European Union; the question of whether potential renewable energy performance standards for electric utilities should be tradable; and, our chosen example, potential cost savings due to market-based policy instruments and heterogeneity of pollution abatement costs.

As with any policy goal, a variety of criteria can and have been brought to bear upon the choice of policy instruments to achieve environmental protection. As the stringency of environmental targets has increased, cost-effectiveness has become a more important criterion for instrument choice.[1] A key factor affecting relative aggregate costs under alternative policy instruments is the heterogeneity of pollution control costs across sources. There are many reasons why the costs of complying with environmental regulations tend to be heterogeneous, including differences in plant location, size, age, and production technology. Location, for example, can affect costs due to differences in the quality and price of inputs (for example, proximity to clean inputs), physical characteristics (for example, urban or rural), and political jurisdiction (for example, pre-existing regulations).

While it is widely recognized that abatement-cost heterogeneity is a fundamental determinant of the potential cost-savings associated with market-based policy instruments, there is surprisingly little analysis of the general relationship between the nature and magnitude of such heterogeneity and the prospective cost savings. Despite the notable absence of such analysis, there is a relevant, albeit small, theoretical literature on the relationship between potential gains from trade and the underlying heterogeneity of consumer preferences and production technology. Most prominent in this literature are studies by Weitzman (1977) and Suen (1990) on the effects of diversity in consumer preferences on the relative efficiency of the price system, and Krueger and Sonnenschein (1967) on the relationship between price divergence across countries and the gains from international trade. In the environmental area, Nichols (1984) explores optimal policies with heterogeneous costs and Mendlesohn (1986) assesses pollution regulation in the presence of heterogeneous benefits and costs. None of these, however, provides a simple framework for directly estimating the cost-savings associated with using market-based policy instruments relative to more commonly used uniform performance standards.

There is also an empirical literature that explores the costs of using alternative policy instruments to address particular environmental problems.[2] These studies are concerned with specific environmental pollutants in specific contexts, ranging from dissolved oxygen in the Fox River of Wisconsin to particulates in Santiago, Chile. Each study uses different types of data at

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[1]For a list of additional candidate criteria for policy instrument choice, see Bohm and Russell (1985). The aggregate level and distribution of the benefits of pollution control may also be affected by the choice of instrument, depending on the degree to which the pollutant is uniformly mixed within the relevant region.

[2]See, for example: Atkinson and Lewis (1974); Atkinson and Tietenberg (1982); Carlson, et al. (2000); Coggins and Swinton (1996); Gollop and Roberts (1983, 1985); Hahn and Noll (1982); Kolstad (1986); Krupnick (1986); Maloney and Yandle (1984); McConnell and Schwartz (1992); O'Neil, et al. (1983); O'Ryan (1996); Perl and Dunbar (1982); and Seskin, Anderson, and Reid (1983).

different levels of aggregation, each makes different simplifying assumptions, and each employs different methods of analysis. Although this differentiation in data and methods may be appropriate for specific cases, little intuition thereby emerges regarding the general relationship between the nature and magnitude of cost heterogeneity and the potential cost savings associated with market-based instruments.[3] Relatively simple formulae that can be employed with a small set of summary statistics can provide a useful lens for conducting initial screenings of environmental problems, so that analysts and decision makers can focus their attention on cases where potential cost savings are greatest. In addition, by clearly demonstrating the relationship between cost savings and different sources of underlying heterogeneity—such as the slope of marginal costs, baseline emissions, and firm size—our analytical results can provide guidance for the design of relatively cost-effective policies in the event "pure" market-based policies are not an option.

Such analysis is important because market-based instruments are by no means a panacea; in some cases, they hold tremendous promise of providing environmental protection cost effectively, but in other cases they are not well suited, for a variety of reasons. It might seem that if costs are homogeneous, a market-based instrument will perform identically to a conventional uniform standard, and that therefore policy makers ought always to choose market-based instruments (because they can presumably perform no worse in terms of aggregate costs and may perform better than command-and control approaches). But market-based instruments may not perform better than conventional standards along a number of dimensions we do not consider here, including: relative administrative costs of the various instruments; possibilities of strategic behavior (Hahn 1984, Misolek and Elder 1989, Malueg 1990) and transaction costs (Stavins 1995) with specific market-based instruments; political costs attendant to moving toward innovative instruments with different distributional consequences (Keohane, Revesz, and Stavins 1998); systematic "over-control" that results from particular applications of command-and-control measures (Oates, Portney, and McGartland 1989); and smaller aggregate benefits of market-based instruments where "hot spots" of emissions or concentrations combine with non-linear damage

[3] Note that the question we are addressing—the relative *cost-effectiveness* of market-based versus conventional policy instruments—is distinct from the question of the overall *efficiency* of price versus quantity instruments (under conditions of uncertainty), a question addressed in a literature which originated with Weitzman (1974).

functions. Therefore, it is valuable to predict the potential cost savings that may be associated with using a market-based instrument for a particular environmental problem.[4]

Our approach is to develop three stylized models of alternative means of achieving an aggregate environmental target. Two are performance-based, command-and-control instruments: a uniform emission rate standard and a uniform percentage reduction standard. We model the uniform performance standards as being in terms of an allowable emission rate per unit of product output or percentage emissions reduction, because these are typical of actual command-and-control regulation (Russell, Harrington, and Vaughan 1986; Helfand 1991).[5] The third instrument is market-based, such as an emissions fee or tradable permit system.

A fundamental feature of the models is that a subset of their parameters represents the nature and degree of cost heterogeneity. We solve each model for the aggregate cost it would imply, and then by comparing results, we derive expressions for the absolute and percentage cost-savings attributable to adopting a market-based instrument. Subsequently, we demonstrate the potential use of these expressions with a specific application using readily available information on nitrogen oxides control in the eastern United States.

Economists frequently develop analytical models of the costs of environmental and other regulation. These range from small-scale, sector-specific, econometric cost-side models to large-scale, integrated assessment models of global climate change. Despite the frequently acknowledged importance of cost heterogeneity, it is a characteristic of the real world that is sometimes (understandably) ignored in such modeling, because of the complexity and the data requirements that it inevitably would introduce.[6] In this context, our work also provides modelers

[4] Even among those environmental problems for which market-based instruments would appear preferable strictly on compliance-cost grounds, there is tremendous variation in the cost-savings that could be anticipated (essentially because of variation in the degree of cost heterogeneity). Tietenberg (1985) assimilated the results from ten analyses of the costs of air pollution control, and in a frequently-cited table, indicated the ratio of actual command-and-control programs to least-cost benchmarks. The resulting ratios ranged from 22.0 to 1.1.

[5] Note in addition that our analysis of a uniform emission rate standard will also hold when the standard is in terms of emissions per unit of some input—assuming that the production function uses the input in fixed proportions to output. Another possibility is a uniform emission or abatement quantity standard, which has been employed in theoretical models, but we know of no examples of its use in actual policy. A uniform quantity standard may be useful as a point of comparison in a model with homogeneous firms, but—as evidenced by its absence from real policy—it becomes unreasonable when firms are heterogeneous, especially in terms of size.

[6] In the simplest market model, for example, one would anticipate that firms with relatively high abatement costs would be driven out of the market by firms with lower abatement costs. In reality, of course, this may not happen because those same firms may enjoy cost advantages along other dimensions, and because there are a variety of frictions in the relevant markets, including those due to the regulatory environment.

with a parsimonious structure for incorporating key elements of heterogeneity into their analytical models of costs for a variety of environmental and other problems.

The cost-savings potentials that are identified with the approach we offer may not reflect precisely the magnitude of realized savings, because we abstract from several other dimensions along which the costs of market-based instruments may differ from those of command-and-control approaches. Many of these additional effects would tend to further increase the cost-effectiveness of market-based policies due to the flexibility and incentives they provide.[7] On the other hand, real-world command-and-control approaches may contain exemptions or other types of "fine-tuning" that increase their cost-effectiveness relative to our stylized representation.[8] The basic message is the same: increased regulatory flexibility can yield increased cost-savings, and the degree of such savings depends on the degree of heterogeneity.

In Section 2, we develop our stylized models of three basic types of policy instruments and identify key general findings. In Section 3, we apply the approach to the policy problem of reducing nitrogen oxide emissions in the eastern United States, and in Section 4, we conclude.

2. A Model of Cost Heterogeneity and Policy Choice

2.1 A Model of Heterogeneous Costs

We posit the common situation in which the government seeks to limit the aggregate emissions, Q, of a set of sources. The output, x_i, of each source is given, as is aggregate output,

[7] First, firms can potentially reduce emissions through three types of activities: product output reduction; input substitution; and end-of-pipe abatement (Spulber 1985; Goulder, et al. 1999). We abstract from the first type of activity by treating output as exogenous, which seems reasonable, because pollution-control costs are typically a very small fraction of total production costs (Jaffe, et al. 1995). Further, we do not differentiate between input substitution and end-of-pipe treatments, considering both as emission abatement. Hence, our stylized command-and-control policy instruments are (uniform) performance standards, not technology mandates. This is important to recognize, because even if firms were perfectly homogeneous, a true technology mandate would not be cost-effective, because it provides no latitude for firms to substitute "cleaner" inputs. Second, our focus is exclusively on static cost-effectiveness, but it is well known that the incentive-structure of market-based instruments can lead to dynamic efficiency gains, both in terms of decreased abatement costs through technological change (Jaffe, Newell, and Stavins 2001) and firm entry and exit (Spulber 1985, Helfand 1991). Third and finally, our analysis is partial-equilibrium in nature. In a general-equilibrium context, particular types of market-based instruments, such as those that combine revenue generation with cuts in pre-existing distortionary taxes, can enjoy additional cost advantages over commensurate command-and-control regulations (Goulder, et al. 1999).

[8] For such regulatory tailoring to increase cost-effectiveness, the characteristics along which regulations are differentiated must coincide with the characteristics along which costs are differentiated, and the relationship must be in the correct direction—that is, the regulation faced by sources with low-cost characteristics must be relatively stringent. Although regulatory differentiation can be motivated by a variety of political and bureaucratic motivations other than costs, one could argue that political-economy incentives may lead high-cost sources to fight regulation more forcefully, leading to relatively "efficient" regulatory differentiation.

X, for all n sources.[9] Emission quantities for each source are given by q_i and are chosen by sources to minimize costs subject to policy constraints. Each source has baseline emissions of q_{0i} in the absence of emission regulation and faces increasing costs of reducing emissions from this baseline. Because we are striving for transparent results, we use a second-order approximation of these costs around baseline emissions:

$$C(q_i) = c_{0i} + c_1 (q_{0i} - q_i) + \frac{c_{2i}}{2}(q_{0i} - q_i)^2,$$

where c_{0i}, c_{1i}, and c_{2i} are source-specific parameters of the emission cost function $C(q_i)$. The marginal cost of emission reductions is therefore given by

$$-C'(q_i) = c_{1i} + c_{2i}(q_{0i} - q_i).$$

Note that $c_{0i} = 0$ because emission costs are zero in the baseline. Furthermore, because the cost-minimizing firm will equate the marginal cost of emission reduction with the price of emissions p, we have $c_{1i} = 0$ because $p = 0$ in the baseline. Finally, we multiply the cost function by x_i^2 / x_i^2 in order to express the variables in per unit of output terms. This translation is useful because: (i) environmental policy discussions are often couched in terms of pollution intensity rather than absolute emissions levels; and (ii) it reduces the degree of correlation that would otherwise exist between the variables due to scale effects.

We are therefore left with the following simplified total and marginal cost functions:

$$C(q_i) = \frac{x_i}{2b_i}\left(a_i - \frac{q_i}{x_i}\right)^2, \qquad (1)$$

$$-C'(q_i) = \frac{1}{b_i}\left(a_i - \frac{q_i}{x_i}\right). \qquad (2)$$

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[9] Note that this framework requires a consistent measure of output for different sources, which is necessary given that we explore the relative cost of uniform performance standards measured in terms of emissions per unit of product output. Such a framework is relevant for exploring many cases where market-based policies have been or may be applied, including control of emissions of sulfur dioxide, nitrogen oxide, and carbon dioxide from electric utilities and large industrial boilers. The sources need not be from the same industry, however, as illustrated by the case of emissions from electric power plants and industrial boilers, both of which do or could face standards in terms of emissions per unit of heat throughput.

where $a_i = q_{0i}/x_i$ is baseline emissions intensity per unit of output, and we have made the substitution $1/b_i = c_{2i} x_i$ in order to simplify the taking of expectations in subsequent parts of the analysis.[10] Solving for q_i ,

$$q_i = (a_i - b_i\, p)\, x_i ,$$

assuming firms are price-takers, we find that each source has a factor demand for emissions that is linear in the price, p, of emissions (relative to other factors). Therefore, b_i is both the slope of the emissions demand function and the reciprocal of the slope of the marginal cost function, expressed per unit of output. The parameter b_i represents the rate at which the source alters its pollution intensity per unit change in the price of pollution; different values of b alter the slope of the marginal cost function. Thus, a_i and b_i are source-specific demand parameters that allow for heterogeneity across sources in the intercept and slope of emission demand and marginal cost.[11] For the sake of clarity, we assume the heterogeneous variables are independently distributed, with mean values $\bar{a}$, $\bar{b}$, and $\bar{x}$. Allowing for correlation among the demand parameters does not change the aggregate compliance cost *ordering* of market-based compared with command-and-control instruments, but it could alter the *magnitude* of the cost difference between these types of policies depending on the magnitude and sign of the correlations between a, b, and x. We comment further on this below.

2.2 Alternative Policies for Emission Allocation

We consider three stylized policies for allocating aggregate emissions of Q among the sources. Two are performance-based instruments: a uniform emission rate standard and a uniform percentage reduction standard. The third is a market-based instrument, such as an emissions fee or tradable permit system.

2.2.1 Cost of a Uniform Emission Rate Standard

A uniform emission rate standard results in emissions from each source of $\tilde{q}_i$ equal to aggregate emissions per unit of output, weighted by source output:

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[10] See Table 1 for examples of units of the variables and parameters.

[11] While we have incorporated heterogeneity directly into the parameters of the cost function, an alternative would be to characterize heterogeneity in underlying variables described earlier, such as location, age, size, and production technology. Because that approach would still involve a further mapping between these underlying variables and costs, it would considerably increase the complexity of attaining our goal, which is to provide a parsimonious, transparent representation of the relationship between cost heterogeneity and cost savings.

$$\tilde{q}_i = \left(\frac{Q}{X}\right)x_i. \tag{3}$$

where X is aggregate output. This assumes perfect compliance, an assumption we also make for the other stylized instruments we consider. We also assume that the standard is binding for the relevant set of sources; that is, each source undertakes non-negative reductions. In addition, note that the same analysis and results will hold when the standard is in terms of emissions per unit of some *input*—assuming that the production function uses the input in fixed proportions to output.

Substituting (3) into (1) we find the cost to each source of the uniform emission rate standard:

$$C(\tilde{q}_i) = \frac{x_i}{2b_i}\left(a_i - \frac{Q}{X}\right)^2. \tag{4}$$

To estimate the aggregate cost of the uniform emission rate standard, we first find the expected value of Equation (4) using a second-order approximation around mean characteristics $\bar{a}$, $\bar{b}$, and $\bar{x}$:

$$\mathrm{E}\left[C(\tilde{q}_i)\right] = \frac{\bar{x}}{2\bar{b}}\left(\bar{a} - \frac{Q}{X}\right)^2 + \frac{1}{2}\left(\frac{\bar{x}}{\bar{b}}\mathrm{V}[a] + \frac{\bar{x}}{\bar{b}^3}\left(\bar{a} - \frac{Q}{X}\right)^2 \mathrm{V}[b]\right), \tag{5}$$

where $\mathrm{V}[\cdot]$ represents the variance of the bracketed parameter.[12]

Multiplying Equation (5) by n, we find the aggregate expected cost of the uniform emission rate standard, denoted as $\mathrm{E}[C(\tilde{Q})]$, which we further simplify by multiplying by $\bar{a}^2/\bar{a}^2$, yielding

$$\mathrm{E}\left[C(\tilde{Q})\right] = \frac{X\bar{a}^2}{2\bar{b}}\left(R^2 + R^2\boldsymbol{b} + \boldsymbol{a}\right), \tag{6}$$

where $R = (\bar{a} - Q/X)/\bar{a}$ is the fractional aggregate reduction in emissions from the baseline to the aggregate emission constraint Q ($0 \le R \le 1$), and $\boldsymbol{a} = \mathrm{V}[a]/\bar{a}^2$ and $\boldsymbol{b} = \mathrm{V}[b]/\bar{b}^2$ are dimensionless measures of heterogeneity or spread in a and b relative to their means; the square roots of $\boldsymbol{a}$ and $\boldsymbol{b}$ are known as *coefficients of variation*.

[12] Higher-order approximations would involve terms for skewness, kurtosis, and higher-order moments of the distribution of b. We note that the skewness term for b would have a negative sign, indicating that positive skewness (i.e., skewed to the right, or a long upper tail) would tend to yield lower costs of a uniform performance standard. This makes intuitive sense because high values for b represent firms with low costs of emission control.

2.2.2 Cost of a Uniform Percentage Reduction Standard

A uniform percentage reduction standard results in emissions from each source of $\hat{q}_i$, where

$$\hat{q}_i = (1 - R)a_i x_i = \frac{a_i}{\bar{a}}\left(\frac{Q}{X}\right)x_i \,. \tag{7}$$

Substituting (7) into (1) we find the cost to each source of the uniform percentage reduction standard,

$$C(\tilde{q}_i) = \frac{x_i}{2b_i}\left(a_i - \frac{a_i}{\bar{a}}\frac{Q}{X}\right)^2,$$

which differs from the uniform emission rate standard (Q/X) by adjusting the standard for each source's baseline emissions relative to the mean ($a_i/\bar{a}$). Proceeding as above, we find the aggregate expected cost of the uniform percentage reduction standard, denoted as $\mathrm{E}[C(\hat{Q})]$:

$$\mathrm{E}\left[C\left(\hat{Q}\right)\right] = \frac{X\bar{a}^2}{2\bar{b}}R^2\left(1 + \boldsymbol{b} + \boldsymbol{a}\right). \tag{8}$$

2.2.3 Cost of a Market-Based Policy Instrument

Under a market-based instrument, each source has an incentive to choose an emissions level q_i^* that minimizes its own costs, so that

$$q_i^* = \left(a_i - b_i p^*\right)x_i\,, \tag{9}$$

where an emissions market of size Q clears at price p^*. In principle, the cost-effective allocation could be implemented either by establishing a tradable permit market of size Q or by setting an emissions fee of p^*, where p^* will equal each source's marginal cost of emissions control (Equation (2)) in equilibrium.

Taking expectations of (9), we find that average emissions will be demanded from a source that has average levels of each characteristic:

$$\mathrm{E}\left[q^*(p^*)\right] = \bar{q} = \left(\bar{a} - \bar{b}p^*\right)\bar{x}\,, \tag{10}$$

where $\bar{q}$ represents average emissions. Solving for p^*, and substituting $Q/X = \bar{q}/\bar{x}$, we find the emissions tax that will deliver aggregate emissions of Q, which also equals the market-clearing permit price for a permit market of size Q:

$$p^* = \frac{1}{\bar{b}}\left(\bar{a} - \frac{Q}{X}\right). \tag{11}$$

Substituting Equation (11) back into Equation (9), we find that each source's cost-effective emissions level is given by:

$$q_i^* = \left(a_i - \frac{b_i}{\overline{b}} \left(\overline{a} - \frac{Q}{X} \right) \right) x_i \,.$$

Following the same approach as before, we find the aggregate expected cost of the market-based instrument, denoted as $\mathrm{E}[C(Q^*)]$:

$$\mathrm{E}\left[C\left(Q^* \right) \right] = \frac{X \overline{a}^2}{2\overline{b}} R^2 \,. \tag{12}$$

2.3 The Potential Cost Savings of Market-Based Policy Instruments

Employing our model of the cost of alternative policy instruments, the aggregate cost savings, $\tilde{\Delta}$, from using a cost-effective policy relative to a uniform emission rate standard is found simply by subtracting Equation (12) from (6):[13]

$$\tilde{\Delta} = \mathrm{E}\left[C\left(\tilde{Q} \right) \right] - \mathrm{E}\left[C\left(Q^* \right) \right] = \frac{X \overline{a}^2}{2\overline{b}} \left(R^2 \boldsymbol{b} + \boldsymbol{a} \right). \tag{13}$$

We can also express the cost savings in percentage terms by dividing Equation (13) by (6):

$$\%\tilde{\Delta} = 1 - \frac{\mathrm{E}[C(Q^*)]}{\mathrm{E}[C(\tilde{Q})]} = 1 - \frac{R^2}{R^2 + R^2 \boldsymbol{b} + \boldsymbol{a}} \,. \tag{14}$$

Likewise, the aggregate cost savings, $\hat{\Delta}$, from using a cost-effective policy relative to a uniform percentage reduction standard is found by subtracting Equation (12) from (8):

$$\hat{\Delta} = \mathrm{E}\left[C\left(\hat{Q} \right) \right] - \mathrm{E}\left[C\left(Q^* \right) \right] = \frac{X \overline{a}^2}{2\overline{b}} R^2 \left(\boldsymbol{b} + \boldsymbol{a} \right), \tag{15}$$

or in percentage terms:

$$\%\hat{\Delta} = 1 - \frac{\mathrm{E}[C(Q^*)]}{\mathrm{E}[C(\hat{Q})]} = 1 - \frac{1}{1 + \boldsymbol{b} + \boldsymbol{a}} \,. \tag{16}$$

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[13]Note that the cost savings approximation is likely to be acceptable for the policy-relevant range of emission reductions, but may not perform as well when aggregate reduction requirements are stringent enough to lead many sources to eliminate all of their emissions under a market-based policy. This can occur in our current model because we do not impose a non-negativity constraint on emissions under a market-based allocation. It is easily seen by evaluating the cost savings at the extreme of 100 percent reductions (i.e., R=1). At 100 percent reductions the expressions suggest positive cost savings, although exact cost savings should be zero because every source would be required to emit zero emissions, facing the same costs under any policy. One could restrict the cost structure in order to avoid this limitation, for example by constraining the model parameters so that a_i/b_i is a constant equal to the marginal abatement cost at zero emissions.

Equations (13)–(16) provide the basis for evaluating the potential cost savings from adopting a market-based policy instrument. Minimal information is required about the relevant set of sources facing environmental regulation: aggregate production of the regulated industry, X; the emissions constraint, Q, which determines R; the mean and variance of the slope of the emissions demand function, $\bar{b}$ and V[b], which determine $\boldsymbol{b}$; and the mean and variance of baseline emissions intensity, $\bar{a}$ and V[a], which determine $\boldsymbol{a}$.

2.4 What Do the Expressions for Cost Savings Tell Us?

The first message from Equations (13)–(16) is that the cost savings of market-based policies relative to uniform performance standards increase in a straightforward proportional manner as a function of greater abatement-cost heterogeneity. This cost heterogeneity comes from two sources. The first is heterogeneity in baseline emissions intensities, $\boldsymbol{a}$, which indicates how much abatement each source will have to do, depending on the policy in place. The second is heterogeneity in the slope of the cost function, $\boldsymbol{b}$, which describes how fast each source's costs rise as additional reductions are sought.

Each source of cost heterogeneity can have an effect independent of the other's presence. This makes it possible to identify a lower-bound of anticipated cost savings if information is available on only one source of heterogeneity, but not the other (assuming distributional independence). In fact, information on baseline emission rates is likely to be more readily available than information on marginal costs. For example, from the U.S. Environmental Protection Agency's National Allowance Data Base, we can easily calculate that the baseline (1985) emission rate of sulfur dioxide for electric utility boilers that must reduce emissions under the sulfur dioxide allowance trading program was about 3.1 lbs/mmBtu on average ($\bar{a} = 3.1$), with a standard deviation of about 1.5 (V[a] = 2.25), resulting in $\boldsymbol{a}$ = 0.23. Equation (14) therefore indicates an estimate of 38% cost savings from using a market-based policy relative to a uniform emission rate standard of 1.2 lbs/mmBtu (R = 0.61), which is the rate that was used to determine initial allocations of sulfur dioxide emission allowances. Heterogeneity in marginal cost functions ($\boldsymbol{b}$ > 0) would increase these savings. Using an econometric approach, with much greater data requirements, Carlson *et al.* (2000) estimated the potential cost savings for this program at about 43%.

It is interesting to note that heterogeneity in source size (x) does not enter the expressions because the market-based policy does not offer any more flexibility along the size dimension than performance standards, which themselves include an adjustment for size differences (on either a per unit of output or percentage basis). Of course, these results depend, to some degree, on the assumption that source size and other heterogeneous variables (*a* and *b*) are independent. We would expect any correlation with *x* to be small, because *a* and *b* are already expressed in rate terms.[14] The effect of correlation between *a* and *b* is straightforward: positive (negative) correlation in *a* and *b* will lower (raise) the cost savings of market-based instruments relative to either of the uniform standards. This makes intuitive sense, because if sources with relatively high baseline emissions tend also to have steeply sloped marginal costs, uniform standards will be even less cost-effective (and vice versa) than if these variables were independent. There is no a priori reason to expect the correlation to be positive or negative.

Next, we turn specifically to Equations (13) and (15), which express the cost savings in dollar terms, and focus on the initial term multiplying the entirety of each of the expressions, $X\overline{a}^2/(2\overline{b})$. This term equals the aggregate cost of 100-percent emission reduction for a homogeneous set of sources. It serves to scale the expression to a degree appropriate for any particular environmental problem, depending on the size of the industry, baseline emission rates, and the slope of marginal control costs. The remaining variables in the expressions, a, b, and *R*, are dimensionless. When the cost savings are expressed in percentage terms, as in (14) and (16), only the dimensionless variables remain. Although expressing the cost savings in percentage terms has obvious appeal, one can lose an overall sense of the importance of the choice at hand. Hence, both forms are useful. Finally, we note that the effect of more stringent reduction rates, *R*, on absolute cost savings is amplified by higher degrees of cost heterogeneity.

These relationships between the cost savings of market-based policies and the various types and degrees of cost heterogeneity are illustrated in Figures 1 and 2. Because general results can be illustrated for cost savings measured in percentage terms, we focus on such measures. Figure 1 portrays the anticipated cost savings (in percentage terms, on the vertical axis) of employing a fully cost-effective market-based policy instrument instead of a uniform emission rate standard in the case of an aggregate emission reduction target of 50%. Increasing

[14] Allowing for correlation among *a*, *b*, and *x*, the expressions for cost savings become: $\tilde{\Delta} = \frac{X\overline{a}^2}{2\overline{b}}\left(R^2\left(b - d\right) + a + 2Rg - 2Rl + R^2 - \frac{\left(R+g\right)^2}{1+d}\right)$, and $\hat{\Delta} = \frac{X\overline{a}^2}{2\overline{b}}\left(R^2\left(a + b - d + 2g - 2l\right) + R^2 - \frac{\left(R+g\right)^2}{1+d}\right)$ where $d = \mathrm{COV}[b,x]/(\overline{b}\overline{x})$, $g = \mathrm{COV}[a,x]/(\overline{a}\,\overline{x})$, and $l = \mathrm{COV}[a,b]/(\overline{a}\overline{b})$.

heterogeneity in the slope of marginal costs is measured on the horizontal axis (in terms of our measure of spread of the slope of emissions demand, b). The general relationship between heterogeneity in the slope of the marginal cost function and cost savings is provided in the figure for four different degrees of heterogeneity in baseline emission rate (in terms of the respective measure of spread, a). Figure 2 provides the analogous cost savings results relative to a uniform percentage reduction standard.

As can be seen in Figure 1, even in the absence of "slope heterogeneity," increasing heterogeneity in the baseline emission rate brings with it greater cost savings due to employing a market-based instrument (see the four vertical intercepts in the figure). Likewise, even when sources are identical in terms of their baseline emission rates ($a = 0$), percentage cost savings increase with greater degrees of heterogeneity in marginal cost function slopes, b. In both cases, there are "decreasing returns" of cost-effectiveness from greater degrees of cost heterogeneity. That is, relatively small degrees of both types of abatement-cost heterogeneity result in market-based instruments enjoying significant advantages over their command-and-control counterparts. But there are limits to these savings.[15]

The clarity of our results comes at the expense of some simplifying assumptions. Depending on the degree to which these assumptions are violated, our results will tend to over- or underestimate the extent of cost savings. In particular, the approximations may be less accurate where: there is a high degree of correlation among the heterogeneous variables; the distributions of these variables are highly skewed; the marginal cost function is highly nonlinear; or the policy goal is very stringent.

3. An Application to Nitrogen Oxides Control

As an example of how these relationships can be employed, we apply the framework to the case of nitrogen oxides (NO_x) reduction by electric utilities in a group of eastern states. When emitted, NO_x emissions and volatile organic compounds react in the presence of sunlight to form compounds that contribute to the formation of ground-level ozone. Ozone in the lower atmosphere can cause a variety of health problems by damaging lung tissue, reducing lung

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[15] The cost-savings expressions and the related figures provide for convenient sensitivity analysis. In Figure 1, it is apparent that when heterogeneity in baseline emission rates (as measured by a) is significant (for example, on the order of 0.4 or greater), potential cost savings are quite insensitive to changes in heterogeneity in the slope of marginal abatement costs (as measured by b).

function, and adversely sensitizing the lungs to other irritants. Ozone tends to be a problem over broad regional areas, particularly in the eastern United States, where it can be transported by wind over hundreds of miles and across state boundaries. Through a multi-year effort known as the Ozone Transport Assessment Group (OTAG), the U.S. Environmental Protection Agency (EPA) worked with eastern states and the District of Columbia, private industry, and environmental advocacy groups to address ozone transport.[16]

We model several different emission control policies for large electric utility boilers in the relevant region, with each policy set to achieve a 53% reduction in aggregate emissions. The policies are (1) a 0.15 lb/mmBtu uniform emission rate standard; (2) a uniform 53% emission reduction standard; and (3) a cost-effective allocation among utilities. The virtue of the approach we have developed is its analytic simplicity and its use of a small set of simple summary statistics. The necessary summary statistics for these data are given in Table 1.[17]

The results are provided in Table 1 and illustrated by the points labeled "NO_x: Utilities" in Figures 1 and 2. Thus, Figure 1 indicates that given the estimated degrees of heterogeneity of the two relevant cost function parameters for electric utility NO_x emissions, our model predicts 51% cost savings from employing a market-based policy instrument relative to a uniform emission rate standard. Our results are in the same range as those of Krupnick and McConnell (1999), who employ a source-by-source programming approach to evaluate cost-effective NO_x control, and find cost savings for utilities of about 46%. For comparison, we also show that the estimated cost savings relative to uniform percent reductions for utilities is 44% (Figure 2). This result illustrates a point made earlier: that percent reduction standards tend to be less costly than uniform emission rate standards, unless, of course, there is no heterogeneity in baseline emission rates, in which case the two policies are identical. Finally, in this case, we found the degree of

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[16] In 1998, EPA issued regulations requiring 22 eastern states and the District of Columbia to submit State Implementation Plans (SIP's) that address the regional transport of ground-level ozone through NO_x reductions (U.S. Environmental Protection Agency 1998). Building on OTAG recommendations, EPA established NO_x budgets for each state, but gave states the flexibility to decide which electric utility boilers, large industrial boilers, and other sources should be required to reduce NO_x emissions, by how much, and the specific policies they must follow to meet the projected budgets (for example, uniform emission rates, percentage reduction standards, or emissions trading). To determine the budgets, EPA chose a control level for large electric utility boilers based on a uniform emission rate standard of 0.15 lb/mmBtu (pounds of NOx per million Btu of boiler heat input).

[17] All of the necessary data on control costs, emissions, and output are available as projections for 2007 (Pechan Associates 1997). We used Equation (1) to compute the slope of each source's emission demand function (b), taking an average in cases where there was more than one emission control scenario available. Costs for utilities are relative to an emission baseline consistent with meeting restrictions imposed by the 1990 Clean Air Act Amendments. We exclude from the analysis sources that already met the relevant performance standard in the baseline.

correlation between the variables to be small. Accounting for correlation in the estimates of cost savings lowered each of the estimates by about 5%.[18]

4. Summary and Conclusions

Policy makers and analysts in the environmental and other policy realms are often faced with situations where it is unclear whether market-based instruments hold significant promise of reducing costs, relative to conventional command-and-control approaches. We have developed some simple expressions that can be employed with modest amounts of information to estimate the potential cost savings associated with designing and implementing market-based policy instruments. Because our analytical models are simple, yet capture key properties of relevant cost functions, they can be used to predict potential cost savings through simple formulae and can improve understanding of the importance of cost heterogeneity and its policy implications in real-world environmental, resource, and other policy contexts.

We identified several key relationships between the forms and magnitude of cost heterogeneity and the anticipated performance of alternative policy instruments. Two primary sources of heterogeneity—baseline emissions and the slope of marginal costs—can be expressed as having independent proportional effects on anticipated cost savings. Through an application to NO_x control in the eastern United States, we demonstrated the use of these results by estimating the anticipated cost savings from use of a market-based policy instrument, relative to both a uniform emission rate standard and a uniform percent reduction standard.

Our approach also provides modelers with a parsimonious structure for incorporating key elements of heterogeneity into their analytical models of costs for a variety of environmental problems. In addition, the framework we have developed may be usefully applied to address a number of other public policy questions. For example, what are the costs of maintaining one-size-fits-all environmental (and other) regulations across heterogeneous regions, such as the countries of Europe, the provinces of Canada, or the states of the United States? And what are the costs of uniform acreage control programs, such as in the European Union, where farms and farmers are heterogeneous across relevant dimensions?

[18] For this case, d = 0.21, g = 0.036, and l = 0.07, yielding $\%\tilde{\Delta} = 45\%$ and $\%\hat{\Delta} = 39\%$.

Table 1. Application to Nitrogen Oxides Control by Electric Utilities in the Eastern United States

Variable	Value
$\overline{a}$ (lb/mmBtu)	0.32
$\mathrm{V}[a]$ (lb/mmBtu)^2	0.010
α	0.098
$\overline{b}$ (lb/mmBtu)/($/lb)	0.15
$\mathrm{V}[b]$ (lb/mmBtu)^2/($/lb)^2	0.015
β	0.68
X (mmBtu)	9.85 x10^9
Q/X (lb/mmBtu)	0.15
R	53%
$C\left(\tilde{Q}\right)$ ($M)	1,990
$C\left(\hat{Q}\right)$ ($M)	1,750
$C\left(Q^*\right)$ ($M)	980
p^* ($/lb)	1.16
$\tilde{\Delta}$ ($M)	1,010
$\%\tilde{\Delta}$	51%
$\hat{\Delta}$ ($M)	770
$\%\hat{\Delta}$	44%

Figure 1. Cost Savings of Market-Based Policy

Relative to Uniform Emission Rate Standard

(53% Reduction in Aggregate Emissions)

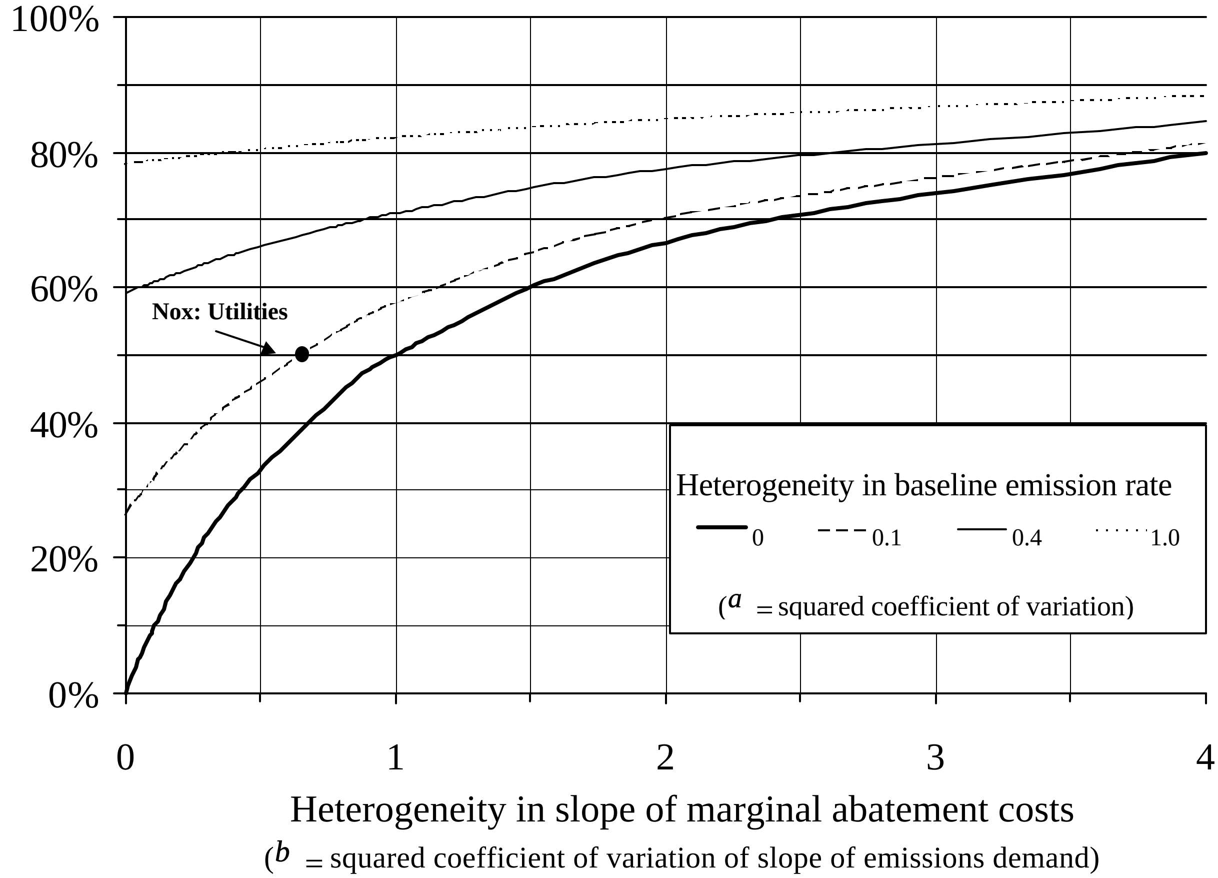
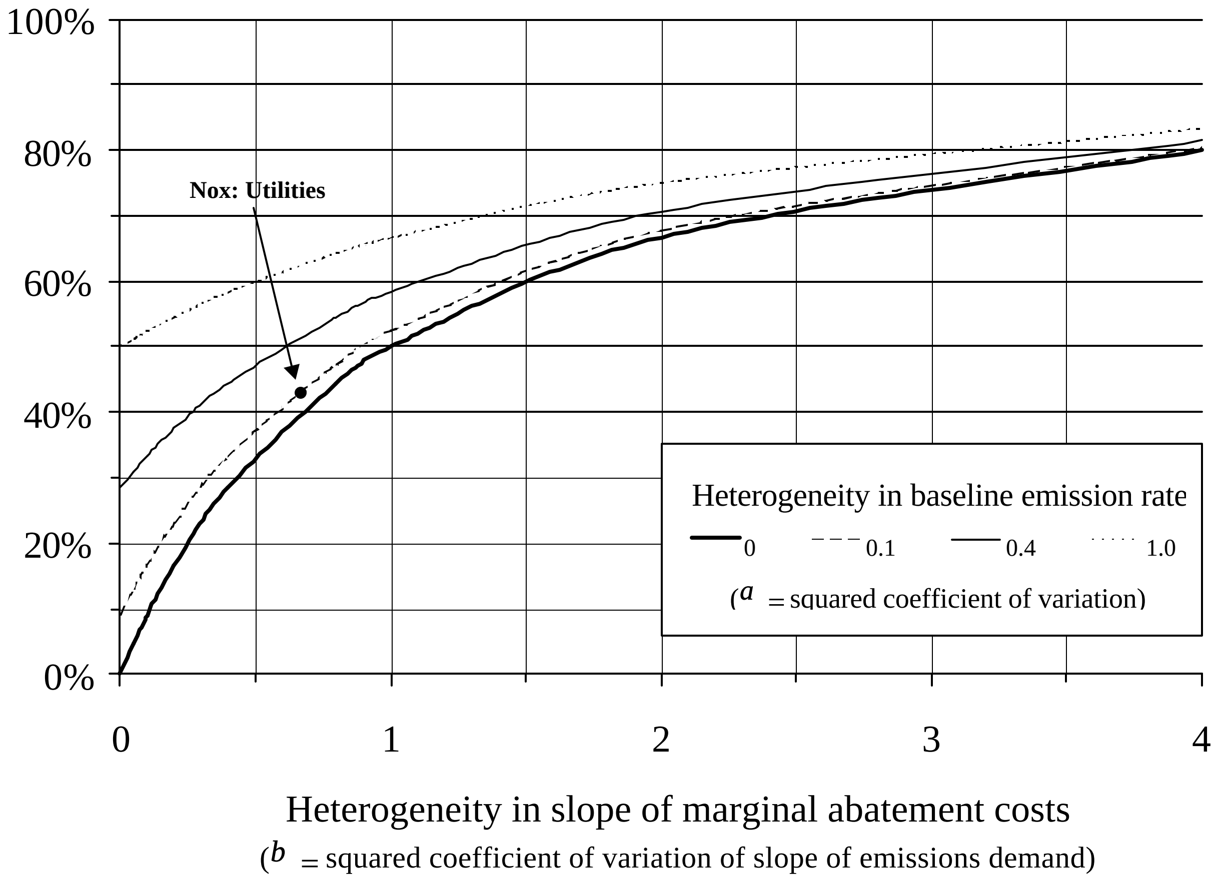


Figure 2. Cost Savings of Market-Based Policy

Relative to Uniform Percent Reduction Standard



Note: The figure applies to any rate of emission reduction because R does not enter into the equation describing percent cost savings relative to a uniform percent reduction standard.

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(xlii) This paper was presented at the International Workshop on "Climate Change and Mediterranean Coastal Systems: Regional Scenarios and Vulnerability Assessment" organised by the Fondazione Eni Enrico Mattei in co-operation with the Istituto Veneto di Scienze, Lettere ed Arti, Venice, December 9-10, 1999.

(xliii)This paper was presented at the International Workshop on “Voluntary Approaches, Competition and Competitiveness” organised by the Fondazione Eni Enrico Mattei within the research activities of the CAVA Network, Milan, May 25-26,2000.

(xliv) This paper was presented at the International Workshop on “Green National Accounting in Europe: Comparison of Methods and Experiences” organised by the Fondazione Eni Enrico Mattei within the Concerted Action of Environmental Valuation in Europe (EVE), Milan, March 4-7, 2000

(xlv) This paper was presented at the International Workshop on “New Ports and Urban and Regional Development. The Dynamics of Sustainability” organised by the Fondazione Eni Enrico Mattei, Venice, May 5-6, 2000.

(xlvi) This paper was presented at the Sixth Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Louvain-la-Neuve, Belgium, January 26-27, 2001

(xlvii) This paper was presented at the RICAMARE Workshop “Socioeconomic Assessments of Climate Change in the Mediterranean: Impact, Adaptation and Mitigation Co-benefits”, organised by the Fondazione Eni Enrico Mattei, Milan, February 9-10, 2001

(xlviii) This paper was presented at the International Workshop “Trade and the Environment in the Perspective of the EU Enlargement ”, organised by the Fondazione Eni Enrico Mattei, Milan, May 17-18, 2001

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(l) This paper was presented at the Workshop “Growth, Environmental Policies and Sustainability” organised by the Fondazione Eni Enrico Mattei, Venice, June 1, 2001

(li) This paper was presented at the Fourth Toulouse Conference on Environment and Resource Economics on “Property Rights, Institutions and Management of Environmental and Natural Resources”, organised by Fondazione Eni Enrico Mattei, IDEI and INRA and sponsored by MATE, Toulouse, May 3-4, 2001

(lii) This paper was presented at the International Conference on “Economic Valuation of Environmental Goods”, organised by Fondazione Eni Enrico Mattei in cooperation with CORILA, Venice, May 11, 2001

(liii) This paper was circulated at the International Conference on “Climate Policy – Do We Need a New Approach?”, jointly organised by Fondazione Eni Enrico Mattei, Stanford University and Venice International University, Isola di San Servolo, Venice, September 6-8, 2001

(liv) This paper was presented at the Seventh Meeting of the Coalition Theory Network organised by the Fondazione Eni Enrico Mattei and the CORE, Université Catholique de Louvain, Venice, Italy, January 11-12, 2002

(lv) This paper was presented at the First Workshop of the Concerted Action on Tradable Emission Permits (CATEP) organised by the Fondazione Eni Enrico Mattei, Venice, Italy, December 3-4, 2001

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