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Correlated Uncertainty and Policy Instrument Choice[1]

ROBERT N. STAVINS

John F. Kennedy School of Government, Harvard University, Cambridge, Massachusetts 02138, and Resources for the Future, Washington, DC 20036

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For two decades, environmental economists have generally maintained that benefit uncertainty is irrelevant for choosing between price and quantity instruments, but that cost uncertainty matters, with the identity of the efficient instrument depending upon the relative slopes of the marginal benefit and cost functions. But, in the presence of simultaneous, correlated uncertainty, such policy instrument recommendations may be inappropriate. With plausible values of relevant parameters, the conventional identification of a price instrument will be reversed, to favor instead a quantity instrument. The opposite reversal—from the choice of a quantity instrument to a price instrument—seems less likely to occur.

1. INTRODUCTION

Policymakers are regularly confronted with the dual tasks of choosing environmental goals and selecting policy instruments to achieve those goals. Both tasks must be carried out in the presence of the significant uncertainty that affects the benefits and the costs of environmental protection. Since Weitzman's [20] classic paper "Prices vs. Quantities," it has been generally acknowledged that benefit uncertainty on its own has no effect on the identity of the optimal (efficient) control instrument, but that cost uncertainty can have significant effects, depending upon the relative slopes of the marginal benefit (damage) and marginal cost functions. Environmental economists have made frequent use of these results.[2]

In the real world, we rarely encounter situations in which there is exclusively either benefit uncertainty *or* cost uncertainty. On the contrary, in the environmental arena, we typically find that the two are present simultaneously. Furthermore, more often than not, it is benefit uncertainty that seems to be of substantially greater magnitude. What can be said about optimal policy instruments under these conditions? This paper addresses this question by drawing upon an element of Weitzman's [20] original analysis that has been neglected by environmental

[1] This paper has benefitted from comments by Martin Weitzman, Wallace Oates, Alex Pfaff, Richard Zeckhauser, and two anonymous referees, and research assistance by Richard Newell. The author alone is responsible for any errors.

[2] In this large and still growing literature, the effect of benefit uncertainty on instrument choice has been slighted, but not ignored. Adar and Griffin [1] made the point in the starkest terms: "... the introduction of uncertainty in the damage function has nothing to say about the choice of policy instruments" (p. 180). Likewise, Fishelson [5] observed that "... the randomness of the parameters of the marginal benefit function is irrelevant to the decision on the policy mean since the expected social losses from a quota and a tax policy are identical" (p. 196). More recently, Baumol and Oates [3] reemphasized that "when the regulator does not know the true position of the benefits curve, ... the resulting error and the corresponding social cost will be the same under effluent charges and marketable permits" (p. 60).

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economists over the intervening 20 years. We demonstrate that within a range of plausible values of relevant parameters, the presence of simultaneous and correlated benefit and cost uncertainty can reverse a conventional finding of price or quantity instrument superiority based upon the usual relative-slopes rule.

In Part 2 of the paper, we briefly review the reasoning behind the classic rule of instrument choice in the presence of uncertainty, and we examine graphically and mathematically what can happen—theoretically at least—when benefit uncertainty and cost uncertainty are simultaneously present and correlated with one another. That begs the question, however, of whether such correlated uncertainty is *likely* to matter in actual policy contexts, and so we turn to this critical and fundamentally empirical issue in Part 3 of the paper. Finally, Part 4 provides a brief conclusion and recommendations for further research.

2. UNCERTAINTY AND INSTRUMENT CHOICE: CAN BENEFIT UNCERTAINTY MATTER?

2.1. *The Standard Analysis*

The general notion of the significance of cost uncertainty, the irrelevance of benefit uncertainty, and the importance of the relative slopes of the two functions for policy instrument choice appeared as early as 1971 in papers by Lerner [12] and by Upton [17], and was formalized by Weitzman [20], Adar and Griffin [1], Fishelson [5], and Roberts and Spence [15].[3] In his very general approach, Weitzman assumed that the random error characterizing uncertainty[4] was sufficiently small to justify quadratic approximations of generalized total cost and total benefit functions—in other words, linear approximations to the respective marginal benefit and marginal cost functions. In this way, he found that the ‘‘comparative advantage’’ of a price instrument over a quantity instrument[5] was given by

$$\Delta_{\mathrm{pq}} \approx \frac{\sigma_{\mathrm{C}}^2 B''}{2C''^2} + \frac{\sigma_{\mathrm{C}}^2}{2C''}, \tag{1}$$

[3] The latter group of authors appears not to have not been aware of one another’s work, but Adar and Griffin [1] refer to Lerner [12], and Fishelson [5] refers to Upton [17]. Lerner [12] provided an intuitive and nearly correct description of the principal results of the ‘‘Weitzman analysis.’’ Lerner [12] noted that relative slopes matter, but suggested incorrectly that (independent) benefit uncertainty and cost uncertainty would have symmetric effects on instrument choice.

[4] Weitzman’s [20] original analysis and most of those that have followed (including the present article) focus on uncertainty on the part of the regulatory agency. Of course, firms that are regulated are also likely to be uncertain about the relevant environmental benefit function, *and* in some cases these firms may also be uncertain about their own marginal costs of control. The latter case was investigated by Adar and Griffin [1], Baron and Myerson [2], and others. When firms are risk neutral, the usual results follow; otherwise not.

[5] Although it is restrictive to limit consideration to the dichotomous choice between price and quantity instruments, this has been the approach of the bulk of the sizable literature that followed Weitzman’s [20] earliest work. For discussions of hybrid instruments, see [15] and [19].

where

Δ_{pq} is the net welfare advantage of the price instrument, relative to the quantity instrument;
B'' is the slope of the marginal benefit function, the second derivative of the total benefit function, B;
C'' is the slope of the marginal cost function, the second derivative of the total cost function, C;
σ_C^2 is the variance of costs;

and the "$\approx$" sign is used to represent "an accurate local approximation" in the traditional Taylor theorem sense.

Despite the frequent citations in the environmental economics literature to Weitzman [20], nearly all environmental studies have followed more closely the related approach of Adar and Griffin [1], who simply *assumed* linearity in the marginal benefit and marginal cost functions.[6] By doing so, they were able to arrive quite directly at an equivalent and exact version of Eq. (1), and to demonstrate their results with a compelling set of simple diagrams using expected and realized marginal benefit and marginal cost functions.

With MC_E and MC_R representing the expected and realized (linear) marginal cost functions, respectively, and MB representing (linear) marginal benefits, Fig. 1 illustrates a situation in which a relatively steeply sloped marginal cost curve argues

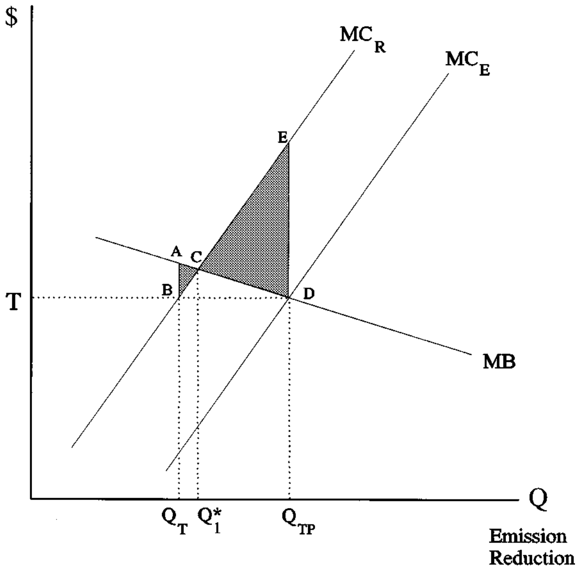

FIG. 1. Cost uncertainty and the choice of policy instrument.

[6] The conventional analysis also assumes that the error terms on the benefit and cost functions both enter additively. We follow this convention. Watson and Ridker [18] relaxed both this and the linearity assumptions, but maintained the implicit assumption of independence of the benefit and cost uncertainty terms.

for the use of a price instrument to minimize expected social losses. T is the magnitude of a Pigouvian tax (price instrument) set to achieve the expected socially optimal emission reduction; Q_{TP} is the quantity of tradeable permits (quantity instrument) allocated to achieve the same goal.[7] Because realized marginal costs are greater than anticipated (for any control level), the *ex post* efficient amount of emission reduction is Q_1^*. Clearly, the social loss associated with the tax option, the triangle ABC, is significantly less than that of the permit program, the triangle CDE.[8] Thus, as indicated in Eq. (1), instrument superiority is a function of the degree of cost uncertainty and the relative slopes of the marginal benefit and marginal cost functions.

Figure 2 illustrates the corollary finding that when the uncertainty is exclusively with marginal benefits, both instruments achieve the same realized level of control and hence exhibit the same social loss (relative to the *ex post* efficient control level, Q_2^* in Fig. 2). Hence, we have the adage that benefit uncertainty has no effect on efficient instrument choice, but cost uncertainty does matter, with the choice being driven by the relevant relative slopes.

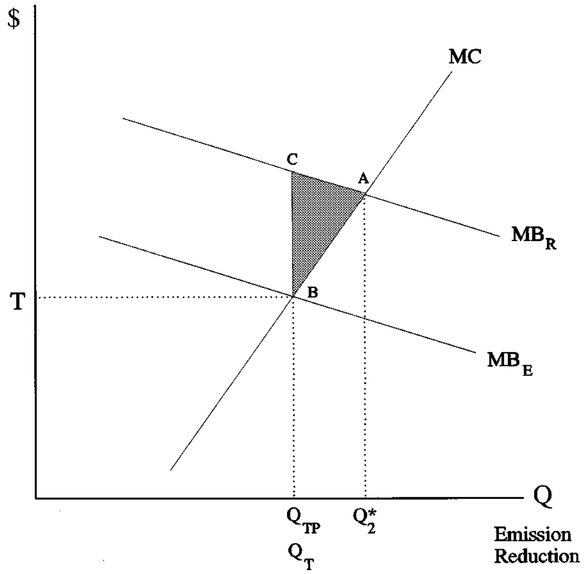

FIG. 2. Benefit uncertainty and the choice of policy instrument.

[7] In the environmental sphere, the quantity instrument need not be a market-based instrument, such as tradeable permits. For this analysis, it could as well be a so-called command-and-control instrument, such as a uniform performance standard. It makes no difference, since a ‘‘Weitzman analysis’’ focuses exclusively on efficiency, assuming cost effectiveness of all instruments [16].

[8] Given the assumed linearity of the functions, we can ignore the triangles and simply note that the departure of the tax outcome, Q_T, from the efficient control level, Q_1^*, is significantly less than the departure of the tradeable-permit outcome, Q_{TP}. The ratio of the social losses is equal to the ratio of the squares of the two departures.

2.2. *Simultaneous Uncertainty in Benefits and Costs*

The above analysis is correct as far as it goes, but it is restricted to situations in which there is *only* cost uncertainty or *only* benefit uncertainty. In the environmental policy context, we rarely encounter such situations. More often, there is simultaneous uncertainty on the two sides of the ledger. To examine this more common situation, we begin simply by combining the expected and realized functions (from Figs. 1 and 2) in a new diagram, Fig. 3. Despite the fact that the same expected and realized functions as before are pictured, we now find that the optimal instrument is no longer the Pigouvian tax, but the tradeable permit system instead: the absolute value of $Q^* - Q_{\mathrm{TP}}$ is less than the absolute value of $Q^* - Q_{\mathrm{T}}$ (and hence, the triangle CDE is smaller than the triangle ABC).

The reversal of relative efficiency of alternative policy instruments from the case of cost uncertainty alone to the case of simultaneous benefit–cost uncertainty is due exclusively to the change in the optimal level of control: compare Q_1^* in Fig. 1 to Q^* in Fig. 3; unchanged from one-figure to the other are Q_{T} and Q_{TP}. A quick examination of the figure suggests two further points worth noting. First, the size of this new effect appears to be proportional to the ratio of the magnitudes of the "shifts" in the marginal benefit and marginal cost functions; and second, if the marginal benefit function had "moved" in the opposite direction (decreased), relative to the "movement" of the marginal cost function, the result would not have been to reverse the choice of a tax instrument, but to strengthen the superiority of that instrument.

How should we think about these results in more general and more rigorous terms? The foundation for the answer to that question was provided by Weitzman [20] two decades ago. In a footnote that inspired surprisingly little subsequent work

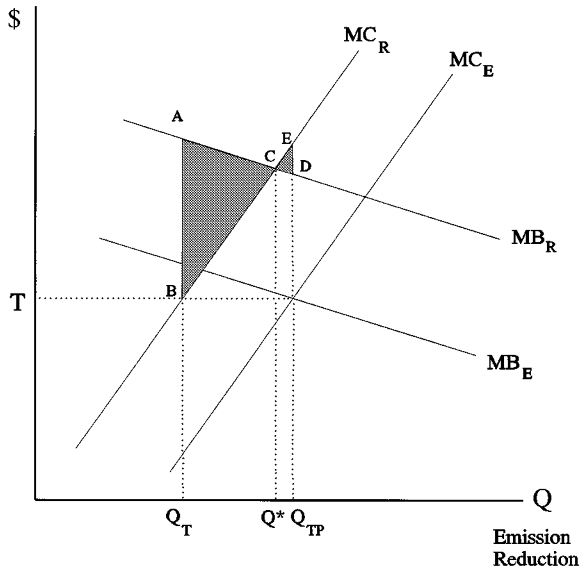

FIG. 3. Simultaneous benefit and cost uncertainty and the choice of policy instrument.

by environmental economists,[9] Weitzman noted that if benefit uncertainty and cost uncertainty are simultaneously present *and* benefits and costs are *not* independently distributed, the correct form of Eq. (1) becomes:[10]

$$\Delta_{pq} \approx \frac{\sigma_C^2 B''}{2C''^2} + \frac{\sigma_C^2}{2C''} - \frac{\sigma_{BC}^2}{C''}, \tag{2}$$

where $\sigma_{BC}^2 = E\{B - E[B]\} \cdot E\{C - E[C]\}$, the covariance of benefits and costs.[11]

In order to explore the full implications of this and understand its relationship with Fig. 3, we rewrite Eq. (2) as

$$\Delta_{pq} \approx \frac{\sigma_C^2}{C''} \cdot \left[\frac{B''}{2C''} + \frac{1}{2} - \frac{\rho_{BC} \cdot \sigma_B}{\sigma_C} \right], \tag{3}$$

where

ρ_{BC} is the correlation (coefficient) between benefits and costs;
σ_B is the standard deviation of benefits; and
σ_C is the standard deviation of costs.

Consistent with the implications of Fig. 3, we can now make several observations, based upon Eq. (3):

1. *When there is statistical dependence between benefits and costs* (*a non-zero correlation*), *benefit uncertainty does matter in our choice of optimal instrument*.

2. *It is always the case that a positive correlation tends to favor the quantity instrument* (*permits*). This is reflected in Fig. 3 by the two realized functions

[9] Yohe's [21] general survey article noted Weitzman's full expression but did not comment upon the possible significance of the additional term or explore its potential policy importance. Inman [8] carried out a theoretical inquiry on the optimal size of government activities (in the wake of California's Proposition 13 restrictions on property taxes) and noted the potential effects of correlated errors, following Weitzman, but did not elaborate on why such correlations might be present and did not examine their numerical significance. Butler and Maher [4] examined a situation related to that of uncertainty, the effect of economic growth on the identification of the optimal policy instrument, where growth affects both marginal costs and marginal benefits. Koenig [10] carried out a theoretical inquiry of alternative policies to regulate stock externalities in an open-access fishery. He allowed for correlation, but did not pursue its consequences. In the analysis that went furthest, Mendelsohn [13] examined an issue closely related to the ‘‘Weitzman problem’’—the choice between (uniform) price and quantity instruments when benefits and abatement costs are heterogeneous. He allowed for correlation between the random variables that characterize the distributions of benefits and costs. Given the similarity of Mendelsohn's policy problem to the choice between price and quantity instruments under conditions of uncertainty, it is not surprising that the expression he derived for the welfare advantage of a price over a quantity instrument [his Eq. (10)] is similar (although not identical) to the Weitzman equation, stated above as Eq. (2). Other papers that recognized the existence of the covariance term in the full Weitzman equation were by Koenig [11] and Yohe [22, 23, 24].

[10] Because it will be helpful in the analysis that follows, we have rearranged the terms from Weitzman's original version found in his footnote on p. 125.

[11] The Appendix provides the equivalent versions in the notation and format used by Adar and Griffin [1] and Baumol and Oates [3].

shifting in the same direction, relative to the respective expected functions. We can see this from Eq. (3) by noting that:

$$\frac{\partial \Delta_{\text{pq}}}{\partial(\sigma_{\text{B}} \cdot \sigma_{\text{C}})} = -\frac{\rho_{\text{BC}}}{C''}. \tag{4}$$

When ρ_{BC} is positive, the right-hand side of Eq. (4) is unambiguously negative, and so increases in benefit and cost uncertainty $(\sigma_{\text{B}}\sigma_{\text{C}})$ favor a quantity instrument. When ρ_{BC} is negative, we have the opposite situation, and so the next observation follows.

3. *A negative correlation always tends to favor the price instrument* (*taxes*), ceteris paribus. This would be reflected in a figure in which the realized marginal benefit and cost functions shifted in opposite directions, relative to their respective expected values.

These initial observations merit some brief discussion to display the intuition behind them in terms of practical public policy. First of all, if Pigouvian taxes, for example, are utilized to control pollutant emissions, firms will respond to unexpectedly high marginal control costs by reducing their control efforts. But if there is a positive correlation between uncertain benefits and uncertain costs, then at the precise time that firms are reducing their control efforts, the marginal benefits of those efforts will be unexpectedly great. Hence, the firms' natural response to the Pigouvian tax will be particularly *inapproriate*. On the other hand, if there is a negative correlation between the marginal benefits and marginal costs of control, then unexpectedly high marginal control costs will be associated with unexpectedly low marginal benefits, meaning that a tax instrument will lead firms to reduce their control efforts (because of high control costs) at times at which the marginal benefits of those efforts are unusually low; hence, the tax instrument leads to particularly *appropriate* actions.

4. *The greater the benefit or the cost uncertainty and the lesser the slope of the marginal cost function, the greater is the impact of any degree of correlation between benefits and costs*. This is validated simply by examining the appropriate partial derivative:

$$\frac{\partial \Delta_{\text{pq}}}{\partial \rho_{\text{BC}}} = -\frac{\sigma_{\text{B}}\sigma_{\text{C}}}{C''}. \tag{5}$$

Note that the right-hand side of Eq. (5) is unambiguously negative, a reminder of the fact that increases in the correlation coefficient always favor the quantity instrument, while decreases always favor the price instrument.

5. *Theoretically these effects can overwhelm the usual relative-slopes instrument recommendation*. It is conceivable that the magnitude (and sign) of the final term in Eq. (3) could be sufficient to change the sign of the entire right-hand side of the equation, thus changing the optimal instrument from a price to a quantity instrument, or vice versa.

6. *The "instrument-neutrality" ordinarily identified with equal absolute valued slopes of the expected marginal benefit and marginal cost functions disappears when there is a significant correlation between benefits and costs*. By setting B'' equal to $-C''$ in Eq.

(3), we have:

$$\Delta_{pq} \approx -\frac{\rho_{BC} \cdot \sigma_B \cdot \sigma_C}{C''} = -\frac{\sigma_{BC}^2}{C''}. \tag{6}$$

Thus, the rule becomes: if (the absolute values of) the slopes are identical and if ρ is negative, a price instrument is optimal; if ρ is positive, a quantity instrument is optimal. Furthermore, we can see in Eq. (6) that with equally sloped marginal benefit and marginal cost functions, the comparative advantage of the price instrument increases (in the presence of a negative correlation) with increases in the magnitude of benefit and cost uncertainty and with decreases in the slope of the marginal cost function.

3. IS BENEFIT UNCERTAINTY LIKELY TO MATTER?

The fact that statistical dependence between the benefits and costs of environmental protection efforts *can* make a difference obviously does not mean that it *will* make a difference. In this part of the paper, we address this fundamental issue by addressing three questions. First, is it reasonable to suggest that benefit uncertainty is significant in the environmental arena, particularly relative to cost uncertainty? Second, is it reasonable to assume that in many cases, the marginal benefits and marginal costs of environmental protection are indeed correlated? Third, even if the first two questions are answered in the affirmative, is there any reason to believe that these factors are likely to be sufficiently important to *overwhelm* a ‘‘conventional analysis’’ of efficient instrument choice, based on the simpler relative-slopes rule?

First of all, while it is true that significant uncertainty continues to envelop our estimates of the costs of achieving environmental goals,[12] even a casual reading of the environmental economics and environmental policy literatures will suggest that benefit uncertainty is ubiquitous. Indeed, most economists and non-economists alike would probably estimate that the magnitude of environmental benefit uncertainty is, at least in some cases, significantly greater than the respective degree of cost uncertainty.[13]

If benefit uncertainty and cost uncertainty are both present, it is necessary to ask whether there is some degree of statistical dependence between them. Now, it seems reasonable to assert that for uniformly mixed pollutant problems, statistical *independence* of stochastic marginal benefits and stochastic marginal costs is a reasonable point of departure, partly because the technological forces driving abatement costs are likely to be different from the forces affecting benefits. But

[12] Only the most ‘‘naive theory of cost’’ would suggest that measuring the costs of environmental regulations is a trivial matter [7]. For an examination of the difficulties of estimating the true costs of environmental protection, see [9].

[13] In order for this comparison to have any meaning, both marginal benefits and marginal costs must be measured in the same units. This is hardly a new constraint, however, since the same is required in a fully deterministic setting.

when one thinks further about this question, various specific scenarios for statistical *dependence* between marginal benefits and marginal costs of environmental protection begin to come to mind. As we see below, it turns out that all but one of these plausible scenarios of statistical dependence is a story of *positive*, as opposed to negative, correlation.

First of all, the weather can be a generator of stochastic shocks that produce correlated impacts on marginal benefits and marginal costs of pollution control. In some cases, this could occur through the effect of the weather on the *formation* of pollutants. For example, the increased ultraviolet radiation that reaches the ground level on a sunny day means more ozone formation from oxides of nitrogen and volatile organic compounds. Hence, the marginal cost of ambient concentration reduction (and risk reduction) would increase. Of course, on beautiful sunny days, people are more likely to be outside, exercising, and breathing the ozone-laden air; hence, the marginal benefits of ambient-reduction would also increase, yielding a *positive* correlation between the relevant marginal benefits and marginal costs.

As another example, we can take the case of air pollution in a major metropolitan area such as Los Angeles. The still air associated with some weather patterns means an increase in the marginal cost of ambient concentration reduction (since the natural concentration-reduction brought about by significant air movements is absent). Likewise, such still air *and* the temperatures associated with it could mean that the most sensitive members of the population—those that suffer from respiratory ailments—would be more sensitive than otherwise to any given level of ambient concentration, producing a positive correlation.[14]

Various types of natural background conditions can generate similar correlations. We may be considering the efficient level of clean-up of an abandoned hazardous waste site. If there is substantial rain and flooding of the site, the marginal cost of clean-up will increase because the material will become more dispersed. At the same time, such inundation of the site will increase the likelihood that the contamination reaches an adjacent potable water source, thus increasing the marginal benefits of clean-up.

Finally, synergistic health effects could also give rise to a positive correlation. For example, a particularly dirty shipment of fuel arrives at an electrical utility. Hence, the marginal costs of sulfur dioxide (SO_2) emission and ambient-concentration reduction increase. At the same time, more of *other* pollutants, such as suspended particulates, may now be emitted. If there are synergistic effects on human health, then we would have a positive correlation between marginal benefits and marginal costs.

All but one of these examples are of *positive* correlations, suggesting in those cases that quantity instruments would be more attractive than otherwise. This takes us to the final question, however: whether or not the ‘‘correlation effect’’ is really likely to reverse the instrument choice we would otherwise make. In other words, under what conditions would a benefit−cost correlation overwhelm the usual

[14] A related story with weather patterns (courtesy of Wally Oates) provides our sole example of a potential *negative* correlation between marginal benefits and marginal costs. The still air associated with the London fog could mean an increase in the marginal costs of reducing ambient concentration of some air pollutants, but the drizzly fog might also reduce the number of persons strolling in the parks and hence reduce the marginal benefits of concentration reduction.

result? To address this question, we set the right-hand side of Eq. (3) equal to zero and solve for the "threshold value" of σ_B/σ_C, denoted $(\sigma_B/\sigma_C)^*$ below:

$$\left[\frac{\sigma_B}{\sigma_C}\right]^* = \left(\frac{1 + \frac{B''}{C''}}{2 \cdot \rho_{BC}}\right). \tag{7}$$

We can now use Eq. (7) to carry out a sensitivity analysis to provide some guidance as to whether or not the correlation effect and related benefit uncertainty are likely to make a real difference, i.e., whether they can overwhelm the policy-instrument recommendation we might otherwise support. Because the above real-world examples of benefit–cost correlations are mostly positive, we focus first on parameter values that will lead us to switch from recommending a price (tax) instrument to a quantity (permit) instrument.

The results of this first sensitivity analysis are found in Table I. These results are somewhat striking. To take one example, even if the marginal cost function is 10 times steeper than the benefit function ($-B''/C'' = 0.10$)—normally favoring heavily a price instrument—and the correlation coefficient (ρ) is no more than $+0.10$, it requires a benefit–cost uncertainty ratio (σ_B/σ_C) of "only" 4.5 to reverse our recommendation from a price to a quantity instrument. The threshold values associated with this and other sets of slopes and correlation coefficients are pictured in Fig. 4.

To be conservative, we can examine the situation with the most extreme ratios of slopes by focusing on the horizontal axis of the figure, where the ratio of $-B''$ to C'' approaches zero. At one extreme, we find that with a correlation coefficient of $+0.05$, a benefit–cost uncertainty ratio of 10.0 is required to reverse the instrument choice from prices to quantities, whereas with a correlation coefficient as high as $+0.50$, all that is required for us to reverse the instrument choice is that benefit uncertainty be at least as great as cost uncertainty. At an intermediate slope ratio of -0.5 (marginal costs twice as steeply sloped as marginal benefits),

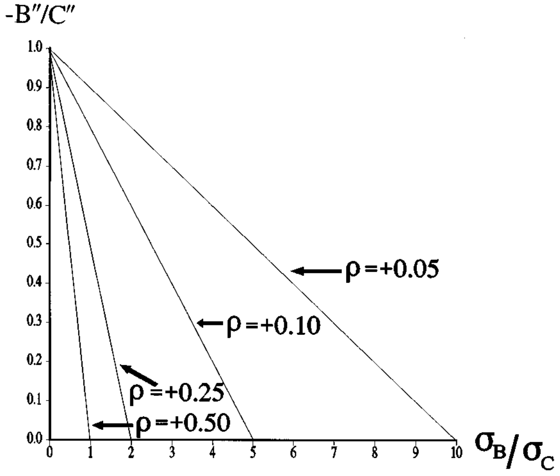

FIG. 4. Parameter values that reverse choice from a price to a quantity instrument.

TABLE I
Parameter Values That Reverse Choice from a Price to a Quantity Instrument

B''/C''	ρ_{BC}	$[\sigma_B/\sigma_C]^*$
− 0.50	0.50	0.5
	0.25	1.0
	0.10	2.5
	0.05	5.0
−0.20	0.50	0.8
	0.25	1.6
	0.10	4.0
	0.05	8.0
−0.10	0.50	0.9
	0.25	1.8
	0.10	4.5
	0.05	9.0

the threshold values of σ_B/σ_C required to overwhelm our normal choice under these conditions (of a price instrument) are 0.5, 1.0, 2.5, and 5.0, for correlation coefficients (ρ) of 0.50, 0.25, 0.10, and 0.05, respectively.

None of this is to suggest that the effect of statistically dependent benefits and costs will inevitably reverse any identification of prices (taxes) as the efficient policy instrument.[15] But the range of plausible parameter values in Table I at least suggests that we should be careful about any quick and potentially naive identification of price (tax) instruments for environmental protection on the grounds alone of cost uncertainty and relative slopes.

Given the smaller number of plausible stories of negative correlations between the marginal benefits and marginal costs of environmental protection, the corresponding analysis of threshold values that would take us from a quantity instrument to a price instrument may be of less consequence. Nevertheless, it is interesting to note that there is a significant asymmetry with the previous analysis. In this case (see Table II and Fig. 5), when the marginal benefit function is 10 times more steeply sloped than the marginal cost function (normally arguing strongly for a quantity instrument), and the correlation coefficient is −0.10, the threshold uncertainty ratio is fully 45.0. Thus, even if there were not such a preponderance of positive (versus negative) correlation stories, we might still

[15] Although the environmental economics literature abounds with estimates for specific environmental policies of the relevant ratio of slopes, B''/C'', reliable empirical estimates of the other crucial parameters, σ_B/σ_C and ρ, are hard to come by. Watson and Ridker [18] drew upon previous studies of air and water pollution control and presented confidence intervals that are suggestive of ratios of σ_B/σ_C ranging from about 2.0 for some forms of local air pollution to about 4.0 for non-point source water pollution. Other studies have presented ranges for estimates of the total costs and benefits of specific policies [14], but more frequently, those studies that have considered both the benefit and cost sides of policies have offered ranges for (total) benefits and simple point estimates for (total) costs [6]. Estimates of σ_B by itself are not uncommon, since most environmental valuation methods involve statistical estimation, but what is needed for empirical implementation is a *set* of internally consistent estimates of all the parameters. It should not be surprising that such sets of estimates (B'', C'', σ_B, σ_C, and ρ) have not been reported, since the potential importance of this set of parameters for policy instrument choice has typically not been recognized.

TABLE II
Parameter Values That Reverse Choice from a Quantity to a Price Instrument

B''/C''	ρ_{BC}	$[\sigma_B/\sigma_C]^*$
− 2.0	−0.50	1.0
	−0.25	2.0
	−0.10	5.0
	−0.05	10.0
−5.0	−0.50	4.0
	−0.25	8.0
	−0.10	20.0
	−0.05	40.0
−10.0	−0.50	9.0
	−0.25	18.0
	−0.10	45.0
	−0.05	90.0

conclude that the overall effect of correlated uncertainty tends to favor quantity instruments.

4. CONCLUSIONS

This paper suggests that for 20 years environmental economists have unfortunately tended to neglect an important insight in Weitzman's [20] analysis ''Prices vs. Quantities,'' namely that in the presence of simultaneous uncertainty in both marginal benefits and marginal costs and some statistical dependence between them, benefit uncertainty expressed through the covariance term *can* make a difference for identifying the efficient policy instrument.

A positive correlation tends to favor the quantity instrument, and a negative correlation favors the price instrument. We have also seen that the size of this

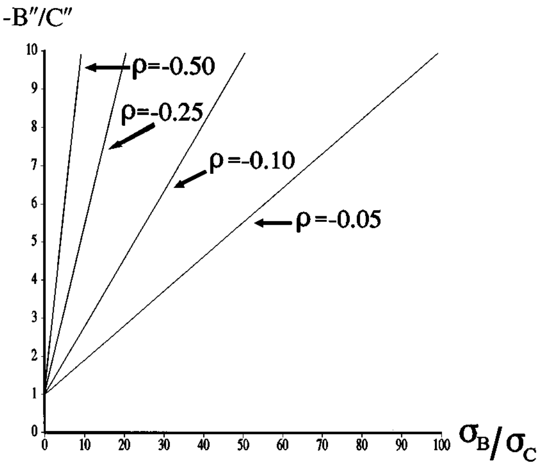

FIG. 5. Parameter values that reverse choice from a quantity to a price instrument.

effect is proportional to the degree of correlation between marginal benefits and marginal costs and the magnitudes of benefit and cost uncertainty. The instrument-neutrality long identified with equal absolute valued slopes of marginal benefits and marginal costs likewise disappears when there exists a significant correlation between them.

All of this is quite intuitive, and it is probably not surprising that these effects can theoretically overwhelm the usual policy instrument choice based upon relative slopes alone. What may be more surprising is our suggestion that with plausible values of the relevant parameters, the conventional identification of a price (tax) instrument for environmental protection (based upon the relative-slopes rule) can in fact be reversed, to favor instead a quantity instrument, such as tradeable emission permits. On the other hand, the results also suggest that it is less likely that the ‘‘correlation effect’’ will reverse a conventional identification of a quantity instrument as being more efficient to a price instrument.

Additional research can move beyond the simple sensitivity analysis carried out in this paper to explore the consequences for efficient instrument choice of actual values of the relevant parameters of the benefits and costs of specific environmental-protection policies.

APPENDIX

This appendix provides interpretations of Eq. (2) from the text, using the notation and format of Adar and Griffin [1] and Baumol and Oates [3], respectively, since these papers—along with Weitzman [20]—are the most frequently cited on this topic in the environmental economics literature. First, Adar and Griffin [1] provided the following expression of the welfare advantage of a quantity instrument over a price instrument [in their Eq. (26)]:

$$E(\tilde{s}) - E(\tilde{z}) = E(\mu^2) \cdot \left[(b - \beta)/2\beta^2\right] \tag{A.1}$$

where

$\tilde{s}$ is the welfare gain for a standards policy;
$\tilde{z}$ is the welfare gain for a tax policy;
μ is a linearly additive error on marginal costs;
b is the negative of the slope of a linear marginal damage function; and
β is the slope of a linear marginal cost function.

In Adar and Griffin's [1] formulation of the problem, the expanded expression that is equivalent to Eq. (2) in the text of this paper is

$$E(\tilde{s}) - E(\tilde{z}) = E(\mu^2) \cdot \left[(b - \beta)/2\beta^2\right] + E(\mu \cdot \epsilon)/\beta, \tag{A.2}$$

where ϵ is a linearly additive error on marginal benefits.

Baumol and Oates [3], drawing upon Adar and Griffin [1], derive the following expression for the welfare advantage of a price instrument over a quantity instrument [in their Eq. (11) on p. 72],

$$W(f^*) - W(q^2) = E(\mu^2) \cdot (\nu - b)/2\nu^2, \tag{A.3}$$

where

$W(f^*)$ is the welfare advantage of a price instrument;
$W(q^*)$ is the welfare advantage of a quantity instrument;
ν is the slope of a linear marginal cost function; and
β is the negative of the slope of a linear marginal benefit function.

In this formulation of the problem, the expanded expression equivalent to Eq. (2) in the text is

$$W(f^*) - W(q^2) = E(\mu^2) \cdot (\nu - b)/2\nu^2 - E(\mu \cdot \epsilon)/\nu. \qquad \text{(A.4)}$$

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