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Prices versus quantities with incomplete enforcement

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Abstract

I study whether incomplete enforcement of a regulation has any impact on the choice between price (e.g., taxes) and quantity (e.g., tradeable quotas) instruments. Results indicate that a second-best design accounting for incomplete enforcement can be implemented equally well with either instrument as long as the benefit and cost curves are known with certainty. If these curves are uncertain to the regulator, however, the quantity instrument performs relatively better than the price instrument. The reason is that the effective amount of control under the quantity instrument is no longer fixed, which makes this instrument come closer to a non-linear instrument.

Keywords: Environmental regulation; Uncertainty; Incomplete enforcement

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1. Introduction

Because regulations are not always fully enforced, it becomes very relevant to ask whether incomplete enforcement has any impact on the regulatory choice between price-based and quantity-based instruments. This control dilemma be-

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tween prices (e.g., taxes) and quantities (e.g., tradeable quotas) was first studied by Weitzman (1974), who showed that uncertainty about the marginal cost of control affects the choice between these two types of instruments. His work suggests that a quantity instrument should be used if the marginal benefit curve is steeper than the marginal cost curve; otherwise, a price instrument should be used.[1] This is because the price instrument leads to lower expected costs while the quantity instrument leads to higher expected benefits.

The literature on (optimal) regulatory enforcement, on the other hand, begins with Becker (1968), who pointed out that because enforcement is costly, it is not socially optimal to identify non-compliant agents all the time but rather do so sporadically and raise sanctions to the maximum feasible level.[2] Building upon both literatures, in this paper I compare price and quantity regulatory instruments under cost and benefit uncertainty as well as incomplete enforcement.

As in Weitzman (1974), my motivating example is that of instrument choice for pollution control, or more precisely, the choice between taxes and tradeable pollution quotas, which continues to attract great attention from environmental policy makers today (Fisher et al., 1996). A good example is given by the current debate on the design of policies (including the choice of instruments) to deal with climate change.

Imperfect monitoring and incomplete enforcement have proven to be very important factors in the practice of environmental regulation (Russell, 1990). The first models of incomplete enforcement used simple schemes to study the impact of enforcement on the performance and design of taxes and pollution standards (Harford, 1978; Viscusi and Zeckhauser, 1979) and tradeable quotas (Malik, 1990). Empirical observations of compliance rates higher than anything predicted by these simple models, however, motivated the development of richer models in the case of pollution standards.

Harrington (1988) modeled incomplete enforcement as a dynamic repeated game between the regulatory agency and firms. Firms detected to be in violation today are subject to more frequent inspections and higher fines tomorrow. In a recent paper, Livernois and McKenna (1999) offered a different explanation for the case of pollution standards. In their model, firms are required to self monitor their pollution and report their compliance status to the environmental agency, which has the enforcement power to bring into compliance any firm that is eventually found to have submitted a false report.[3] Both models produce

[1] A vast literature has followed, including Roberts and Spence (1976), Yohe (1978), Finkelshtain and Kislev (1997), Baldursson and von der Fehr (1998) and Hoel and Karp (1998). These authors have focused mostly but not exclusively on the comparison between taxes and tradeable quotas for pollution control.

[2] Subsequent literature includes, among many others, Stigler (1970), Kaplow and Shavell (1994) and Livernois and McKenna (1999).

[3] An effective enforcement policy should not only fine violators, but also bring violators under compliance (Russell, 1990).

compliance in cases in which the expected penalty for noncompliance is insufficient to prevent violations in the earlier models. To date, however, no such models have been developed for the case of taxes and tradeable quotas; consequently, developing these models is one objective of the present paper.

Although I frame the analysis of the paper within the context of environmental policy, nothing specific in the model indicates that its results do not apply in other contexts. As in Weitzman (1974), I restrict the analysis to linear instruments,[4] employing a multi-period framework with additive uncertainty in the marginal benefit and cost curves. I also assume that the regulatory choice and design remain unchanged over time.[5] To model incomplete enforcement, I use a simplified version of the multi-period model developed by Livernois and McKenna (1999), adapted to the cases of taxes and tradeable quotas.

I first show that a second-best design accounting for incomplete enforcement can be implemented equally well with either the price or the quantity instrument when cost and benefit curves are known with certainty. However, if the regulator is uncertain about the benefit and cost curves, the quantity instrument performs relatively better than the price instrument. In fact, if the slope of the marginal benefit curve is equal to the slope of the marginal cost curve, the quantity instrument provides higher expected social welfare than the price instrument. The reason is that, with incomplete enforcement, the effective (or observed) amount of control under the quantity instrument is no longer fixed, but endogenously determined, depending upon the shape of the actual (i.e., ex-post) marginal cost curve. For example, if the marginal cost curve proves to be higher than expected by the regulator, some firms would choose not to comply with the regulation; consequently, the effective amount and cost of control would be lower than expected.

When the amount of control is endogenous to the actual cost of control, welfare differences between price and quantity regimes change in two ways: the advantage of prices over quantities on the cost side and the advantage of quantities over prices on the benefit side are reduced. Overall, however, the advantage of prices over quantities is reduced. This results is because incomplete enforcement 'softens' the quantity regime, making it resemble a non-linear instrument, as in Roberts and Spence (1976). When costs prove to be higher than expected, in Roberts and Spence (1976) firms pay some large fee instead of buying quotas, which is superior to using just quotas; here, some firms choose not to comply.

The rest of the paper is organized as follows. In Section 2, I present the model

[4] Although in theory, nonlinear instruments provide higher welfare (Dasgupta et al., 1980; and Roberts and Spence, 1976), in practice they have not been used by policy makers (Stavins, 2001).

[5] The regulator may (imperfectly) deduce uncertainty shocks with a lag from the aggregate behavior of firms. But either because he must adhere to the original regulatory design or because new sources of shocks arise all the time, the issue of uncertainty is never resolved. See Weitzman (1974) for a complete discussion of these issues.

and explain compliance under prices (taxes) and quantities (tradeable quotas). In Section 3, I explore the second-best design under incomplete enforcement for two cases: that in which benefit and cost curves are known with certainty, and that in which these curves are uncertain. In Section 4, I address the central question of instrument choice under benefit and cost uncertainty and incomplete enforcement. Concluding remarks are offered in Section 5.

2. The model

Consider the following multi-period model of infinite horizon. Beginning in period 1, a continuum of firms of mass 1 are subject to an environmental regulation that could take the form of either taxes (the price instrument) or tradeable quotas (the quantity instrument). Let τ be the tax level the regulator sets in each period under the price regime, and x the number of quotas the regulator distributes in each period under the quantity regime.

In the absence of regulation, each firm emits one unit of pollution in each period. Pollution can be abated at a cost c per period. The value of c differs across firms according to the (continuous) density function $g(c)$ and cumulative density function $G(c)$ defined over the interval $[\underline{c},\bar{c}]$. These functions are commonly known by both firms and the welfare-maximizing regulator. Although the regulator does not know the control cost of any particular firm, he can derive the aggregate abatement cost curve for the industry, $C(q)$, where $0 \le q \le 1$ is the aggregate quantity of emissions reduction in any given period.[6] The regulator also knows that the benefit curve from emissions reduction in any given period is $B(q)$. As usual, I assume that $B'(q) > 0$, $B''(q) \le 0$, $C'(q) > 0$, $C''(q) \ge 0$, $B'(0) > C'(0)$, and $B'(q) < C'(q)$ for q sufficiently large.

The regulator is also responsible for ensuring individual firms' compliance with either the price or the quantity instrument. Firms are required to monitor their own emissions and submit a compliance status report to the regulator. Emissions are not observed by the regulator except during costly inspection visits, when they can be measured accurately. Thus, some firms may have an incentive to report themselves as being in compliance when, in reality, they are not. The compliance report also includes either tax payments or details of quota transfers, which are assumed to be tracked at no cost by the regulator. As an example, someone submitting a report with one unit of pollution and no tax payment can identified easily. Similarly, a firm A submitting a report with one unit of pollution and a 'false' quota transfer from firm B can be easily identified, since B would not report a transfer for which it does not get paid. To corroborate the truthfulness of reports

[6] The aggregate cost curve is $C(q) = \int_{\underline{c}}^{y} c\,dG$, where $y = G^{-1}(q)$. Note that $C'(q) = y$, $C'(0) = \underline{c}$, and $C''(q) = 1/g(y)$.

received, however, the regulator must observe emissions, which is a costly process.

The cost of each inspection is v, which I assume to be large enough that full compliance is not socially optimal (Becker, 1968).[7] Therefore, in order to verify reports' truthfulness, the regulator randomly inspects those firms reporting compliance through pollution reduction to monitor their emissions (or check their abatement equipment). Each firm reporting compliance faces a probability ϕ of being inspected. Firms found to be in disagreement with their reports are levied a fine F ($\leq \bar{F}$, where $\bar{F}$ is the maximum feasible fine, which value is beyond the control of the regulator) and brought under compliance in the next period.[8] To come under compliance, firms can reduce pollution or, depending on the regulatory regime, either pay taxes or buy quotas. Firms reporting noncompliance face the same treatment, so it is always in a firm's best economic interests to report compliance, even if that is not the case.[9] Finally, I assume that the regulator does not alter its policy of random inspections in response to information acquired about firms' type, so each firm submitting a compliance report faces a constant probability ϕ of being inspected.[10]

We now turn to describing firms' optimal compliance under each regulatory regime (i.e., taxes and tradable quotas) when enforcement is incomplete.

2.1. Compliance with prices (taxes)

Given the tax level τ, inspection probability ϕ and fine F (assume for the moment that $\phi F < \tau$), each firm seeks the compliance strategy that minimizes its expected discounted cost of compliance. Depending on the value of these parameters and its marginal abatement cost c, a firm will follow one of two possible strategies: (i) compliance and submission of a truthful report (S_{CT}), and (ii) noncompliance and submission of a false report declaring compliance (S_{NF}). Compliance can be achieved by either reducing pollution or paying the tax. Because the horizon is infinite, a firm following a particular strategy at date t will

[7] Alternatively, we can simply say that the regulator lacks sufficient resources to induce full compliance.

[8] To make sure that a non-compliant firm found submitting a false report is in compliance during the next period (but not necessarily the period after), we can assume that the regulator always inspects the firm during that next period, and in the case the firm is found to be out of compliance again, the regulator raises the penalty to something much more severe.

[9] Noncompliance and truth-telling could be a feasible strategy if firms reporting noncompliance were subject to a fine lower than F. See Kaplow and Shavell (1994) and Livernois and McKenna (1999) for details.

[10] As game theoretic models of incomplete enforcement have shown (for example, Harrington, 1988), the regulator clearly can improve upon a uniform inspection probability after learning (maybe imperfectly) about firms' type. But because the amount of control would still be depending on the actual control costs, the main result of the present paper would not change.

find it optimal to follow the same strategy at date $t+1$. The date subscript is therefore omitted in the calculations that follow.[11]

Let us first consider the case in which a firm has relatively low control costs, that is, $c < \tau$. Such a low-cost firm will never consider paying taxes as part of its compliance strategy. If S_{CT} is its optimal strategy, it will comply by reducing pollution. Conversely, if S_{NF} is its optimal strategy, should it be found submitting a false compliance report, it will return to compliance by reducing pollution instead of paying taxes.

The expected discounted cost of adopting strategy S_{CT} (compliance and truth-telling) for a low-cost firm is given by

$$Z^l_{CT} = c + \delta Z^l_{CT} \tag{1}$$

where δ is the discount rate and superscript 'l' signifies a low-cost firm. In this period, the firm incurs a cost c from pollution reduction, and during the next period, the firm incurs the present value of following S_{CT} again. Solving (1) gives

$$Z^l_{CT} = \frac{c}{1-\delta} \tag{2}$$

The expected discounted cost of adopting strategy S_{NF} (noncompliance and false reporting) for the same low-cost firm (i.e., $c < \tau$) is given by

$$Z^l_{NF} = 0 + \phi(F + \delta c + \delta^2 Z^l_{NF}) + (1-\phi)(\delta Z^l_{NF}) \tag{3}$$

In this period, the firm incurs no abatement costs. If the firm is found to have submitted a false report, which happens with probability ϕ, the firm must immediately pay the fine F and return to compliance during the next period by reducing pollution at cost c (which is cheaper than paying the tax τ). After that, the firm follows S_{NF} again, with an expected cost of Z^l_{NF}. If the firm is not inspected, which happens with probability $1-\phi$, the firm incurs no cost during this period, and next period follows S_{NF} again, with an expected cost of Z^l_{NF}. Solving (3) gives

$$Z^l_{NF} = \frac{\phi(F + \delta c)}{(1-\delta)(1+\phi\delta)} \tag{4}$$

A low-cost firm is indifferent between following S_{CT} or S_{NF} if $Z^l_{CT} = Z^l_{NF}$. Letting $\tilde{c}$ be the marginal cost that makes $Z^l_{CT} = Z^l_{NF}$, we have that

$$\tilde{c} = \phi F \tag{5}$$

is the 'cut-off' point for a truthful compliance report when $c < \tau$. Thus, if $\underline{c} \le c \le \tilde{c}$, the firm follows S_{CT}, whereas if $\tilde{c} < c < \tau$, the firm follows S_{NF}. Note that $\tilde{c} < \tau$ by the assumption that $\phi F < \tau$; otherwise all low-cost firms would be in

[11] Montero (1999) develops a simpler one-period model yielding the same qualitative results.

compliance. We will return to this point after exploring the compliance behavior of all firms.

Let us now consider the case of a high-cost firm, that is, a firm for which $c \geq \tau$. Such a firm will never consider reducing pollution as part of its compliance strategy. If S_{CT} is its optimal strategy, it will comply by paying taxes. Conversely, if S_{NF} is its optimal strategy, when found submitting a false compliance report, it will return to compliance by paying taxes instead of reducing pollution. As before, the expected discounted cost of adopting strategy S_{CT} (compliance and truth-telling) for a high-cost firm is given by

$$Z^h_{CT} = \tau + \delta Z^h_{CT} \tag{6}$$

In this period, the firm incurs a cost τ corresponding to the tax payment, and during the next period the firm incurs the present value of following S_{CT} again. Solving (6) gives

$$Z^h_{CT} = \frac{\tau}{1-\delta} \tag{7}$$

The expected discounted cost of adopting strategy S_{NF} (noncompliance and false reporting) for a high-cost firm is given by

$$Z^h_{NF} = 0 + \phi(F + \delta\tau + \delta^2 Z^h_{NF}) + (1-\phi)(\delta Z^h_{NF}) \tag{8}$$

In this period, the firm incurs no abatement costs. If the firm is found to have submitted a false report, which happens with probability ϕ, the firm must immediately pay the fine F and return to compliance next period by paying taxes (which is cheaper than reducing pollution). After that, the firm follows S_{NF} again, with an expected cost of Z^h_{NF}. If the firm is not inspected, which happens with probability $1-\phi$, the firm does not incur any cost in this period, and next period follows S_{NF} again with an expected cost of Z^h_{NF}. Solving (8) gives

$$Z^h_{NF} = \frac{\phi(F + \delta\tau)}{(1-\delta)(1+\phi\delta)} \tag{9}$$

Because $\phi F < \tau$ by assumption, it is not difficult to show that $Z^h_{NF} < Z^h_{CT}$, so a high-cost firm will always follow S_{NF}.

Firms' compliance behaviors can be grouped according to their abatement costs as follows: *compliant* firms have very low abatement costs (i.e., $\underline{c} \leq c \leq \tilde{c}$) and always comply by reducing emissions; *non-compliant* firms have medium and high costs (i.e., $\tilde{c} < c \leq \bar{c}$). A non-compliant firm that is inspected returns to compliance by either reducing pollution if its abatement cost is in the medium range (i.e., $\tilde{c} < c \leq \tau$) or by paying taxes if its abatement cost is high (i.e., $\tau < c \leq \bar{c}$). Note that the above compliance characterization breaks down if $\phi F \geq \tau$. In such a case, there will be full compliance: low-cost firms (i.e., $\underline{c} \leq c \leq \tau$) will reduce pollution all the time, and high-cost firms (i.e., $\tau < c \leq \bar{c}$) will always pay taxes. Although

$\phi F \geq \tau$ is possible if inspection costs v are very low, in this paper we are interested in the case of partial compliance, or incomplete enforcement. Note also that if $\phi = 1$ and $F < \tau$, it is still possible to have a fraction of non-compliant firms.[12]

When there is only partial compliance with the tax regime, the effective amount of pollution reduction by the industry any given year is expected to be

$$q_e(\tau) = G(\tilde{c}) + \gamma[G(\tau) - G(\tilde{c})] \tag{10}$$

where the first term of the right-hand side represents reductions from low-cost compliant firms and the second term represents reductions from a fraction $\gamma = \phi/(1 + \phi)$ of formerly non-compliant firms that came into compliance this period by reducing one unit of pollution (subscript 'e' signifies effective amount).[13] As in Livernois and McKenna (1999), the second term of (10) shows that enforcement power yields much higher compliance rates than can simply be attributed to the fine F.

Similarly, the effective control costs incurred by the industry are expected to be

$$C_e(\tau) = \int_{\underline{c}}^{\tilde{c}} c dG + \gamma \int_{\tilde{c}}^{\tau} c dG \tag{11}$$

Note that as ϕ and/or F increases, $\tilde{c}$ approaches τ and $C_e(\tau)$ approaches $C(q)$.

2.2. Compliance with quantities (tradeable quotas)

Because firms' behavior is not affected at the margin, it makes no difference whether the regulator distributes x tradeable quotas for free or auctions them off. Without loss of generality, consider the regulator auctions off a total of x pollution quotas in every period and that the auction clearing price in any given period is p

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[12] Montero et al. (2000) presents evidence supporting this situation in the case of a system of tradeable quotas. All firms are inspected once a year, but many fail to comply with the regulation.

[13] Following the notation from Livernois and McKenna (1999), to determine γ, denote by K_t the number of non-compliant firms (i.e., those firms that follow S_{NF}) that are in compliance at date t, and by N_t the number of non-compliant firms that are out of compliance at date t, and let $K_t + N_t = 1$. In other words, K_t are non-compliant firms that were inspected in $t - 1$ and brought under compliance at date t. The value of K_t can then be obtained

$$K_t = \phi N_{t-1}$$

Note that in this multi-period model, at $t - 1$ there are N_{t-1} firms facing a probability ϕ of being inspected. Using $N_{t-1} = 1 - K_{t-1}$ and setting $K_t = K_{t-1}$ for steady state gives

$$K = \frac{\phi}{1 + \phi}.$$

(quotas cannot be banked).[14] By simply replacing τ by p in Section 2.1's analysis, we can infer an apparent 'compliance equivalence' between taxes and tradeable quotas. But because in the case of a quantity instrument p is endogenously determined, compliance with both instruments would be the same as long as the allocation x yields an equilibrium price p identical to the tax level τ.

To find the market equilibrium price of quotas p (or more specifically, the auction clearing price), we impose the market clearing condition that sales equal purchases[15]

$$x = \gamma[G(\bar{c}) - G(p)] \tag{12}$$

where $\gamma = \phi/(1+\phi)$ is again the fraction of non-compliant firms that are in compliance this period. The left-hand side of (12) is the total number of quotas supplied by the regulator, while the right-hand side is purchases from high-cost firms (i.e., $c > p$) following S_{NF} strategy that in this period come under compliance by buying quotas instead of reducing pollution. Solving (12) gives

$$p = G^{-1}(1 - \frac{x}{\gamma}) \tag{13}$$

where $G^{-1}(1 - x/\gamma)$ can be viewed as the marginal cost c just after $1 - x/\gamma$ units of pollution have been reduced.[16] Since the equilibrium price of quotas under full compliance would be $G^{-1}(1-x)$, which occurs when firms are in compliance all the time (in this model, when $\gamma = 1$), it is immediate that incomplete enforcement lowers the equilibrium price of quotas. The reason for this result is simply that noncompliance and quotas are (imperfect) substitutes, which depresses the net demand for quotas and therefore their price.

Finally, because compliance with quantities is similar to compliance with prices, the effective amount of pollution reduction, $q_e(x)$, and effective control costs, $C_e(x)$, under the quantity regime can be directly obtained, respectively, from Eqs.

[14] Note also that considering auctioned quotas instead of grandfathered quotas leaves both the tax and quota instrument in a similar position regarding revenue-recycling issues.

[15] To see that grandfathered quotas and auctioned quotas are equivalent, let us write the market clearing condition under grandfathered quotas (each firm receives x quotas for free)

$$xG(\tilde{c}) + x\gamma(G(p) - G(\tilde{c})) + x(1-\gamma)(G(\bar{c}) - G(\tilde{c})) = (1-x)\gamma(G(\bar{c}) - G(p))$$

On the left-hand side we have three types of sellers of quotas: compliant firms, a fraction γ of non-compliant firms that came into compliance this period by reducing emission so they can now sell their quotas in the market, and a fraction $(1-\gamma)$ of non-compliant firms that are not in compliance today. On the right-hand side we have the buyers of quotas: non-compliant firms that are in compliance this period by buying quotas instead of reducing pollution. Developing the expression above yields (12).

[16] Note that for a uniform distribution of $g(c) = 1/C'' = 1/(\bar{c} - \underline{c})$, we have

$$p = \bar{c} - \frac{C''}{\gamma}x$$

(10) and (11). It only requires replace τ by p, where $p = p(x)$ as shown by (13). Having understood firms' compliance behavior under incomplete enforcement, we now turn its effects on optimal instrument design and on instrument choice.

3. Optimal design under incomplete enforcement

Optimal instrument design (regardless of whether the instrument is price or quantity-based) is necessarily a second-best problem for reasons of asymmetrical information regarding c, uncertainty regarding $B(q)$ and $C(q)$, and the focus on linear instruments (i.e., prices or quantities). In this section I derive optimal designs for τ and x. I first consider the case in which benefit and cost curves are known with certainty, then repeat the analysis under uncertainty.

3.1. Certainty in cost and benefit curves

To find the second-best tax τ and optimal enforcement parameters F and ϕ, the regulator maximizes social welfare for any given period

$$W(\tau,F,\phi) = B(q_e(\tau)) - C_e(\tau) - v[\phi G(\tilde{c}) + (\gamma + \phi(1-\gamma))(G(\bar{c}) - G(\tilde{c}))] \tag{14}$$

where $q_e(\tau)$ is given by (10) and $C_e(\tau)$ is given by (11). The first two terms on the right-hand side give net benefits from pollution control, and the last term is the total cost of inspection per period. The number of inspections is obtained as follows. The first term in the bracket, $\phi G(\tilde{c})$, is the number of low-cost compliant firms that are inspected in each period. Among the non-compliant firms, $G(\bar{c}) - G(\tilde{c})$, during each period a fraction γ are in compliance today because the were inspected a period earlier. The regulator needs visit these firms to ensure that they are in fact in compliance. And finally, each non-compliant firm that remains out of compliance today (the number of which corresponds to the remaining fraction $1-\gamma$), faces a probability ϕ of being inspected.

While the optimal τ and ϕ are obtained by solving first-order conditions $\partial W/\partial\tau = 0$ and $\partial W/\partial\phi = 0$, the optimal F is equal to $\bar{F}$, the maximum feasible fine (Becker, 1968; Kaplow and Shavell, 1994). We assume that $\bar{F}$ and the optimal values of τ and ϕ are such that $\phi\bar{F} < \tau$.[17]

Under the quantity regime, the regulator sets x, F, and ϕ to maximize

$$W(x,F,\phi) = B(q_e(x)) - C_e(x) - v[\phi G(\tilde{c}) + (\gamma + \phi(1-\gamma))(G(\bar{c}) - G(\tilde{c}))] \tag{15}$$

[17] In practice, fines seem to be relatively low, as discussed by Livernois and McKenna (1999).

Since x is a function of p (see (13)), the regulator can simply replace x by p in (15) and determine the optimal p along ϕ and F, which is equivalent to maximizing (14). Because compliance strategies between prices and quantities are identical if $\tau = p$, as discussed in Section 2, we establish the following

Proposition 1. *When cost and benefit curves are known with certainty, it is irrelevant whether the regulator uses prices* (τ) *or quantities* (x) *to achieve the second-best outcome. Both instruments provide the same social welfare.*

We have seen that incomplete enforcement does not affect instrument choice if cost and benefit curves are known with certainty and the regulator implements a second-best design.[18] It remains for this section to determine whether such design remains optimal when the regulator is uncertain about both curves.

3.2. Cost and benefit uncertainty

In general, regulators must choose policy goals and instruments in the presence of significant uncertainty concerning both $B(q)$ and $C(q)$. Note, however, that while both the regulator and firms are uncertain about the true shape of the benefit curve, firms generally know or have a better sense than the regulator of the true value of their costs.

So far I have not assumed any particular shape for the benefit and cost curves. To keep the model tractable after the introduction of uncertainty, however, I follow Weitzman (1974) and Baumol and Oates (1988) in considering linear approximations for the marginal benefit and cost curves and additive uncertainty. Then, let the (certain) benefit and cost curves be, respectively

$$B(q) = \underline{b}q + \frac{B''}{2}q^2 \tag{16}$$

$$C(q) = \underline{c}q + \frac{C''}{2}q^2 \tag{17}$$

where $\underline{b} \equiv B'(0) > 0$, $B'' < 0$, and $C'' \equiv \bar{c} - \underline{c} > 0$ are all fixed coefficients.[19]

Next, let the regulator's prior for the marginal benefit curve be $\partial B(q,\eta)/\partial q = B'(q) + \eta$, where η is a stochastic term such that $E[\eta] = 0$ and $E[\eta^2] > 0$. In addition, for the marginal cost curve, let his prior be $c(\theta) = c + \theta$, where θ is another stochastic term such that $E[\theta] = 0$ and $E[\theta^2] > 0$. I assume that θ is

[18] If the regulator does not implement the second best design, incomplete enforcement does affect choice (see Montero, 1999).

[19] Note first that the linear marginal cost curve results simply from a uniform distribution for $g(c)$. Further, the notation $\underline{b}$ is meant to be consistent with $\underline{c}$ in the cost curve.

common to all individual costs $c \in [\underline{c},\bar{c}]$, which produces the desired 'parallel' shift of the aggregate marginal cost curve, $C'(q)$, by the amount θ. In other words, $\partial C(q,\theta)/\partial q = C'(q) + \theta$. Recall that the realization of θ is observed by all firms before they make and implement their compliance (and production) plans.[20]

The regulator's planning problem now is to choose the levels of τ or x and also ϕ and F that maximize expected social welfare. In the case of taxes, the regulator maximizes

$$W(\tau,F,\phi,\eta,\theta) = E\big[B(q_e(\tau,\theta),\eta) - C_e(\tau,\theta) \\ - v(\gamma + \phi(1-\gamma) - \gamma(1-\phi)G(\tilde{c}-\theta))\big] \quad (18)$$

where $q_e(\tau,\theta)$ and $C_e(\tau,\theta)$ can be derived from (10) and (11) as[21,22]

$$q_e(\tau,\theta) = \int_{\underline{c}+\theta}^{\tilde{c}} g(c-\theta)dc + \gamma \int_{\tilde{c}}^{\tau} g(c-\theta)dc \quad (19)$$

$$C_e(\tau,\theta) = \int_{\underline{c}+\theta}^{\tilde{c}} cg(c-\theta)dc + \gamma \int_{\tilde{c}}^{\tau} cg(c-\theta)dc \quad (20)$$

Substituting (19) and (20) into (18), and using the linear approximations above for the benefit and cost curves, the first-order condition for τ is

$$E\left[(\underline{b}+\eta)\frac{\gamma}{C''} + B'' q_e(\tau,\theta)\frac{\gamma}{C''} - \frac{\gamma\tau}{C''}\right] = 0 \quad (21)$$

where

$$q_e(\tau,\theta) = \frac{\gamma(F+\tau) - (\underline{c}+\theta)}{C''} = q_e(\tau) - \frac{\theta}{C''} \quad (22)$$

After taking expectation, it becomes clear that the first-order condition (21) is

[20] While it is true that the regulator may (imperfectly) deduce uncertainty with a lag from the aggregate behavior of firms, I am assuming that he adheres to the original regulatory design from the beginning of time. Alternatively, we can say that new sources of uncertainty arise continually, so the issue of uncertainty is never resolved. For example, we can let θ and η follow (independent or correlated) random walks. The computation of compliance strategies would be the same, but the computation of the welfare function would differ a bit because the variance of θ and η would grow linearly with time.

[21] Since $c(\theta) = c + \theta$, we replace dG by $g(\cdot)dc$ and $g(c)$ by $g(c-\theta)$, so we still have that $G(\underline{c}+\theta-\theta) = 0$ and $G(\bar{c}+\theta-\theta) = 1$.

[22] Note that if $\theta > 0$, inspection costs increase because there are more non-compliant firms.

independent of η and θ. Similarly, it is not difficult to show that the first-order condition for $\underline{\phi}$ is also independent of η and θ.[23] These two findings, along with the fact that $\bar{F}$ continues to be the optimal fine, imply that uncertainty does not affect the design of the price instrument.

In the case of tradeable quotas, the regulator chooses x, ϕ, and F to maximize

$$W(x,F,\phi,\eta,\theta) = E[B(q_e(x,\theta),\eta) - C_e(x,\theta) \\ - \upsilon(\gamma + \phi(1-\gamma) - \gamma(1-\phi)G(\tilde{c} - \theta))] \tag{23}$$

where $q_e(x,\theta)$ and $C_e(x,\theta)$ can be directly obtained, respectively, from (19) and (20) by simply replacing τ by the appropriate p, which is defined next.

As before, we can express x as a function of p and solve (23) for p instead of x. However, the equivalence with taxes is not so immediate as in the certainty case, because now p is a random variable for the regulator. In fact, using the market clearing condition (13) and a uniform distribution for $g(c)$, we have

$$p(x,\theta) = (\bar{c} + \theta) - \frac{C''}{\phi}x = \bar{p} + \theta \tag{24}$$

where $\bar{p} = \bar{p}(x) \equiv E[p(x,\theta)]$. Eq. (24) shows, as in the case of complete enforcement, that the equilibrium price of quotas adapts to the actual costs of control.

Thus, solving for x in (23) is equivalent to solving for $\bar{p}$. Using (24), we can express the effective amount of control, $q_e(x,\theta)$, and the effective cost of control, $C_e(x,\theta)$, as functions of $\bar{p}$. Replacing τ by $\bar{p} + \theta$ in (19) and (20), the first-order condition for $\bar{p}$ becomes

$$E\left[(\underline{b} + \eta)\frac{\gamma}{C''} + B''q_e(x,\theta)\frac{\gamma}{C''} - \frac{\gamma(\bar{p} + \theta)}{C''}\right] = 0 \tag{25}$$

where

$$q_e(x,\theta) = \frac{\gamma(F + p) - (\underline{c} + \theta)}{C''} = q_e(\bar{p}) - \frac{(1-\gamma)\theta}{C''} \tag{26}$$

[23] The first-order condition for ϕ is

$$E\left[(\underline{b}+\eta)\frac{F}{C''}\frac{\partial\gamma}{\partial\phi} + B''\cdot\left(q_e(\tau) - \frac{\theta}{C''}\right)\frac{F}{C''}\frac{\partial\gamma}{\partial\phi} - \frac{\phi F^2}{C''} - \frac{\tau^2}{2C''}\frac{\partial\gamma}{\partial\phi} + \frac{F^2}{2C''}\frac{\partial(\gamma\phi^2)}{\partial\phi} \\ - \upsilon\cdot\left(1 + \frac{\partial(\gamma(1-\phi))}{\partial\phi} - \frac{\partial(\gamma(1-\phi))}{\partial\phi}\frac{\phi F - \underline{c} - \theta}{C''} - \gamma(1-\phi)\frac{F}{C''}\right)\right] = 0$$

Taking expectations, the first-order condition becomes independent of η and θ.

Eq. (26) is one key result of this paper, so deserves some explanation. Because $\gamma < 1/2$, Eq. (26) shows that the effective amount of control under a quantity regime with incomplete enforcement, $q_e(x,\theta)$, is endogenous to the actual (i.e., ex-post) cost of control.[24] Indeed, if the actual cost of control happens to be higher than the regulator expected (i.e., $\theta > 0$), $q_e(x,\theta)$ will be lower. This is simply because the fraction $G(\tilde{c})$ of compliant firms reduces to $G(\tilde{c} - \theta)$ as costs increase. Conversely, if the actual cost of control happens to be lower than the regulator expected (i.e., $\theta < 0$), $q_e(x,\theta)$ will be higher.

Taking expectations on (25), we find that the first-order condition for $\bar{p}$ is identical to the first-order condition for τ stated in (21). Thus, if the enforcement policy is exogenous to the regulator, which is to say that the regulator takes ϕ and F as given when setting τ or x, uncertainty does not affect the design of the price instrument, and therefore, $\bar{p} = \tau$. However, if the regulator also decides upon ϕ, the first-order condition for ϕ may depend on the uncertainty parameters η and θ, so the optimal design for x and ϕ may change from the certainty case.[25] The reason for this is that γ interacts with θ in both $q_e(x,\theta)$ and $C_e(x,\theta)$, which does not happen in neither $q_e(\tau,\theta)$ nor $C_e(\tau,\theta)$.[26]

In summary, we can establish the following result

Proposition 2. *If the enforcement policy is exogenous* (*i.e.*, *ϕ and F are taken as given by the regulator*), *neither cost nor benefit uncertainty alters the second-best design for either prices or quantities*. *If the enforcement policy is endogenous* (*i.e.*, *ϕ and F are determined by the regulator*), *the price design remains the same as the certainty case while the optimal quantity design may differ from the certainty case*.

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[24]Recall that $\gamma = 1$ under full compliance.

[25]The first-order condition for ϕ under the quantity regime is

$$E\left[(\underline{b}+\eta)\frac{(F+\theta)}{C''}\frac{\partial\gamma}{\partial\phi} + B''\cdot\left(q_e(\bar{p}) - \frac{(1-\gamma)\theta}{C''}\right)\frac{(F+\theta)}{C''}\frac{\partial\gamma}{\partial\phi} - \frac{\phi F^2}{C''} - \frac{(\bar{p}+\theta)^2}{2C''}\frac{\partial\gamma}{\partial\phi} \right.$$
$$\left. + \frac{F^2}{2C''}\frac{\partial(\gamma\phi^2)}{\partial\phi} - v\cdot\left(1 + \frac{\partial(\gamma(1-\phi))}{\partial\phi} - \frac{\partial(\gamma(1-\phi))}{\partial\phi}\frac{\phi F - \underline{c} - \theta}{C''} - \gamma(1-\phi)\frac{F}{C''}\right)\right] = 0$$

After taking expectations, it is immediate that the deterministic part of the first-order condition is equal to the first-order condition under the tax regime. The stochastic part of the first-order condition is given by

$$E[2C''\eta\theta - (C'' - 2(1-\gamma)B'')\theta^2]\frac{1}{2(C'')^2}\frac{\partial\gamma}{\partial\phi}$$

In general, this stochastic term has a smaller weight than the deterministic term in the solution of the first-order condition above, and vanishes for reasonable values of the different parameters. For example, the term goes to zero when $E[\eta\theta] = 0$, $B'' = (3/4)C''$, and $\phi = 1/2$.

[26]In fact, in $q_e(x,\theta)$, $(1-\gamma)$ multiplies θ (see Eq. (26)), and in $C_e(x,\theta)$, γ multiplies $(\bar{p} + \theta^2)$.

4. Instrument choice

We now turn to the central question of this paper: whether there should be any preference for prices over quantities (or vice versa) when the regulator is uncertain about cost and benefit curves and enforcement is incomplete. To explore this question, we estimate the difference between the expected social welfare under the price instrument and that under the quantity instrument, which is given by

$$\Delta_{pq} \equiv E[W(\tau^*,\theta,\eta) - W(x^*,\theta,\eta)] \qquad (27)$$

where τ^* and x^* are, respectively, the optimal price and quantity designs (including enforcement parameters).

Either design, τ^* or x^*, is (second-best) optimal ex-ante, but because of uncertainty neither will be optimal ex-post. The relevant question here then becomes: which instrument comes closer to the ex-post optimum? The normative implication of (27) is that if $\Delta_{pq} > 0$, prices (i.e., taxes) provide higher expected welfare than quantities, and accordingly, ought to be preferred. If $\Delta_{pq} < 0$, quantities (i.e., tradeable quotas) ought to be preferred.

To simplify things, I develop (27) under the assumption that if the optimal price design is the triple $\{\tau^*, \phi(\tau^*), \bar{F}\}$, the optimal quantity design is the triple $\{x^*, \phi(x^*), \bar{F}\}$, where $\bar{p}(x^*) = \tau^*$. This strictly happens only when the stochastic term in the first-order condition for ϕ under the quantity regime goes to zero; otherwise, it is a good approximation because the stochastic term has a relatively small weight.[27] Alternatively, I could simply consider an exogenous enforcement policy under which ϕ and F are given. In either case, $p = \bar{p}(x^*) + \theta = \tau^* + \theta$ (see Eq. (24)), which simplifies computation greatly, as we shall see.

Expression (27) can be conveniently rewritten as (enforcement costs are the same in either design)

$$\Delta_{pq} = E[\{B(q_e(\tau,\theta),\eta) - B(q_e(x,\theta),\eta)\} - \{C_e(\tau,\theta) - C_e(x,\theta)\}] \qquad (28)$$

The first curly bracket of the right-hand side of (28) is the difference in environmental benefits provided by the two instruments, whereas the second curly bracket is the difference in abatement costs. From Weitzman's (1974) analysis, we know that under full compliance both brackets are negative. This is because the quantity instrument fixes the amount of reduction increasing both expected benefits (due to certainty in the amount of reduction) and expected costs (due to less flexibility to comply) relative to the price instrument.

[27] Note that if this assumption is relaxed the advantage of quantities over prices increases by some small amount. The 'non-stochastic' quantity design $\{\bar{p} = \tau^*, \phi(\tau^*), \bar{F}\}$ is no longer optimal when the stochastic term in the first-order condition for ϕ differs from zero.

Using linear approximations, expression (28) becomes

$$\Delta_{pq} = E\left[\left\{ (\underline{b} + \eta)(q_e(\tau,\theta) - q_e(x,\theta)) + \frac{B''}{2}\left(q_e^2(\tau,\theta) - q_e^2(x,\theta)\right) \right\} - \left\{ \gamma \int_p^\tau cg(c-\theta)dc \right\} \right] \tag{29}$$

where $q_e(\tau,\theta)$, $p(x,\theta)$, and $q_e(x,\theta)$ are given by (22), (24), and (26), respectively. Substituting these expressions into (29) yields

$$\Delta_{pq} = E\left[\left\{ (\underline{b} + \eta)\left(\frac{-\gamma\theta}{C''}\right) + \frac{B''}{2}\left(\frac{-2\gamma\theta}{C''}q_e(\tau) + \frac{\gamma(2-\gamma)\theta^2}{(C'')^2}\right) \right\} + \left\{ \frac{\gamma(2\theta\tau + \theta^2)}{2C''} \right\} \right] \tag{30}$$

Taking expectation and assuming that $E[\theta\eta] = 0$, Eq. (30) reduces to

$$\Delta_{pq} = \gamma(2-\gamma)\frac{E[\theta^2]B''}{2(C'')^2} + \gamma\frac{E[\theta^2]C''}{2(C'')^2} \tag{31}$$

where the first term of the right-hand side is the difference in expected benefits and the second term is the difference in expected costs. Finally, rearranging (31) leads to

$$\Delta_{pq} = \frac{\gamma E[\theta^2]}{2(C'')^2}((2-\gamma)B'' + C'') \tag{32}$$

where $\gamma = \phi/(1+\phi)$ is the fraction of non-compliant firms that are in compliance today.

Expression (32) is the main result of the paper. Its implications can be better understood if we substitute $\gamma = 1$ into (32), which corresponds to the case of full compliance. In such a case, Weitzman's (1974) result suggests using prices as long as the marginal cost curve is steeper than the marginal benefit curve; that is to say, as long as $C'' > |B''|$. With incomplete enforcement, however, the advantage of prices over quotas diminishes, given that $2 - \gamma > 1$. In fact, if $C'' = |B''|$, quantities ought to be the preferred policy instrument. Only if $C'' > (2-\gamma)|B''|$, prices ought to be preferred.[28]

Simple comparative statics of (32) indicates, on the one hand, that as ϕ increases, γ also increases and Δ_{pq} approaches Weitzman's result. On the other hand, changes in F do not affect (32) directly. The reason is that changes in F

[28]Note that if the assumption $\bar{p}(x^*) = \tau^*$ is relaxed, quantities are strictly preferred when $C'' = (2 - \gamma)|B''|$.

affect the cut-off point $\tilde{c}$ for both regulatory regimes in a similar way so that the expected differences between $B(q_e(\tau,\theta),\eta)$ and $B(q_e(x,\theta),\eta)$ and between $C_e(\tau,\theta)$ and $C_e(x,\theta)$ do not change. However, a large increase in F (or ϕ) may lead to full compliance if the value of ϕF exceeds τ and p, in which case we must substitute $\gamma = 1$ into (32).

We can summarize the main result of the paper in the following proposition

Proposition 3. *In the presence of uncertainty, incomplete enforcement significantly reduces the advantage of prices* (τ) *over quantities* (x). *Quantities should always be preferred over prices if* $C'' < (2-\gamma)|B''|$. (*If the stochastic term in the first-order condition for* ϕ *under the quantity regime is different than zero, quantities may also be preferred over prices even if* C'' *is slightly greater than* $(2-\gamma)|B''|$.)

To understand Proposition 3, it is useful to explain Weitzman's (1974) rationale for using prices over quantities. As long as miscalculating the ex-post optimum amount of control has lower welfare consequences than miscalculating the ex-post optimum (marginal) cost of control, which happens when the marginal cost curve is steeper than the marginal benefit curve, prices are preferred. In a quantity regime with full compliance, the amount of control remains fixed while the cost of control is subject to large swings because of uncertainty. If the marginal cost curve is very steep, the (marginal) cost of control can deviate significantly from the ex-post optimum; situation in which a price instrument that fixes the marginal cost of control turns more appropriate.

With incomplete enforcement, however, the effective (or observed) amount of control under a quantity instrument, $q_e(x,\theta)$, is no longer fixed, as shown by (26). Instead, it adapts to the actual cost of control. Indeed, if the marginal cost curve proves to be higher than expected by the regulator, more firms would choose not to comply, and consequently, both the effective amount of control and the cost of control would be lower than expected.

The fact that the effective reduction $q_e(x,\theta)$ now becomes uncertain has two effects on the welfare comparison between prices and quantities that can be explained using (31). The first effect is captured in the first term of the right-hand side of (31) that shows that the advantage of quantities over prices on the benefit side is reduced to $\gamma(2-\gamma) < 1$ relative to the case of full compliance (i.e., $\gamma = 1$).[29] The second effect is captured in the second term of the right-hand side of (31) that shows that the advantage of prices over quantities on the cost side is reduced to $\gamma < 1$. Because $\gamma(2-\gamma) > \gamma$, the second effect dominates and the overall advantage of prices over quantities is reduced. From (31) one also observes that incomplete enforcement makes both the marginal benefit curve and the

[29] From the concavity of the benefit curve, uncertainty in the reduction level reduces expected benefits.

marginal cost curve to look flatter, but because $\gamma(2-\gamma)>\gamma$, it makes the marginal cost curve even more so. In addition, note that as γ falls, the welfare difference between the two instrument shrinks and disappears when there is no compliance at all (i.e., $\gamma=0$).

The intuition behind these results is that incomplete enforcement 'softens' the quantity regime, making it resemble a non-linear instrument, as in Roberts and Spence (1976). Indeed, when costs prove to be higher than expected, some firms choose not to comply, increasing the effective amount of pollution. The technical reason for the regime softening is the (multiplicative) interaction between γ and θ that exists in both $q_e(x,\theta)$ and $C_e(x,\theta)$, which is not present in neither $q_e(\tau,\theta)$ nor $C_e(\tau,\theta)$.[30]

Finally, note from (30) that if marginal cost and marginal benefit curves are positively correlated (that is, if $E[\theta\eta]>0$), an additional negative term enters into (32) that increases the advantage of quantities over prices; otherwise, benefit uncertainty does not intervene.[31]

5. Conclusions

In this paper I have shown that incomplete enforcement has great significance in the regulator's the choice between price-based (taxes) and quantity-based (tradeable quotas) instruments. I found that under cost and benefit uncertainty as well as incomplete enforcement, a quantity instrument performs relatively better than a price instrument. In fact, if the slopes of the marginal benefit and marginal cost curves are the same, the quantity instrument should be preferred. The reason is that in a quantity regime with incomplete enforcement, the effective (or observed) amount of control is no longer fixed, but rather endogenously determined by the actual (ex-post) cost of control.

The implications of the paper are general enough to apply to any regulatory situation, but they seem particularly relevant to environmental regulation, where the debate over instrument choice is very relevant and imperfect monitoring and incomplete enforcement are of great concern. Examples range from the control of particulate matter in less developed countries' urban areas to the control of greenhouse gases to prevent global warming. In fact, Montero et al. (2000) explain that incomplete enforcement was one main factor behind the poor performance of a system of tradeable quotas designed to curb particulate matter in Santiago, Chile.

A desirable extension of the paper would be to consider additional enforcement

[30] In fact, from (22) we observe that the change in the effective amount of reduction, $q_e(\tau,\theta)$, due to a change θ in the marginal costs is not affected by the enforcement variables γ and F. The change is always θ/C''. Similarly, the fluctuations of $C_e(\tau,\theta)$ due to θ are independent of γ and F.

[31] See Stavins (1996) for a complete discussion of the effect of correlated uncertainty on instrument choice.

policies. One possibility might be to explore game theoretic models of incomplete enforcement, in which the regulator can improve upon a fixed inspection probability after learning about firms' type. If we consider the model of Harrington (1988), for example, we find that the main result of the paper should not change because a firm's expected amount of pollution abatement depends directly on the firm's abatement cost. Both compliance rate and pollution abatement are expected to increase as the cost of abatement decreases. Another possibility might be to simply consider a fine F and no enforcement power (see Viscusi and Zeckhauser, 1979; and Malik, 1990) and convex marginal cost curves for individual firms. But again, the effective amount of control is likely to depend on actual costs. The only case in which incomplete enforcement might not affect instrument choice would involve an enforcement scheme in which the amount of control is unaffected by the changes in control costs, which seems unlikely.

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