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Abstract:

We consider the pricing of a uniformly mixed pollutant when enforcement is costly with a model of optimal, possibly firm-specific, emissions taxes and their enforcement. We argue that optimality requires an enforcement strategy that induces full compliance by every firm. This holds whether or not regulators have complete information about firms' abatement costs, the costs of monitoring them for compliance, or the costs of collecting penalties from noncompliant firms. Moreover, ignoring several unrealistic special cases, optimality requires discriminatory emissions taxes except when regulators are unable to observe firms' abatement costs, the costs of monitoring individual firms, or any firm-specific characteristic that is known to be jointly distributed with either the firms' abatement costs or their monitoring costs. In many pollution control settings, especially those that have been subject to various forms of environmental regulation in the past, regulators are not likely to be so ill-informed about individual firms. In these settings, policies that set or generate a uniform pollution price like conventional designs involving uniform taxes and competitive emission trading with freely-allocated or auctioned permits will not be efficient.

Keywords: Compliance, Enforcement, Emissions Taxes, Monitoring, Asymmetric Information, Uncertainty

JEL Classification: L51, Q58

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Abstract: We consider the pricing of a uniformly mixed pollutant when enforcement is costly with a model of optimal, possibly firm-specific, emissions taxes and their enforcement. We argue that optimality requires an enforcement strategy that induces full compliance by every firm. This holds whether or not regulators have complete information about firms' abatement costs, the costs of monitoring them for compliance, or the costs of collecting penalties from noncompliant firms. Moreover, ignoring several unrealistic special cases, optimality requires discriminatory emissions taxes except when regulators are unable to observe firms' abatement costs, the costs of monitoring individual firms, or any firm-specific characteristic that is known to be jointly distributed with either the firms' abatement costs or their monitoring costs. In many pollution control settings, especially those that have been subject to various forms of environmental regulation in the past, regulators are not likely to be so ill-informed about individual firms. In these settings, policies that set or generate a uniform pollution price like conventional designs involving uniform taxes and competitive emission trading with freely-allocated or auctioned permits will not be efficient.

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The Optimal Pricing of Pollution When Enforcement is Costly

1. Introduction

In a first-best world of environmental policy, an optimal tax to control emissions of a uniformly mixed pollutant involves a uniform per unit tax set equal to marginal damage from emissions at the efficient level of aggregate emissions. Alternatively, a competitive emissions trading program with either freely-allocated or auctioned permits will generate a uniform price for pollution that is the same as the first-best tax. In a first-best world, however, regulations do not have to be enforced and regulators have complete information about all the benefits and costs of pollution control. These assumptions are always violated in real world applications. In this paper, therefore, we consider the optimal pricing of pollution when compliance must be enforced and regulators may have only incomplete information about firms' costs of controlling their emissions and the costs of regulatory enforcement. The model is cast as the joint determination of optimal, possibly firm-specific, emissions taxes and their enforcement.

We demonstrate two new results with significant policy relevance. First, under a constant expected marginal penalty for tax evasion and the assumption that collecting tax revenue from compliant firms is cheaper than collecting penalties from noncompliant firms, the optimal policy requires sufficient enforcement effort to induce full compliance by all firms. This is true even when regulators have only incomplete information about firms' abatement costs and the costs of enforcement. In the theoretical literature on compliance with emissions taxes most authors simply assume that full compliance is not or can not be achieved (e.g., Harford 1978, 1987; Sandmo 2002, Montero 2002, Cremer and Gahvari 2002, and Macho-Stadler and Perez-Castrillo 2006). This is also true in most theoretical analyses of the compliance and enforcement problem in emissions trading schemes (e.g., Malik 1990, Keeler 1991, Stranlund and Dhanda 1999, Montero 2002).[1] Without downplaying the relevance of examining incentive-based policies when enforcement is not sufficient to induce full compliance, our work suggests that these situations involve sub-optimal policy designs.

Our second main result is that, except for unrealistic special cases, discriminatory taxes are optimal except when regulators are unable to observe firms' abatement costs, the costs of monitoring individual firms for compliance, or any firm-specific characteristic (e.g., input and output levels, production and abatement technologies, etc.) that is known to be jointly distributed with either the firms' abatement costs or their monitoring costs. In this case, a regulator is unable to distinguish firms from one another and, therefore, is unable to determine discriminatory tax rates. However, in many situations, perhaps even most situations, regulators will not be so ill-informed. In most real settings, particularly in developed countries, firms have been subject to some form of pollution control for many years. Consequently, regulators have prior experience with and knowledge about the firms that can be used to construct an optimal policy. For example, past experience is likely to have provided regulators with information about the costs of monitoring different firms. Moreover, past experience may have allowed regulators to determine how observable firm characteristics like output, levels and kinds of inputs, abatement and production technologies, etc., are jointly distributed with their abatement or monitoring costs. We demonstrate that with this type of information, even though it may be incomplete, optimality requires discriminatory pollution prices.

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[1] Still others in this literature restrict themselves to only full compliance outcomes (Malik 1992, Stranlund and Chavez 2000, Chavez and Stranlund 2003). Only Stranlund (2006) considers the optimal design of emission trading policies with costly enforcement. He demonstrates that when regulators are fully informed about firms' costs of controlling their emissions the optimal policy calls for inducing full compliance.

An important consequence of our work is that when regulators have enough information to distinguish firms from one another in a meaningful way, any emissions control policy that sets or generates a uniform price cannot be optimal. In particular, conventional designs involving uniform tax rates as well as competitive emissions trading with freely-allocated or auctioned permits cannot be fully efficient.

While our result that enforcement costs will typically call for discriminatory pollution prices is not widely known, we do not claim that it is entirely new.[2] Cremer and Gahvari (2002), examine the optimal design of an emissions tax policy for homogeneous firms under the assumptions of costly enforcement and that tax revenue is used to offset other taxes in an economy. While they obviously obtain an optimal uniform tax for a particular industry because of their assumption of identical firms within the industry, they also recognize that the tax rate will be different in other industries in part because of differences in marginal enforcement costs and abatement costs. One could easily use their results to argue that discriminatory taxes are likely to be optimal in an industry composed of heterogeneous firms.

Our work differs from Cremer and Gahvari's in several important ways. First, while they determine optimal taxes and their enforcement jointly as we do, they limit their analysis to policies that generate positive violations by all firms. In contrast, we argue that the optimal policy should induce full compliance, which suggests that Cremer and Gahvari limited themselves to policies that are, in fact, sub-optimal. The second important difference between our work and Cremer and Gahvari's is that they assume complete information about firms' abatement and enforcement costs throughout their work, while we investigate the extent to which

[2] Beyond the control of uniformly mixed pollutants from point sources, which is the setting for this work as well as all of the literature we discuss, it is well known that discriminatory emissions taxes are optimal when pollutants are spatially differentiated (see Xepapadeas (1997), chapter 2 section 8 for references, including zonal taxes) and when emissions are generated by nonpoint sources (e.g., Segerson 1988).

discriminatory taxes remain optimal when regulators have incomplete information about abatement and enforcement costs.[3] Finally, Cremer and Gahvari (2002) also investigate how recycling emissions tax revenue to reduce other taxes in an economy affects optimal emissions taxes. In contrast, we assume that tax revenue is not used to offset other taxes in order to focus on the roles of costly enforcement and incomplete information in determining optimal pollution prices.

Malik (1992) provides an early hint that policies that generate a uniform pollution price are likely to be sub-optimal when one accounts for enforcement costs. Malik models a competitive emissions trading program under complete information that is enforced to achieve full compliance and demonstrates that even though the permit market leads to a distribution of emission control that minimizes aggregate abatement costs, it does not minimize the sum of aggregate abatement and enforcement costs. An important distinction between our work and Malik's is that he is concerned with the optimal distribution of emissions while we are concerned with the optimal distribution of emissions prices. The two approaches are obviously complementary, but our pricing approach is instructive because it illuminates what we believe is the fundamental reason for the sub-optimality of emissions trading that Malik identifies; that is, a competitive emissions trading policy leads to a uniform price, while enforcement costs typically call for discriminatory prices.

Our model differs from Malik's in other important ways as well. First, he simply assumes that regulators devote sufficient enforcement resources to induce full compliance in an emission

[3] In a recent contribution, Bontems and Bourgeon (2005) consider optimal environmental taxes under incomplete information and costly enforcement. They take a standard revelation approach that relies on eliciting truthful reports by firms of their "types". (See Lewis (1996) for a review of this approach.) In their work, a policy consists of a type-specific lump sum tax, an emissions standard, a monitoring probability, and a fine for violating the standard. This is very different from the way environmental economists and policymakers usually think of emissions taxes. Emissions taxes are usually per unit taxes, no restrictions are placed on firms' emissions, and noncompliance occurs if a firm attempts to evade its tax liability by under-reporting its emissions.

trading program, while we demonstrate that inducing full compliance to a tax regulation is optimal. Second, like Cremer and Gahvari (2002), Malik (1992) assumes complete information throughout his work, while we consider optimal pollution pricing when regulators have only incomplete information.

The rest of the paper is organized as follows. In the next section we develop a model of compliance behavior under emissions taxes. In section 3, we lay out the components of the costs of enforcing a policy of emissions taxes, which include the costs of monitoring firms, and the expected costs of collecting penalties from noncompliant firms. We then demonstrate that an optimal tax policy must induce full compliance by every firm, even when a regulator has only incomplete information about firms' abatement costs and the costs of enforcement. In section 4 we use our full-compliance result to determine optimal emissions taxes. The optimal design will typically involve discriminatory taxes except when a regulator has rather poor information about firms' abatement and monitoring costs. In fact, we specify the exact limit on the quality of the regulator's information at which it becomes optimal to set a uniform tax. We discuss this interpretation as well as other implications of our results in section 5, and conclude in section 6.

2. Compliance behavior under emissions taxes

The regulatory model of this paper is the standard one in which a regulator first commits itself to a tax policy and its enforcement and then the regulated firms react to this policy with their choices of emissions and compliance. In this section we determine the firms' responses to any tax/enforcement policy.

Throughout consider a fixed set N of heterogeneous risk-neutral firms. These firms may or may not belong to the same industry, but each emits the same uniformly mixed pollutant. A summary of the costs of all the methods firm *i* can use to reduce its emissions is given by its abatement cost function, $C_i(q_i)$, which is strictly decreasing and strictly convex in its emissions q_i.[4] The firm's emissions are taxed at rate t_i. The firm is required to submit a report of its emissions, r_i, and it is noncompliant if it attempts to evade some part of its tax liability by reporting $r_i < q_i$.

The regulator cannot observe the firm's emissions without a costly audit. Let π_i denote the probability that the regulator is able to determine *i*'s compliance status. Like most other authors, we assume that monitoring produces a measure of emissions that is accurate enough to judge a firm's compliance status without error. The detection probability is common knowledge and the regulator commits itself to it at the outset. If monitoring reveals that *i* has under-reported its emissions, it faces a unit penalty of ϕ on $q_i - r_i > 0$.[5] We assume that $\phi > t_i$ throughout. This allows full compliance to be a possible outcome throughout the paper. No upper bound is placed on ϕ, because none of our results depend on setting arbitrarily high penalties.

To simplify our analysis we restrict it to policies that motivate all firms to reduce their emissions below what they would chose in the absence of any sort of regulatory control, but that do not cause any firm to choose zero emissions. Under these policies firm *i* chooses it emissions and emissions report to solve:

$$\begin{aligned} &\min_{(q_i, r_i)} C_i(q_i) + t_i r_i + \pi_i \phi (q_i - r_i) \\ &s.t. \quad q_i - r_i \geq 0, r_i \geq 0. \end{aligned} \qquad [1]$$

[4] A firm's abatement cost is the reduction in its profit that comes from reducing its emissions below what it would choose in the absence of an inducement to control its emissions (Montgomery 1972).

[5] Our assumption of a linear penalty function is not common in the literature. Most authors assume that the penalty function, or at least the expected penalty function, is strictly convex (e.g., Harford 1978, 1987; Sandmo 2002, Cremer and Gahvari 2002, and Macho-Stadler and Perez-Castrillo 2006). We briefly address the use of linear penalties vs. convex penalties in the next section.

Restricting the firm to $q_i - r_i \geq 0$ follows from the fact that a firm will never have an incentive to report that its emissions are higher than they really are.[6] Let $\mathcal{L}$ denote the Lagrange equation for [1] and let λ_i denote the multiplier attached to the constraint $q_i - r_i \geq 0$. Then, the following first-order conditions are both necessary and sufficient to determine the firm's optimal choices of emissions and emissions report:

$$\mathcal{L}_q = C_i'(q_i) + \pi_i \phi - \lambda_i = 0; \qquad [2]$$

$$\mathcal{L}_r = t_i - \pi_i \phi + \lambda_i \geq 0,\ r_i \geq 0,\ r_i(t_i - \pi_i \phi + \beta_i) = 0; \qquad [3]$$

$$\mathcal{L}_\lambda = -(q_i - r_i) \leq 0,\ \lambda_i \geq 0,\ \lambda_i(q_i - r_i) = 0. \qquad [4]$$

Making the common assumption that a firm will comply if it is indifferent between compliance and noncompliance, [3] reveals that a firm's optimal emissions report is:

$$r_i = \begin{cases} q_i \text{ if } & t_i \leq \pi_i \phi \\ 0 \text{ if } & t_i > \pi_i \phi. \end{cases} \qquad [5]$$

Thus, the firm provides a truthful report of its emissions when the tax does not exceed the expected marginal penalty. When the tax does exceed the expected marginal penalty, it is cheaper for the firm to report zero emissions and face the expected penalty than to pay the tax.

When $t_i \leq \pi_i \phi$ so that the firm is motivated to report its emissions truthfully, [3] becomes $t_i = \pi_i \phi - \lambda_i$. Combining this with [2] yields the familiar result that the firm chooses its emissions to equate its marginal abatement cost to the tax, that is, $C_i'(q_i) + t_i = 0$. However, when $t_i > \pi_i \phi$ and the firm under-reports its emissions, [4] indicates that $\lambda_i = 0$, and [2] becomes $C_i'(q_i) + \pi_i \phi = 0$, indicating that a noncompliant firms chooses its emissions to equate its

[6] If $q_i < r_i$, then the firm could reduce its abatement costs by allowing its emissions to increase to r_i without incurring additional costs.

marginal abatement cost to the expected marginal penalty it faces. Thus, a firm's optimal choice of emissions is:

$$q_i = \begin{cases} q_i(t_i) \mid C_i'(q_i) + t_i = 0, \text{ if } t_i \leq \pi_i \phi \\ q_i(\pi_i \phi) \mid C_i'(q_i) + \pi_i \phi = 0, \text{ if } t_i > \pi_i \phi. \end{cases} \quad [6]$$

Since we assume that an optimal tax/enforcement policy is designed under incomplete information about firms' abatement costs, it is worthwhile at this point to specify what a regulator can and cannot know about firm behavior. Although a regulator knows how firms will choose their emissions in response to a tax and enforcement strategy, it cannot know exactly what a firm's emissions will be because it lacks complete information about its abatement costs. Moreover, if the regulator chooses not to induce compliance by a firm, it is uncertain about the extent of the firm's violation because this depends on the firm's choice of emissions. However, since the regulator controls the variables that fully determine a firm's compliance status; i.e., the tax and the expected marginal penalty, the regulator does know whether a firm will be compliant or not.

3. The costs of enforcing emissions taxes and the optimality of full compliance

The regulatory objective of this paper is to choose a system of individualized emissions taxes and enforcement strategies to minimize the expected social costs of the regulation. These costs include the regulator's expectations of aggregate abatement costs, pollution damage, and enforcement costs. In this section we focus on expected enforcement costs, which consist of the regulator's expectations of aggregate monitoring costs and the costs of collecting penalties from noncompliant firms. Under the assumption that collecting tax revenue from compliant firms is cheaper than collecting penalties from noncompliant firms, we state and prove a sort of "cost-effective enforcement" result. More specifically, we ask how a tax/enforcement policy should be designed to minimize the expected enforcement costs of inducing an arbitrary, fixed, and likely unknown set of individual emissions, and show that a policy that minimizes expected enforcement costs requires that each individual firm's tax be equal to the expected marginal penalty it faces. Consequently, all firms are fully compliant. In the next section we incorporate this "cost-effective enforcement" result into the determination of taxes that result in the optimal distribution of individual emissions.

The unit penalty for evaded taxes is fixed throughout this paper, so the regulator's policy instruments are individual taxes and detection probabilities, (t_i, π_i), $i = 1, \dots, n$, which induce emissions reports and emissions, (r_i, q_i), $i = 1, \dots, n$, according to [5] and [6], respectively. Assume that the actual cost of monitoring firm i is the increasing and convex function $m_i(\pi_i)$, and aggregate monitoring costs are $\sum_N m_i(\pi_i)$. The regulator does not have complete information about monitoring costs because it is not certain of the parameters of m_i, $i = 1, \dots, n$. We allow the costs of monitoring the firms to vary to reflect the possibility that the regulator will find it harder to determine the compliance status of some firms than others.[7] The linearity of aggregate monitoring costs in individual monitoring costs is not essential. To obtain the results of this paper it is sufficient to assume that aggregate monitoring costs are increasing and convex in the individual detection probabilities.

We assume throughout that tax revenue and revenue from penalizing noncompliant firms are simple transfers with no real effects. Despite this, society is not indifferent about collecting them; in particular, penalizing noncompliant firms may involve significant costs. These include

[7] This assumption is closely related to the assumption that individuals vary in their probabilities of apprehension, which was first analyzed by Bebchuk and Kaplow (1993). Macho-Stadler and Perez-Castrillo (2006) assume heterogeneous probabilities of apprehension in their study of enforcing emissions taxes.

the government's costs of generating sufficient evidence to get a court to agree with their finding of violation and the imposition of a penalty. Moreover, accused firms may mount costly challenges to any finding of violation and the imposition of a penalty, to which the government may then respond with its own costly efforts to fight off these challenges.[8] On the other hand, a compliant firm reports the full extent of its emissions, and in doing so, essentially admits liability for these emissions. With this admission of liability, the government does not need to generate the evidence that would be necessary to impose a penalty for noncompliance. Moreover, a firm that admits its liability is not likely to challenge the imposition of the tax.

Therefore, we think that it is reasonable to assume that imposing and collecting penalties from noncompliant firms is more costly that collecting taxes from compliant firms, and incorporate this assumption into our model. To do so in a simply way, suppose that collecting emissions taxes is costless, but that $s_i > 0$ is the cost of collecting the penalty from firm *i* if it is caught evading its tax liability. Although s_i may be a function of the size of the firm's penalty, our results do not depend on specifying such a relationship. Let the aggregate expected costs of collecting penalties be linear in the costs of collecting penalties from individual firms. If N^{nc} denotes the subset of firms that are noncompliant, the aggregate expected costs of collecting penalties are $\sum_{N^{nc}} \pi_i s_i$. As with aggregate monitoring costs, the linearity of aggregate expected sanctioning costs is not essential. For our results it is sufficient to assume that aggregate expected sanctioning costs are montonically increasing in the costs of sanctioning individual firms.

[8] Although it is perfectly reasonable to assume that penalizing firms is costly, none of the work in the literature on enforcing emissions taxes that we are aware of deals explicitly with the costs of collecting penalties. In the literature on enforcing emissions trading policies, only Stranlund (2006) assumes that imposing and collecting penalties is costly. Costly sanctions are also not very common in the much larger literature on optimal law enforcement; however, see Polinsky and Shavell (1992) for an analysis of how costly sanctions affect the determination of optimal law enforcement.

Finally, like the cost of monitoring individual firms, the regulator need not have complete information about the cost of collecting penalties from individual firms.[9]

Despite our rather weak assumptions about the expected costs of enforcing emissions taxes, we are able to prove the following proposition concerning the optimal enforcement of these policies.

Proposition 1: Consider a tax/monitoring policy, (t_i, π_i), i = 1, … , n, and an exogenous constant marginal penalty that satisfies $\phi > t_i$, i = 1, … , n. Suppose that firms react to this policy with emissions q_i, i = 1, … , n. This distribution of emissions is achieved with minimum expected aggregate enforcement costs only if $t_i = \pi_i\phi$ for each i = 1, … , n. With taxes and monitoring set in this way, each firm is fully compliant.

Proof: The proof proceeds by showing that any policy involving $t_i \neq \pi_i\phi$ for some i can be modified to reduce enforcement costs without changing the distribution of emissions. First suppose that $t_i > \pi_i\phi$ for some i. Then, [5] indicates that $r_i = 0$, and [6] indicates that $q_i = q_i(\pi_i\phi)$; that is the firm is fully noncompliant. Alternatively, hold π_i constant so that aggregate monitoring costs do not change, but reduce t_i so that $t_i = \pi_i\phi$. The firm will then choose $r_i = q_i(\pi_i\phi)$ so that it is now compliant, but it does not change it emissions because $q_i(\pi_i\phi) = q_i(t_i)$. Moreover, changing t_i in this way does not affect the decisions of any of the

[9] Any enforcement strategy is likely to involve fixed monitoring costs and sanctioning costs, which we do not model. Adding these fixed costs does not change any of the results of our work as long as they are not so high that it is optimal to forego regulation altogether.

other firms. However, reducing t_i to $t_i = \pi_i\phi$ eliminates the expected costs of penalizing the firm; hence, aggregate expected enforcement costs are reduced.

Now suppose that $t_i < \pi_i\phi$ for some *i*. In this case, [5] and [6] reveal that $r_i = q_i(t_i)$; that is, the firm is compliant. However, if π_i is reduced so that $t_i = \pi_i\phi$, the firm does not change its choice of emissions and it remains compliant. This change in π_i does not affect the decisions of the other firms, but aggregate expected enforcement costs are reduced because expected monitoring costs decrease. QED.

It is important to note that the proposition holds even if a regulator is uncertain about firms' abatement costs. Of course, uncertainty about abatement costs implies that the regulator cannot be certain about the distribution of individual emissions that will result from a particular policy, (t_i, π_i), $i = 1, \dots, n$, but the proposition does not depend on knowing how individual emissions are distributed. Whatever q_i, $i = 1, \dots, n$, results from a particular policy, the expected enforcement costs of holding the firms to this distribution of emissions are minimized by choosing $t_i = \pi_i\phi$, $i = 1, \dots, n$. Moreover, the proposition holds even if the regulator is uncertain about the parameters of enforcement costs. All the regulator has to know is that expected aggregate monitoring costs are increasing in individual monitoring levels, and expected aggregate sanctioning costs are increasing in the costs of penalizing individual firms. Because the strategy $t_i = \pi_i\phi$, $i = 1, \dots, n$, minimizes the expected enforcement costs of inducing a fixed set of individual emissions, we shall incorporate this strategy into our determination of optimal taxes and their enforcement in the next section.

That this strategy induces full compliance by each firm is a new result with significant relevance for the determination of optimal emissions taxes. As noted in the introduction, the related literature has not dealt squarely with the possibility that inducing full compliance may be a component of an optimal tax policy. For example, Montero (2002), in his study of price vs. quantity regulation with costly enforcement, explicitly assumes that monitoring costs are large enough and penalties are restricted enough so that full compliance is not socially optimal (page 439). Although the unit penalty is not restricted in our work, all that is required is that it exceed each firm's tax rate. Given this assumption, optimality requires full compliance regardless of monitoring costs. To be sure, monitoring costs will affect the optimal tax rates, but they do not affect the decision to induce full compliance.

Similarly, but not as explicitly, Cremer and Gahvari's (2002) work is clearly focused on optimal taxes and their enforcement in situations involving less than full compliance. They simply sidestep the possibility that optimality may call for full compliance by ignoring the natural zero-boundary constraint on firms' unreported emissions. Instead they assume that firms' choices of unreported emissions are always interior choices (see their first-order condition for an emissions report, (8a) on page 391). Our proposition suggests that Cremer and Gahvari may have limited themselves unnecessarily to suboptimal enforcement strategies.

Macho-Stadler and Perez-Castrillo (2006) also focus solely on imperfect compliance by assuming a constant emissions tax and the regulatory objective of minimizing aggregate emissions with a fixed enforcement budget that is not sufficient to induce full compliance.[10] While limited enforcement resources are certainly a factor in many real instances of

[10] Garvie and Keeler (1994) examine the choices of a budget-constrained enforcer under emissions standards, while Stranlund and Dhanda (1999) do the same in the context of competitive emissions trading.

environmental policy enforcement, our proposition suggests that in designing a truly optimal tax policy regulators should allocate sufficient enforcement resources to achieve full compliance.

The focus on positive violation choices by Cremer and Gahvari (2002), Macho-Stadler and Perez-Castrillo (2006), and several others (e.g., Harford (1978 and 1987) and Sandmo (2002)), is accomplished, in part, with the assumption that expected penalty functions are strictly convex. We know of no empirical justification for this assumption, nor are we aware of any efficiency reason to prefer strictly convex expected penalty functions for tax evasion to linear expected penalty functions.[11] Moreover, expected penalties are strictly convex either because monitoring probabilities or penalties are strictly convex in unreported emissions. The first case involves a questionable assumption because a regulator's monitoring activity would then depend on actual violations: but, of course, a firm's violation cannot be known until it is monitored. If monitoring probabilities are independent of unreported emissions, then strict convexity of the expected penalty function comes from marginal penalties that are increasing in violation levels. We are not aware of any tax policy that specifies an increasing marginal penalty. On the other hand, a constant marginal penalty is a very natural choice of penalty because the marginal incentive to evade the tax is the constant tax rate.

Our reading of the literature suggests that the primary justification for strictly convex expected penalties is to allow analysts to focus on situations involving positive violations. In contrast, we assume that the expected marginal penalty function is linear, which forces us to take the boundary condition of zero violations seriously, and ultimately leads us to the optimality of inducing full compliance.   While our choice to model constant expected marginal penalties is one reason we find that inducing full compliance is optimal, it is not the only reason. Our

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[11] Although, for a competitive emissions trading program that seeks to achieve an aggregate emissions target cost-effectively, Stranlund (2006) demonstrates that a linear penalty and monitoring to induce full compliance is preferred to a strictly convex penalty and monitoring that allows noncompliance.

assumption that it is costly to collect penalties from noncompliant firms is crucial. In fact, the fundamental value of inducing full compliance is to avoid these costs.

4. Optimal emission taxes under incomplete information

Having characterized an optimal enforcement strategy, we incorporate this strategy into the determination of optimal taxes when a regulator has only incomplete information about firms' abatement costs and the costs of monitoring them for compliance. The focus of our analysis is on whether an optimal tax policy involves discriminatory taxes or whether a regulator should set a single tax that applies uniformly to all firms. Clearly, if a regulator's information about individual firms is so poor that it is unable to distinguish them from one another in a meaningful way, it has no basis for choosing discriminatory taxes. While such poor information may be characteristic of some pollution control settings, it certainly is not a universal feature. In fact, we suspect that in many situations, particularly those in which firms have been subject to control policies in the past, regulators can probably observe individual firm characteristics, like output, inputs, abatement equipment, and production technologies, that provide some information about their unknown abatement and monitoring cost parameters. For example, past experience may have provided regulators with a great deal of information about the difficulty of monitoring the emissions from different firms. Perhaps they know that larger facilities with more points of discharge are harder to monitor than smaller facilities. Regulators may have also learned that certain kinds of abatement and production technologies make monitoring more or less difficult than other technologies. Past experience may have also allowed regulators to derive estimates of the parameters of firms' abatement costs as functions of observable firm characteristics.

Consequently, we let x_i denote a vector of observable characteristics of firm *i*, and assume that a regulator knows that these characteristics are jointly distributed with the parameters of the firms' abatement and monitoring costs in the population of regulated firms. Knowledge of the joint distribution of the firms' cost parameters and at least some of their observable characteristics allows the regulator to form a joint probability density function of the unknown cost parameters for each firm that is conditioned on the firm's observable characteristics. The regulator can then use these conditional distributions to determine optimal individual tax rates and their enforcement. This policy is determined to maximize the regulator's conditional expectation of the sum of aggregate abatement costs, aggregate monitoring costs, and the damage from the firms' emissions.

First consider expected abatement costs. Let the conditional expectation of firm *i*'s abatement cost function be $E\left(C_i(q_i) \mid x_i\right)$, where *E* denotes the expectation operator throughout. Recall from Proposition 1 that it is optimal to set a firm's tax equal to its expected marginal penalty $(t_i = \pi_i \phi)$ so that it is compliant, and from [6], a firm will then choose its emissions so that its marginal abatement cost is equal to the tax rate. Therefore, the regulator's conditional expectation of the firm's choice of emissions under the tax t_i is

$$E\left(q_i(t_i) \mid x_i\right) = q_i \mid -E\left(C_i'(q_i) \mid x_i\right) = t_i \,. \qquad [7]$$

Using [7], the regulator can specify its conditional expectation of the firm's abatement costs in terms of the tax;

$$E\left(C_i(t_i) \mid x_i\right) = E\left(C_i(q_i(t_i)) \mid x_i\right). \qquad [8]$$

Then, given the regulator's observations of all x_i, $i = 1, \ldots, n$, its conditional expectation of the aggregate abatement costs generated by its tax policy t_i, $i = 1, \ldots, n$, is

$$\sum E\left(C(t_i) \mid x_i\right). \quad [9]$$

From here on, summations are over all regulated firms.

The marginal effect of changing a single tax, t_i, on the regulator's conditional expectation of aggregate abatement costs is simply the marginal effect on the regulator's expectation of the abatement costs of that firm. From [8] this effect is $E\left(C_i'(q)q_i'(t_i)) \mid x_i\right)$. Since the regulator knows the firm will choose its emissions so that $-C_i'(q_i) = t_i$,

$$\frac{dE\left(C_i(t_i) \mid x_i\right)}{dt_i} = -t_i E\left(q_i'(t_i)) \mid x_i\right) > 0. \quad [10]$$

The sign of [10] follows because the regulator's conditional expectation of the firm's marginal emissions response to a change in its tax is negative. That is, from [7],

$$E\left(q_i'(t_i) \mid x_i\right) = -E\left(1 / C_i''(q_i) \mid x_i\right) < 0. \quad [11]$$

Like the firms' abatement costs the regulator is uncertain about the costs of monitoring individual firms for compliance, but it can evaluate the conditional expectations of the firms' monitoring costs. For firm *i* this is $E\left(m_i(\pi_i) \mid x_i\right)$. Since optimal enforcement requires $t_i = \pi_i \phi$, the regulator's expectation of the cost of monitoring *i* in terms of the tax is $E\left(m_i(t_i / \phi) \mid x_i\right)$, and its expectation of how the cost of monitoring *i* changes with t_i is

$$\frac{dE\left(m_i(t_i / \phi) \mid x_i\right)}{dt_i} = \frac{E\left(m_i'(\pi_i) \mid x_i\right)}{\phi} > 0. \quad [12]$$

The regulator's expectation of the monitoring cost of maintaining compliance by the firm increases with its tax to offset the firm's increased incentive to evade a higher tax. Given the regulator's observations of x_i, $i = 1, \ldots, n$, its conditional expectation of aggregate monitoring costs in terms of its tax policy t_i, $i = 1, \ldots, n$, is

$$\sum E\left(m_i(t_i/\phi) \mid x_i\right). \qquad [13]$$

The marginal affect on the regulator's conditional expectation of aggregate monitoring costs of a change in a single tax, t_i, is given by [12].

Lastly, the regulator must evaluate how its policy affects its conditional expectation of pollution damage. We assume that the firms' emissions are uniformly mixed so damage is an increasing and convex function, D, of aggregate emissions. For simplicity, suppose that the regulator knows the damage function; however, it remains uncertain about how much damage its policy will produce, because it is uncertain about how each firm will respond to its tax. It does, however, know the conditional expectation of how each firm will respond, $E\left(q_i(t_i) \mid x_i\right)$, $i = 1, \ldots, n$, so pollution damage at the regulator's conditional expectation of aggregate emissions is,

$$D\left(\sum E(q_i(t_i) \mid x_i)\right). \qquad [14]$$

The regulator's conditional expectation of the change in damage from a change in the tax on firm i is

$$D'\left(\sum E(q_i(t_i) \mid x_i)\right) E\left(q_i'(t_i) \mid x_i\right) < 0. \qquad [15]$$

We now have all the components of social costs. Let $W(t_1, \ldots, t_n \mid x_1, \ldots, x_n)$ denote the regulator's expectation of social costs in terms of a policy of well-enforced individual emissions taxes, t_i, $i = 1, \ldots, n$, conditional on its observations of x_i, $i = 1, \ldots, n$. Note that $W(t_1, \ldots, t_n \mid x_1, \ldots, x_n)$ is the sum of [9], [13], and [14]; that is,

$$\begin{aligned} W(t_1, \ldots, t_n \mid x_1, \ldots, x_n) = \sum E\left(C(t_i) \mid x_i\right) + \sum E\left(m_i(t_i/\phi) \mid x_i\right) \\ + D\left(\sum E(q_i(t_i) \mid x_i)\right). \end{aligned} \qquad [16]$$

Suppose that $W(t_1, \ldots, t_n \mid x_1, \ldots, x_n)$ is strictly convex in t_i, $i = 1, \ldots, n$, for all possible realizations of x_i, $i = 1, \ldots, n$, and that an optimal policy involves strictly positive individual taxes. Then, the optimal tax rates are determined by $\partial W / \partial t_i = 0$, i = 1, …, n. Since $\partial W / \partial t_i$ is equal to the sum of [10], [12], and [15], the first-order conditions for the optimal taxes can be written as:

$$-t_i E\left(q_i'(t_i)) \mid x_i\right) + \frac{E\left(m_i'(\pi_i) \mid x_i\right)}{\phi} = -D'\left(\sum E(q_i(t_i) \mid x_i)\right) E\left(q_i'(t_i) \mid x_i\right),\ i = 1, \ldots, n. \quad [17]$$

The left-hand side of [17] for a particular firm *i* is the regulator's expectation of the marginal costs of increasing the firm's tax, which consists of the impact of the increased tax on the regulator's expectation of the firm's abatement costs and on its expectation of the costs of monitoring the firm. The right hand-side is the regulator's expectation of the marginal reduction in aggregate damage from increasing *i*'s tax.

Now, take any two firms, *i* and *j*, and use [17] to calculate

$$t_i - t_j = \frac{1}{\phi}\left(\frac{E\left(m_i'(\pi_i) \mid x_i\right)}{E\left(q_i'(t_i) \mid x_i\right)} - \frac{E\left(m_j'(\pi_j) \mid x_j\right)}{E\left(q_j'(t_j) \mid x_j\right)} \right). \quad [18]$$

Our last proposition follows directly from [18], so it is offered without formal proof.

Proposition 2: An optimal policy of emissions taxes under incomplete information about firms' abatement and monitoring costs involves discriminatory taxes if and only if

$E\left(m_i'(\pi_i) \mid x_i\right) / E\left(q_i'(t_i) \mid x_i\right) \neq E\left(m_j'(\pi_j) \mid x_j\right) / E\left(q_j'(t_j) \mid x_j\right)$ for some *i* and *j*.

5. Discussion of Proposition 2

Proposition 2 reveals the condition under which enforcement costs induce optimal discriminatory taxes and, in doing so, helps us specify conditions that would lead to a uniform tax. Several of the conditions that induce a single tax rate are quite unrealistic. For example a uniform tax will be optimal if the firms' marginal monitoring costs and their marginal emissions responses to taxation are the same. This is true as well if the firms' observable characteristics are all the same.

Another unrealistic possibility is that the firms' marginal monitoring costs are all zero. In this case, [17] reduces to $t_i = D'\left(\sum E(q_i(t_i)\,|\,x_i)\right)$, which is the familiar result that optimality requires a uniform tax that is set equal to marginal damage at the efficient level of the regulator's expectation of aggregate emissions.[12]

However, it seems to us that the most relevant condition under which a uniform tax is optimal is when a regulator is unable to observe any firm characteristic that it knows to be jointly distributed with the parameters of the firms' abatement and monitoring costs. In this case the regulator's expectations of the firms' marginal monitoring costs and emissions responses are the same, because it has no way to distinguish the firms from one another. Thus, we would argue that the fundamental justification for setting a uniform tax to control a uniformly mixed pollutant is that a regulator has very poor information about individual firms.[13]

As we've already noted, we do not believe regulators will be so ill-informed in many real settings. When a regulator has somewhat better, but still incomplete, information about individual firms, [18] indicates that their tax rates will vary except in unrealistic special cases. Admittedly, the number of distinct optimal tax rates may be small if a regulator has only coarse information about individual firms. For example, suppose that a control situation involves the firms from a number of industries, and that the regulator knows something about how monitoring or abatement costs differ across the industries, but is unable to distinguish firms within particular industries. In this case, the number of distinct tax rates may simply be equal to the number of

[12] With [17] it is straightforward to demonstrate that costly enforcement generally implies that individual tax rates are below marginal damage. Consequently, individual and aggregate emissions are higher than if enforcement was costless.

[13] We recognize, however, that even when regulators have sufficient information to impose discriminatory taxes, other considerations may limit their ability to do so. Legal prohibitions against discriminatory taxation may prevent regulators from implementing a fully optimal tax policy. Even if discriminatory taxes are lawful, they may not be politically feasible. In all likelihood some firms will perceive discriminatory taxes as unfair and lobby against their use. Successful lobbying efforts could lead to a uniform tax when discriminatory taxes are appropriate.

industries involved. Or, imagine a control setting involving the emissions of the firms in a single industry that use only a small number of distinct abatement technologies to control their emissions. If this piece of information is the only characteristic that a regulator knows is jointly distributed with the firms' abatement or monitoring costs, the number of distinct tax rates may be equal to the number of available control technologies. Depending on the degree of heterogeneity in the population of regulated firms, more detailed information about each of them may lead to a greater number of distinct tax rates.

When a regulator can distinguish firms from others, their tax rates will vary with the variation in $E\left(m_i'(\pi_i) \mid x_i\right) / E\left(q_i'(t_i) \mid x_i\right)$, i = 1, …, n. Recall from [11] that $E\left(q_i'(t_i) \mid x_i\right) = -E\left(1/C_i''(q_i) \mid x_i\right) < 0$. Therefore, individual tax rates vary if there is variation in the regulator's conditional expectations of the firms' marginal monitoring costs, or if there is variation in its expectations of the reciprocal of the slopes of their marginal abatement costs, or both. It is particularly noteworthy that optimal emissions taxes will likely vary across firms even if the marginal cost of monitoring each of them for compliance is the same. Therefore, simply recognizing that monitoring is costly will often be sufficient justification for imposing discriminatory taxes.

Since $E\left(q_i'(t_i) \mid x_i\right) < 0$ and $E\left(m_i'(\pi_i) \mid x_i\right) > 0$, their ratio is negative. From [18], then, $t_i < t_j$ if and only if $\left| E\left(m_i'(\pi_i) \mid x_i\right) / E\left(q_i'(t_i) \mid x_i\right) \right| < \left| E\left(m_j'(\pi_j) \mid x_j\right) / E\left(q_j'(t_j) \mid x_j\right) \right|$. For firm i, $E\left(m_i'(\pi_i) \mid x_i\right) / E\left(q_i'(t_i) \mid x_i\right)$ reflects the regulator's expectation of the marginal monitoring costs associated with inducing lower emissions from the firm with a well-enforced tax. Inducing a marginal decrease in the emissions of a firm with a more steeply sloped marginal abatement cost curve (i.e., higher $C_i''(q_i)$) requires a relatively greater increase in its tax and, consequently, a relatively greater increase in monitoring to maintain the firm's compliance. Therefore, to conserve monitoring costs, optimal taxes will tend to be lower for firms that the regulator expects have relatively steep marginal abatement cost functions. For the same reason, optimal tax rates will tend to be lower for firms that the regulator expects are more difficult to monitor, and hence, have higher marginal monitoring cost functions.

One of the most important implications of Proposition 2 is that, when regulators have sufficient information to set discriminatory taxes, any policy that sets or generates a single price for pollution cannot be fully efficient. These policies include conventional designs involving uniform emissions taxes, or transferable permit programs with freely-given or auctioned permits. But it is the single pollution price that drives much of our understanding of price-based control and that leads to the most important reason for designing and implementing price-based policies. That reason is the ability of these policies to induce a distribution of individual emissions control that minimizes the aggregate abatement costs of achieving some aggregate emissions target, even when a target cannot be guaranteed because of incomplete information. A single pollution price motivates firms to choose emissions so that their marginal abatement costs are equal to the price. Since they all face the same price, all of their marginal abatement costs are equal in equilibrium, which forms the set of necessary conditions for minimizing aggregate abatement costs. Clearly this result requires a uniform pollution price, and just as clearly, when it is optimal to set discriminatory prices, aggregate abatement costs will not be minimized. Using our approach it is easy to demonstrate that achieving an aggregate emissions target (at least in expectation) with lowest possible expected aggregate abatement costs plus expected enforcement costs cannot be achieved with a single price—minimizing this sum requires discriminatory prices.

6. Conclusion

We have examined the optimal pricing of a uniformly mixed pollutant when enforcement is costly and regulators have incomplete information about firms' abatement costs and the costs of enforcement, and have demonstrated two new results. First, an optimal policy calls on regulators to devote sufficient enforcement resources to induce full compliance by all firms. This is true regardless of the quality of information regulators have about individual firms' abatement costs and the costs of enforcement. Second, enforcement costs will typically induce discriminatory pollution prices, except when regulators have very poor information about individual firms. More specifically, unrealistic special cases aside, a policy that sets or generates a uniform price will be optimal only when regulators are unable to use observable firm characteristics to form conditional expectations of individual firm's abatement costs and the costs of monitoring them for compliance. Although there are certainly pollution control settings in which regulators have such poor information, there are many others, particularly those that have been subject to environmental controls in the past, in which regulators are likely to have some information that allows them to distinguish firms from one another. In these cases, uniform pricing of pollution cannot be efficient.

There are, of course, several ways to extend the results of our work. For example, given the political appeal of emissions trading policies, it is probably worth exploring whether trading schemes can be modified in straightforward ways to generate the correct firm-specific prices. Modifications to these policies to induce the correct prices may involve permit trading ratios among firms that differ from the one-for-one trading schemes that characterize conventional emissions trading. Another option might be to combine one-for-one permit trading with firm-specific taxes to account for differences in the optimal pollution prices.

Reexamining our results in more difficult control situations may also be worthwhile. In this work we have focused on the control of uniformly mixed pollutants, largely because this is the setting that drives much of what we understand about price-based pollution control. Moreover, it is the one setting in which conventional wisdom calls for setting a uniform emissions tax, or implementing transferable or auctioned permit schemes that generate a uniform permit price. Of course, in contrast to what we perceive to be conventional wisdom, we've argued that the presence of enforcement costs will typically call for discriminatory pricing of a uniformly mixed pollutant. There are other control situations that call for discriminatory pricing, even under the assumption of costless enforcement. These include nonpoint pollution problems and problems involving spatially-differentiated pollutants. In these cases it is the nature of the pollutant that leads to discriminatory pricing. Adding the enforcement dimension to these control problems will likely generate two motivations for discriminatory pricing. How enforcement costs and the nature of the pollutant interact to determine optimal pollution prices is likely to be a fruitful area for future research.

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