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Abstract: We consider the pricing of a uniformly mixed pollutant with a model of optimal, possibly firm-specific, emissions taxes and their enforcement under incomplete information about firms' abatement costs, enforcement costs, and pollution damage. We argue that optimality requires an enforcement strategy that induces full compliance by every firm, except possibly when a regulator can base the probabilities of detecting individual violations on observable correlates of violators' actual emissions. Moreover, optimality requires discriminatory taxes, except when a regulator is unable to use observable firm-level characteristics to gain some information about the variation in firms' abatement costs or 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 are inefficient.

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

JEL Codes: *L51, Q58.*

1. Introduction

In a first-best world an optimal tax to control emissions of a uniformly mixed pollutant involves a uniform per unit tax set equal to marginal damage at the efficient level of aggregate emissions. Alternatively, competitive emissions trading 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 have only incomplete information about firms' abatement costs, the costs of regulatory enforcement, and the damages from pollution. Our model is cast as the joint determination of optimal, possibly firm-specific, emissions taxes and their enforcement.

Our efforts produce several new results. After laying out a model of emissions tax compliance in the next section, in section 3 we determine firm-specific tax/enforcement policies that achieve an uncertain distribution of individual emissions with minimum expected enforcement costs. A key feature of our work is that we assume that it is costless to collect emissions taxes, but that it is costly to collect penalties for tax evasion. We first demonstrate that under a constant expected marginal penalty for tax evasion, a cost-effective tax/enforcement policy requires sufficient enforcement effort to induce full compliance by all firms.

In the theoretical literature on compliance with emissions taxes most authors simply assume that full compliance is not or cannot be achieved [5, 8, 9, 12, 16]. This is also true in most theoretical analyses of the compliance and enforcement problem in emissions trading schemes [11, 15, 16, 19].[1] Without downplaying the relevance of examining the performance of incentive-based policies when enforcement cannot induce full compliance, our work suggests that these situations may involve sub-optimal policy designs.

However, our assumption of a constant expected marginal penalty for tax evasion is not common in the theoretical literature on compliance with incentive-based policies. Most authors assume expected penalties that are some combination of strictly convex penalty functions, and probabilities of detecting violations that may depend on firms' emissions reports, on the regulator's expectation of their emissions, or on their actual emissions. These assumptions are not justified by actual enforcement strategies or by deriving efficient enforcement strategies.

Consequently, to examine the robustness of our full-compliance result, in section 4 we ask whether it is possible to reduce the expected enforcement costs of achieving an uncertain distribution of individual emissions with a non-constant expected marginal penalty that results in some level of tax evasion. We find that a regulator cannot use noncompliance along with any combination of the firms' emissions reports, its expectations of their emissions, or strictly convex penalty functions to form a cost-effective tax/enforcement policy—all such strategies result in higher expected enforcement costs than inducing full compliance with a constant expected marginal penalty. However, monitoring effort can be reduced if the probabilities of detecting firms' violations can be based on observable correlates of their actual emissions. Whether such a strategy reduces expected enforcement costs depends on the tradeoff between reduced monitoring costs and the expected sanctioning costs that arise from punishing violations.

Our third result comes from determining optimal firm-specific emissions taxes under the assumption that it is not possible to improve on an enforcement strategy that induces full

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[1] Some others in this literature restrict themselves to only full compliance outcomes [4, 14, 20].

compliance. In section 5 we show that discriminatory taxes are optimal except when observable firm characteristics do not reveal any information about the variation in the firms' marginal abatement costs or the marginal costs of monitoring them for compliance. In this case, the regulator has such poor information about individual firms that it cannot distinguish them from one another in a useful way. While this lack of information is certainly characteristic of some pollution control settings, regulators will not be so ill-informed in others. Particularly in developed countries, firms have been subject to environmental regulation for many years. Consequently, we suspect that there are many situations in which prior experience has provided regulators with information about the costs of monitoring firms, and may have allowed them to determine how observable firm characteristics (e.g., output, inputs, abatement and production technologies, etc.) are jointly distributed with their abatement or monitoring costs. With this information, even though it is incomplete, optimality requires discriminatory pollution prices.

We cannot claim that this result is entirely new. Cremer and Gahvari [5] also examine the optimal design of an emissions tax that is costly to enforce, but they limit their analysis to policies that generate positive violations by all firms and they assume complete information about firms' abatement and enforcement costs. Their results suggest that tax rates may vary across industries in part because of differences in enforcement and abatement costs. Besides showing that optimality will often require full compliance, we extend Cremer and Gahvari's work by determining the extent to which discriminatory taxes remain optimal when regulators have incomplete information about abatement and enforcement costs.

Malik [14] provides an early hint that a uniform pollution price may be inefficient when one accounts for enforcement costs. He models a competitive emissions trading program under complete information that is enforced to achieve full compliance, and demonstrates that emission trading leads to a distribution of emission control that 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 approaches are clearly complementary, but our approach illuminates what we believe is the fundamental reason for the sub-optimality of emissions trading: a competitive emissions trading policy leads to a uniform price, while enforcement costs typically call for discriminatory prices.

An important consequence of this result is that when regulators have some knowledge about how abatement and monitoring costs vary across firms, any emissions control policy that sets or generates a uniform price cannot be optimal. In particular, the policies that drive our conventional wisdom about the value of incentive-based policies, like those involving Pigouvian taxes and competitive emissions trading, are actually suboptimal policies.[2] But it is the single pollution price that drives much of our understanding of incentive-based control and that leads to the most important reason for implementing these policies. That is the ability of these policies to produce a distribution of individual emissions control that minimizes the aggregate abatement costs of achieving some aggregate emissions target, even when the 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 in equilibrium, and this forms the set of necessary conditions for minimizing aggregate abatement costs. Clearly, when it is optimal to set

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[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 [23], chapter 2 section 8 for references).

discriminatory prices, firms' marginal abatement costs will differ, and aggregate abatement costs will not be minimized. Thus, the main justification for implementing policies that price pollution is not valid when discriminatory prices are optimal.

2. A Model of Compliance Behavior under Emissions Taxes

Throughout we consider a fixed set of *n* heterogeneous risk-neutral firms. These firms may not belong to the same industry, but each emits the same uniformly mixed pollutant. A regulator has incomplete information about the firms' abatement costs, but we allow for the possibility that it can use observable characteristics of the firms to distinguish their costs from one another. For example, past environmental control may have provided enough information to the regulator to allow it to estimate the parameters of firms' abatement costs as functions of observable production and abatement technologies, or levels and kinds of inputs and outputs. Let the abatement cost function of *i* be $C(q_i, x_i, \varepsilon_i)$, which is strictly decreasing and strictly convex in its emissions q_i. The variable ε_i is known to the firm but is a random variable from the regulator's perspective, and x_i is a vector of observable characteristics of the firm. Note that the functional form of abatement costs does not vary across firms, but individual abatement costs vary with differences in x_i and ε_i.

Firm *i*'s emissions are taxed at rate t_i. It is required to submit an emissions report, r_i, and it is noncompliant if it reports $r_i < q_i$. The regulator cannot determine the firm's compliance status without a costly audit. Let π_i denote the probability that the regulator is able to make this determination and suppose that it can judge a firm's compliance without error. The detection probability is common knowledge and the regulator commits to it at the outset. If monitoring reveals that *i* has under-reported its emissions, it pays a unit penalty of ϕ_i on $q_i - r_i > 0$. Note that the expected penalty is linear under this specification. This assumption is not common in the literature, so we address the value of enforcement strategies that produce alternative forms of the expected penalty function in section 4.[3] The unit penalty may vary among firms to allow for the possibility that this may be part of an efficient policy, but we restrict it to be no more than a maximal value $\overline{\phi}$, which does not vary. We also assume that $\phi_i > t_i$ throughout. This is a natural assumption because the penalty can be interpreted as recovering evaded taxes plus a punitive element. More importantly, this assumption ensures that full compliance is a possible outcome with less than certain monitoring throughout the paper.

To simplify our analysis we restrict it to policies that motivate all firms to reduce their emissions below what they would release in the absence of regulatory control, but that do not cause any firm to choose zero emissions. Moreover, we assume that each firm has sufficient assets so that the total of its tax payment plus possible penalties cannot force it into bankruptcy. Under these assumptions firm *i* chooses it emissions and emissions report to solve:

$$\begin{aligned} &\min_{(q_i, r_i)} C(q_i, x_i, \varepsilon_i) + t_i r_i + \pi_i \phi_i (q_i - r_i) \\ &s.t. \qquad q_i - r_i \geq 0,\ r_i \geq 0. \end{aligned} \tag{1}$$

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[3] Linear penalties are also not common in the literature. They are, however, common for actual emissions trading schemes (see [2] for several examples). There is less documented evidence for actual emissions taxes. However, Poland's sulfur dioxide and nitrogen oxide taxes impose a constant fine of 10 times the tax for noncompliance [24]. Under Sweden's tax on NO_X, violators pay their unreported tax liability plus interest (personal communication with Claes Englund, officer of the Swedish NOx program). While this may not appear to be much of a deterrent, for our purposes all that matters is that it is a linear fine.

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. Let $\mathcal{L}$ denote the Lagrange equation for (1) and let λ_i denote the multiplier attached to the constraint $q_i - r_i \geq 0$. The following first-order conditions are then both necessary and sufficient to solve (1):

$$\mathcal{L}_q = C_q(q_i, x_i, \varepsilon_i) + \pi_i \phi_i - \lambda_i = 0; \tag{2}$$

$$\mathcal{L}_r = t_i - \pi_i \phi_i + \lambda_i \geq 0,\ r_i \geq 0,\ r_i(t_i - \pi_i \phi_i + \lambda_i) = 0; \tag{3}$$

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

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:

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

Thus, the firm truthfully reports its emissions if and only if its tax does not exceed the expected marginal penalty. Some may object to our formulation of the regulator's enforcement strategy on the grounds that it is implausible that a regulator would not react with an automatic audit if it received a report of zero emissions. While this is certainly true, we show in the next section that it will never be optimal to set the enforcement parameters so that a firm reports zero emissions.

When $t_i \leq \pi_i \phi_i$ so that the firm truthfully reports its emissions, (3) becomes $t_i = \pi_i \phi_i - \lambda_i$. 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, $-C_q(q_i, x_i, \varepsilon_i) = t_i$. However, when $t_i > \pi_i \phi_i$ and the firm under-reports its emissions, (4) indicates that $\lambda_i = 0$. In this case (2) becomes $-C_q(q_i, x_i, \varepsilon_i) = \pi_i \phi_i$; that is, a noncompliant firm chooses its emissions to equate its marginal abatement cost to the expected marginal penalty. Thus, a firm's optimal choice of emissions is:

$$q_i = \begin{cases} q(t_i, x_i, \varepsilon_i) & \mid \; C_q(q_i, x_i, \varepsilon_i) + t_i = 0, \quad \text{if} \;\; t_i \le \pi_i \phi_i \\ q(\pi_i \phi_i, x_i, \varepsilon_i) & \mid \; C_q(q_i, x_i, \varepsilon_i) + \pi_i \phi_i = 0, \;\; \text{if} \;\; t_i > \pi_i \phi_i . \end{cases} \tag{6}$$

3. The Costs of Enforcing Emissions Taxes and the Optimality of Full Compliance

The regulatory objective of this paper is to choose firm-specific 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 show how a tax/enforcement policy with a constant expected marginal penalty should be designed to minimize the expected enforcement costs of inducing an arbitrary and imperfectly known set of individual emissions.

We allow the costs of monitoring to vary across firms.[4] Plant location may affect inspection costs and plants with more discharge points may be harder to monitor than others. Moreover, the variation in firms' abatement and production technologies, particularly if they belong to different industries, may also produce variation in monitoring costs. As with firms' abatement costs, the regulator is uncertain about the costs of monitoring individual firms, but it might possess information about how monitoring costs are correlated with observable firm characteristics. Consequently, let the cost of monitoring firm *i* be $m(\pi_i, x_i, \mu_i)$, which is increasing in the detection probability π_i. The regulator is uncertain about monitoring costs because it cannot observe the parameter μ_i, but it may have some information about how these costs vary with the firms' observables x_i. We assume that aggregate monitoring costs are the

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[4] This assumption is closely related to the assumption that individuals vary in their probabilities of apprehension, which was first analyzed by Bebchuk and Kaplow [3].

sum of the individual monitoring costs functions; thus, the conditional expectation of aggregate monitoring costs is $E\left(\sum m(\pi_i, x_i, \mu_i)\right)$, where E denotes the expectation operator and summations are over all regulated firms throughout the paper.

Tax and penalty revenues 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 the government's costs of generating evidence to get a court to agree with its finding of a violation and imposition of a penalty. Accused firms may mount costly challenges to a sanction, and the government may respond with its own costly efforts to fight off these challenges.[5] On the other hand, a compliant firm reports the full extent of its emissions and, in doing so, admits liability for these emissions. With this admission the government does not need to generate the evidence that would be necessary to impose a penalty. Moreover, a firm that admits its liability is not likely to challenge the imposition of the tax.

Therefore, we assume that collecting 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. Like the costs of monitoring individual firms, the regulator may not have complete information about the costs of collecting penalties from individual firms. Although s_i may be a function of the size of the

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[5] Although it is reasonable to assume that imposing sanctions is costly, no work in the literature on enforcing emissions taxes that we are aware of deals with these costs. In the literature on enforcing emissions trading, only Stranlund [21] assumes that collecting penalties is costly. Assuming costly sanctions is only a bit more common in the literature on enforcing emissions standards (e.g., [1] and [13]). This assumption is more common in the larger literature on optimal law enforcement (e.g., [17]).

firm's penalty and possibly its observable characteristics, our results do not depend on specifying these relationships. We do, however, assume that the aggregate expected cost of collecting penalties is linear in the costs of collecting penalties from individual firms.[6]

Despite our 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/enforcement policy (t_i, π_i, ϕ_i), $i = 1, \ldots, n$, with $t_i < \phi_i \le \overline{\phi}$ for each i. Suppose that firms react to this policy with emissions q_i, $i = 1, \ldots, n$. This distribution of emissions is achieved with minimum expected aggregate enforcement costs only if $t_i = \pi_i \overline{\phi}$ for each $i = 1, \ldots, n$. With taxes and monitoring set in this way, each firm is compliant.

Proof: The proof proceeds by first showing that any policy involving $t_i \ne \pi_i \phi_i$ for some i can be modified to reduce expected enforcement costs without changing the distribution of emissions. First suppose that $t_i > \pi_i \phi_i$ for some i. Then, (5) and (6) indicate $r_i = 0$ and $q_i = q(\pi_i \phi_i, x_i, \varepsilon_i)$. Alternatively, hold π_i constant so that aggregate monitoring costs do not change, but reduce t_i so that $t_i = \pi_i \phi_i$. The firm will then choose $r_i = q_i$ so that it is now compliant, but it does not change it emissions because $q(\pi_i \phi_i, x_i, \varepsilon_i) = q(t_i, x_i, \varepsilon_i)$. Changing t_i in this way does not affect the decisions of the other firms. However, it eliminates the expected costs of penalizing i, thereby reducing aggregate enforcement costs. Now suppose that $t_i < \pi_i \phi_i$ for some i. (5) and (6) reveal that the firm is compliant so that $r_i = q(t_i, x_i, \varepsilon_i)$. However, reducing π_i so that $t_i = \pi_i \phi_i$ reduces aggregate monitoring costs without changing the firm's emissions and compliance

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[6] Any enforcement strategy will also involve fixed costs. Adding these costs does not change our results as long as they are not so high that it is optimal to forego regulation altogether.

choices, or the decisions of the other firms. Hence, minimizing expected aggregate enforcement costs requires $t_i = \pi_i \phi_i$ for each *i*. Moreover, aggregate monitoring costs are minimized by setting the individual penalties as high as possible. Therefore, minimizing expected aggregate enforcement costs requires $t_i = \pi_i \overline{\phi}$ for each $i = 1, \dots, n$. QED.

It is important to note that the proposition holds despite the regulator's uncertainty about the firms' abatement costs. Although this uncertainty implies that the regulator does not know the exact distribution of individual emissions that will result from a particular policy, the expected enforcement costs of holding the firms to whatever distribution of emissions is produced are minimized by choosing $t_i = \pi_i \overline{\phi}$, $i = 1, \dots, n$. Moreover, the proposition holds despite the regulator's uncertainty about monitoring and sanctioning costs. All the regulator has to know is that aggregate monitoring costs are increasing in individual monitoring levels, and aggregate sanctioning costs are increasing in the costs of penalizing individual firms.[7]

The cost-effectiveness of inducing full compliance depends on three assumptions that differ from the rest of the literature on enforcing incentive-based environmental policies. Our assumption that it is costly to collect penalties from noncompliant firms is crucial, because the

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[7] Clearly, inducing full compliance requires the regulator to commit to a monitoring strategy. A few authors have modelled enforcement of environmental regulations when a regulator cannot commit to monitoring strategies (e.g. [6] and [7]). We maintain the more common assumption of regulatory commitment, because there is clear value to the ability to commit, and we observe real cases in which regulators do commit to enforcement strategies that achieve full (or nearly full) compliance (e.g. EPA's SO_2 and NO_X Trading programs).

fundamental value of inducing full compliance is to avoid these costs. In the absence of sanctioning costs, Proposition 1 does not hold because society would be completely indifferent between allowing noncompliance and inducing full compliance. Moreover, we have given the regulator the freedom to choose firm-specific tax rates. All others assume a uniform tax rate that is often fixed. Finally, no one else to our knowledge specifies enforcement strategies that produce constant expected marginal penalties. We now examine the robustness of our full-compliance policy recommendation under non-constant expected marginal penalties.

4. The Robustness of the Optimality of Full Compliance

The focus on positive violation choices in the literature on emissions tax enforcement is accomplished in part with expected marginal penalties that are functions of the firms' choices of emissions, emissions reports, and evaded taxes. For example, Harford [8, 9] and Sandmo [18] assume expected penalties of the form $\pi_i(q_i, r_i) f_i(q_i - r_i)$, where f_i is a strictly convex penalty function.[8] In this section we ask the following question: Can a regulator reduce expected enforcement costs by designing a tax/enforcement policy with a non-constant expected marginal penalty that results in some level of tax evasion? Since aggregate expected monitoring and sanctioning costs are linear in the costs of monitoring and sanctioning individual firms, we can address this question from the perspective of alternative policies for a single firm and apply the result in the aggregate.

It is useful to introduce a small amount of new notation for this section. Denote a tax/enforcement policy for firm *i* as p_i, consisting of a tax and expected penalty function, under

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[8] Malik [15] and vanEgteren and Weber [22] assume the same form in the context of emissions trading, except that a firm's permit holding substitutes for its emissions report.

which the firm optimally chooses its emissions $q\left(p_i, x_i, \varepsilon_i\right)$ and emissions report $r\left(p_i, x_i, \varepsilon_i\right)$. Using the firm's decision criterion, the regulator can form conditional expectations of the firm's emissions and emissions report, $\overline{q}\left(p_i\right) = E\left(q\left(p_i, x_i, \varepsilon_i\right)\right)$ and $\overline{r}\left(p_i\right) = E\left(r\left(p_i, x_i, \varepsilon_i\right)\right)$.

We consider three policies that induce the same expected emissions from the firm. The first is the policy of Proposition 1, which we denote as $p_i^c = \left[t_i^c, \pi_i^c \phi_i (q_i - r_i)\right]$. We do not set the unit penalty at its maximum level in this section because, as will be clear shortly, our analysis depends on being able to vary ϕ_i. However, we maintain our assumption that $t_i < \phi_i$. Recall that motivating the firm to be compliant with minimal monitoring requires $t_i^c = \pi_i^c \phi_i$. The regulator's conditional expectation of the firm's emissions under p_i^c is $\overline{q}\left(p_i^c\right)$.

The other policies, $p_i^q = \left[t_i^q, \pi_i(q_i, r_i) f_i(q_i - r_i)\right]$ and $p_i^{\overline{q}} = \left[t_i^{\overline{q}}, \pi_i\left(\overline{q}\left(p_i^{\overline{q}}\right), r_i\right) f_i(q_i - r_i)\right]$, feature non-constant expected marginal penalties. Under p_i^q, the detection probability is based in part on the firm's actual emissions. Of course, it is not possible to do this directly because a firm's emissions are unknown until it is actually audited. Sandmo [18] recognizes this, but justifies conditioning monitoring on a firm's emissions by assuming that emissions produce observable correlates that a regulator can use to allocate its monitoring effort. Perhaps higher emissions are associated with more smoke leaving a pollution source, or elevated ambient concentrations of a pollutant can be linked to emissions from a particular source. When emissions do not have such observable correlates an alternative is that the regulator forms an expectation of the firm's emissions and uses it to refine its monitoring strategy. (Malik [15] suggests this approach). This leads to policy $p_i^{\overline{q}}$, under which the detection probability is conditioned on the regulator's expectation of the firm's emissions $\overline{q}\left(p_i^{\overline{q}}\right)$.

To simplify our analysis we assume that the functional forms of π_i and f_i are the same under p_i^q and $p_i^{\overline{q}}$, and that π_i and f_i' are linear functions. The latter assumptions imply that the regulator's prior expectation of the detection probability it will have to maintain under policy $p_i \in \left(p_i^q, p_i^{\overline{q}}\right)$ is $E\left[\pi\left(q\left(p_i, x_i, \varepsilon_i\right), r\left(p_i, x_i, \varepsilon_i\right)\right)\right] = \pi\left(\overline{q}\left(p_i\right), \overline{r}\left(p_i\right)\right)$, and that its expectation of the firm's marginal penalty is $E\left[f'\left(q\left(p_i, x_i, \varepsilon_i\right) - r\left(p_i, x_i, \varepsilon_i\right)\right)\right] = f'\left(\overline{q}\left(p_i\right) - \overline{r}\left(p_i\right)\right)$.[9]

The results of this section are based on comparisons of the detection probability under p_i^c to the regulator's expectations of the detection probabilities under p_i^q and $p_i^{\overline{q}}$ that induce the same expected emissions from the firm. Clearly, detection probabilities are easily adjusted by changing marginal penalties. So our results do not depend on arbitrary differences in marginal penalties, we assume that the equilibrium expected marginal penalties under p_i^q and $p_i^{\overline{q}}$ are equal to the marginal penalty under p_i^c; that is, $\phi_i = f'\left(\overline{q}\left(p_i\right) - \overline{r}\left(p_i\right)\right)$ for $p_i \in \left(p_i^q, p_i^{\overline{q}}\right)$. Under these conditions we obtain the following proposition, which is proved in the Appendix.

Proposition 2: Suppose that a regulator wishes to induce a fixed level of expected emissions from a firm. Relative to inducing the firm's compliance with a constant expected marginal penalty, a regulator can reduce its expected monitoring of the firm if and only if the probability

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[9] Obviously, we must have $\pi\left(\overline{q}\left(p_i\right), \overline{r}\left(p_i\right)\right) \in [0,1]$. The upper bound constraint is satisfied in our analysis because we are looking for the possibility that $\pi\left(\overline{q}\left(p_i\right), \overline{r}\left(p_i\right)\right) < \pi_i^c$, and $\pi_i^c < 1$ because of our assumption that $t_i^c < \phi_i$. Moreover, $\pi\left(\overline{q}\left(p_i\right), \overline{r}\left(p_i\right)\right)$ must be greater than zero to achieve the emissions reduction achieved by p_i^c.

of detection is a strictly increasing function of the firm's actual emissions and the regulator implements an enforcement strategy that it expects will result in the firm's noncompliance.

Since inducing full compliance with a constant expected marginal penalty does not incur sanctioning costs, implementing an enforcement strategy that results in firms' noncompliance can only reduce expected enforcement costs if it involves significantly lower detection probabilities. Since expected detection probabilities are lower only if they are increasing in the firms' actual emissions, any tax/enforcement policy that the regulator expects will result in firms' noncompliance and that features any combination of a strictly convex penalty function, the firms' emissions report, and the regulator's expectations of the firms' emissions will produce higher expected enforcement costs than a policy that motivates the firms to be compliant with constant expected marginal penalties. These are new results that clarify the value of enforcement strategies that are commonly assumed by others.

Note carefully that Proposition 2 does tell us that making detection probabilities increasing functions of the firms' actual emissions and allowing them to be noncompliant will lead to lower expected enforcement costs. This will happen only when the expected value of reduced monitoring effort outweighs the additional expected costs of penalizing noncompliance; however, there is nothing in our model that guarantees this. Moreover, it may not be possible to base a monitoring strategy on a firm's actual emissions. We have already noted that a regulator cannot do this directly because a firm's emissions are hidden until it is actually audited. It may be possible to do so indirectly if emissions have observable correlates that a regulator can use to refine its monitoring strategy, but not all types of emissions have such useful correlates. Thus, the opportunities to use noncompliance to reduce expected enforcement costs may be quite limited. Certainly, these opportunities are much more limited than what is implied by the existing literature.[10]

5. Optimal Emission Taxes under Incomplete Information and Costly Enforcement

Given our obvious pessimism about the value of using firms' noncompliance to reduce the expected costs of enforcing emissions taxes, in this section we incorporate the full compliance strategy of Proposition 1 to determine optimal emissions taxes under incomplete information and costly enforcement. Our primary focus now is on whether an optimal policy involves discriminatory taxes or whether a regulator should set a single tax that applies to all firms.

Suppose that pollution damage is an imperfectly known, increasing function of aggregate emissions, $D\left(\sum q_i, \delta\right)$, where δ is a random variable. The regulator knows the joint distribution of the firms' unknown abatement and monitoring cost parameters, their observable characteristics, and the unknown damage parameter. With this knowledge it forms a conditional expectation of the social costs of pollution and its control:

$$E\left\{\sum C(q_i, x_i, \varepsilon_i) + \sum m(\pi_i, x_i, \mu_i) + D\left(\sum q_i, \delta\right)\right\}. \tag{7}$$

Since the regulator will enforce the optimal policy so that all firms are compliant, from Proposition 1 it constrains the minimization of (7) by choosing $t_i = \pi_i \bar{\phi},\ i = 1, \ldots, n$. From (6), under this policy the regulator knows that the firms will choose their emissions so that

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[10] An anonymous reviewer suggested that we could interpret our detection probability as the probability of detecting *and* punishing noncompliant choices. If the likelihood of conviction is increasing in the size of a firm's violation, then a regulator may be able to exploit an increasing likelihood of punishing violators to reduce its monitoring effort.

$C_q(q_i, x_i, \varepsilon_i) + t_i = 0,\ i = 1, \ldots, n,$ which implicitly define their emissions as $q_i = q(t_i, x_i, \varepsilon_i),$ $i = 1, \ldots, n.$ Substituting $t_i = \pi_i \bar{\phi}$ and $q_i = q(t_i, x_i, \varepsilon_i),\ i = 1, \ldots, n,$ into (7) gives us the regulator's conditional expectation of social costs in terms of well-enforced, firm-specific tax rates:

$$E\left\{\sum C(q(t_i, x_i, \varepsilon_i), x_i, \varepsilon_i) + \sum m(t_i / \bar{\phi}, x_i, \mu_i) + D\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right)\right\}. \qquad (8)$$

To make sure that each detection probability is not greater than one, individual taxes are constrained by $t_i \le \bar{\phi},\ i = 1, \ldots, n.$ Assuming that (8) is strictly convex in $(t_1, \ldots, t_n)$ and that optimality calls for individual taxes that are strictly greater than zero and strictly less than $\bar{\phi}$, the following first-order conditions uniquely identify the optimal tax rates:

$$\begin{aligned} &E\left(C_q(q(t_k, x_k, \varepsilon_k), x_k, \varepsilon_k) q_t(t_k, x_k, \varepsilon_k)\right) + E\left(m_\pi(t_k / \bar{\phi}, x_k, \mu_k)\right)\big/\bar{\phi} \\ &\qquad + E\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right) q_t(t_k, x_k, \varepsilon_k)\right) = 0,\ k = 1, \ldots, n. \end{aligned}$$

Substitute $C_q(q_k, x_k, \varepsilon_k) + t_k = 0,\ k = 1, \ldots, n,$ into these and rearrange the results to obtain

$$t_k = \frac{E\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right) q_t(t_k, x_k, \varepsilon_k)\right)}{E\left(q_t(t_k, x_k, \varepsilon_k)\right)} + \frac{E\left(m_\pi(t_k / \bar{\phi}, x_k, \mu_k)\right)}{\bar{\phi} E\left(q_t(t_k, x_k, \varepsilon_k)\right)},\ k = 1, \ldots, n. \qquad (9)$$

Using the definition of the covariance between random variables, the first terms on the right hand side of equations (9) are

$$E\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right)\right) + \frac{Cov\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right), q_t(t_k, x_k, \varepsilon_k)\right)}{E\left(q_t(t_k, x_k, \varepsilon_k)\right)},\ k = 1, \ldots, n, \qquad (10)$$

where *Cov* denotes the covariance operator. Moreover, use $C_q(q_k, x_k, \varepsilon_k) + t_k = 0,\ k = 1, \ldots, n,$ to obtain $q_t(t_k, x_k, \varepsilon_k) = -1\big/C_{qq}(q_k, x_k, \varepsilon_k),\ k = 1, \ldots, n.$ Substitute these and (10) into (9) to obtain

$$t_k = E\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right)\right) + \frac{Cov\left(D'\left(\sum q(t_i, x_i, \varepsilon_i), \delta\right), -1\big/C_{qq}(q_k, x_k, \varepsilon_k)\right)}{E\left(-1\big/C_{qq}(q_k, x_k, \varepsilon_k)\right)}$$

$$+\ \frac{E\left(m_{\pi}(t_k/\bar{\phi},x_k,\mu_k)\right)}{\bar{\phi}E\left(-1/C_{qq}(q_k,x_k,\varepsilon_k)\right)},\ k=1,\ldots,n. \tag{11}$$

Note that the first term on the right hand side is the regulator's expectation of marginal damage. Since this term appears in all of the equations in (11), our final proposition follows immediately.

Proposition 3: An optimal policy of well-enforced emissions taxes under uncertainty about firms' abatement costs, their monitoring costs, and pollution damage involves discriminatory taxes if and only if

$$\begin{aligned}&\frac{Cov\left(D'\left(\sum q(t_i,x_i,\varepsilon_i),\delta\right),-1/C_{qq}(q_j,x_j,\varepsilon_j)\right)}{E\left(-1/C_{qq}(q_j,x_j,\varepsilon_j)\right)}+\frac{E\left(m_{\pi}(t_j/\bar{\phi},x_j,\mu_j)\right)}{\bar{\phi}E\left(-1/C_{qq}(q_j,x_j,\varepsilon_j)\right)}\\ &\neq\frac{Cov\left(D'\left(\sum q(t_i,x_i,\varepsilon_i),\delta\right),-1/C_{qq}(q_k,x_k,\varepsilon_k)\right)}{E\left(-1/C_{qq}(q_k,x_k,\varepsilon_k)\right)}+\frac{E\left(m_{\pi}(t_k/\bar{\phi},x_k,\mu_k)\right)}{\bar{\phi}E\left(-1/C_{qq}(q_k,x_k,\varepsilon_k)\right)},\end{aligned} \tag{12}$$

for some *j* and *k*.

Proposition 3 indicates that there are three potential sources of variation in optimal individual emissions taxes: variation in the regulator's conditional expectations of the marginal costs of monitoring the firms, $E\left(m_{\pi}(t_k/\bar{\phi},x_k,\mu_k)\right),\ k=1,\ldots,n$; variation in its conditional expectations of the reciprocal of the slopes of the firms' marginal abatement cost functions, $E\left(-1/C_{qq}(q_k,x_k,\varepsilon_k)\right),\ k=1,\ldots,n$, and variation in the covariances between marginal damage and the reciprocal of the slopes of the firms' marginal abatement cost functions. Note that when the firms' observable characteristics do not provide the regulator with any information about the variation of the slopes of the firms' marginal abatement costs or the marginal costs of monitoring them for compliance, the terms on both sides of equation (12) do not vary across firms, and the regulator chooses a uniform tax because it cannot distinguish the firms from one another. Thus, very poor information about individual firms appears to be the fundamental justification for setting a uniform tax to control a uniformly mixed pollutant.

When a regulator has somewhat better information about the firms, their optimal tax rates will vary. The first terms on both sides of (12) are interesting because they do not depend at all on the costs of enforcement. That is, even if one assumes zero enforcement costs, incomplete information about firms' abatement costs can produce variation in optimal tax rates when the regulator has some information that allows it to distinguish the slopes of the firms' marginal abatement cost functions from one another.[11]

However, we are mainly interested in how enforcement costs induce discriminatory taxes, which is captured by the variation in $E\left(m_{\pi}(t_k/\bar{\phi}, x_k, \mu_k)\right) \big/ \bar{\phi} E\left(-1 \big/ C_{qq}(q_k, x_k, \varepsilon_k)\right)$, $k = 1, \ldots, n$. Since this term is negative, the optimal tax on a firm will tend to be lower as this term is lower. This is intuitive because it reflects the regulator's conditional expectation of the increase in monitoring costs associated with inducing lower emissions from a 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 $C_{qq}(q_k, x_k, \varepsilon_k)$) 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 steeper marginal abatement cost functions. For the same reason, tax rates will tend to be lower for firms that the regulator expects are more difficult to monitor, and hence,

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[11] To our knowledge, the result that uncertainty about abatement costs by itself can produce discriminatory pollution prices is new. Given the focus of this paper on enforcement costs we do not explore this issue in depth here, but we think that it is an interesting area for future research.

have higher marginal monitoring cost functions.

Suppose that the slopes of the firms' marginal abatement cost functions vary and the regulator has some information about this variation. Then the optimal tax rates will vary across the firms even if their monitoring cost functions do not vary. Thus, discriminatory taxes do not require variation in monitoring costs. This is noteworthy because it implies that recognizing that enforcement is costly will often be sufficient justification for imposing discriminatory taxes.

Admittedly, the number of distinct 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 industries. In this case the number of distinct tax rates may simply be equal to the number of industries involved. Or, imagine a 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 can use to distinguish the firms' abatement or monitoring costs, the number of 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.[12]

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[12] We recognize that differentiated taxes can produce moral hazard problems. In our model a firm faces a lower tax than another if the regulator's expectation of the marginal monitoring costs associated with inducing a lower level of emissions is higher. This may lead firms to attempt to lower there tax rates by investing in reducing their "monitorability" as in Heyes [10]. This issue deserves further investigation.

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. We have argued that optimality requires sufficient enforcement resources to induce full compliance by all firms, except possibly when the probabilities of detecting violations are increasing functions of observable correlates of their actual emissions. Moreover, enforcement costs will typically induce discriminatory pollution prices, except when regulators have very poor information about individual firms. When regulators have at least some information about how monitoring and abatement costs vary across firms, conventional incentive-based policies like Pigouvian taxes and competitive emissions trading are inefficient.

Appendix: Proof of Proposition 2

A policy $p_i^c = \left[t_i^c, \pi_i^c \phi_i (q_i - r_i) \right]$ motivates the firm to report its true level of emissions because $t_i^c = \pi_i^c \phi_i$. Under p_i^c the firm chooses its emissions so that $-C_q \left(q_i, x_i, \varepsilon_i \right) = t_i^c$, from which the regulator forms its expectation of the firm’s emissions $E\left(q\left(t_i^c, x_i, \varepsilon_i \right) \right) = \overline{q}\left(p_i^c \right)$. Substitute this into $-C_q \left(q_i, x_i, \varepsilon_i \right) = t_i^c$ to obtain the identity $-E\left(C_q \left(\overline{q}\left(p_i^c \right), x_i, \varepsilon_i \right) \right) \equiv t_i^c$.

Under $p_i^q = \left[t_i^q, \pi_i (q_i, r_i) \, f(q_i - r_i) \right]$, the firm’s expected costs are $C(q_i, x_i, \varepsilon_i) + t_i^q r_i$ $+ \pi_i (q_i, r_i) \, f_i (q_i - r_i)$. Assuming that this function is strictly convex in (q_i, r_i), and the firm chooses $q_i > 0,\ r_i > 0,$ and $q_i - r_i \geq 0$, its optimal q_i and r_i are determined from:

$$C_q (q_i, x_i, \varepsilon_i) + \left(\partial \pi_i / \partial q_i \right) f_i (q_i - r_i) + \pi_i (q_i, r_i) \, f_i'(q_i - r_i) - \lambda_i = 0; \tag{A.1}$$

$$t_i^q + \left(\partial \pi_i / \partial r_i \right) f_i (q_i - r_i) - \pi_i (q_i, r_i) \, f_i'(q_i - r_i) + \lambda_i = 0; \tag{A.2}$$

$$-(q_i - r_i) \leq 0,\ \lambda_i \geq 0,\ \lambda_i (q_i - r_i) = 0, \tag{A.3}$$

where, λ_i is a Lagrange multiplier. From (A.1)—(A.3) the regulator calculates $E\left(q\left(p_i^q, x_i, \varepsilon_i \right) \right)$ $= \overline{q}\left(p_i^q \right)$ and $E\left(r\left(p_i^q, x_i, \varepsilon_i \right) \right) = \overline{r}\left(p_i^q \right)$, which upon substitution into (A.1) and (A.2) yields:

$$\begin{aligned} &E\left(C_q \left(\overline{q}\left(p_i^q \right), x_i, \varepsilon_i \right) \right) + \left(\partial \pi_i / \partial q_i \right) f_i \left(\overline{q}\left(p_i^q \right) - \overline{r}\left(p_i^q \right) \right) \\ &\qquad + \pi_i \left(\overline{q}\left(p_i^q \right), \overline{r}\left(p_i^q \right) \right) f_i'\left(\overline{q}\left(p_i^q \right) - \overline{r}\left(p_i^q \right) \right) - \lambda_i \equiv 0; \end{aligned} \tag{A.4}$$

$$\begin{aligned} &t_i^q + \left(\partial \pi_i / \partial r_i \right) f_i \left(\overline{q}\left(p_i^q \right) - \overline{r}\left(p_i^q \right) \right) \\ &\quad - \pi_i \left(\overline{q}\left(p_i^q \right), \overline{r}\left(p_i^q \right) \right) f_i'\left(\overline{q}\left(p_i^q \right) - \overline{r}\left(p_i^q \right) \right) + \lambda_i \equiv 0; \end{aligned} \tag{A.5}$$

Combine (A.4) and (A.5) to obtain

$$-E\left(C_q \left(\overline{q}\left(p_i^q \right), x_i, \varepsilon_i \right) \right) \equiv t_i^q + \left(\partial \pi_i / \partial q_i + \partial \pi_i / \partial r_i \right) f_i \left(\overline{q}\left(p_i^q \right) - \overline{r}\left(p_i^q \right) \right). \tag{A.6}$$

If p_i^q and p_i^c produce the same expected emissions from the firm, then p_i^q is constructed so that $-E\left(C_q\left(\overline{q}\left(p_i^q\right), x_i, \varepsilon_i\right)\right) = -E\left(C_q\left(\overline{q}\left(p_i^c\right), x_i, \varepsilon_i\right)\right)$. Thus, equating (A.6) and $-E\left(C_q\left(\overline{q}\left(p_i^c\right), x_i, \varepsilon_i\right)\right) \equiv t_i^c$ yields

$$t_i^q = t_i^c - \left(\partial \pi_i / \partial q_i + \partial \pi_i / \partial r_i\right) f_i\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right). \tag{A.7}$$

To compare the detection probability under p_i^c to the expected detection probability under p_i^q, substitute $t_i^c = \pi_i^c \phi_i$ into (A.7) and substitute the result into (A.5) to obtain

$$\pi_i^c \phi_i - \pi_i\left(\overline{q}\left(p_i^q\right), \overline{r}\left(p_i^q\right)\right) f_i'\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right) = \left(\partial \pi_i / \partial q_i\right) f_i\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right) - \lambda_i . \tag{A.8}$$

So that our results do not depend on the difference in marginal penalties, substitute $\phi_i = f_i'\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right)$ into (A.8) and rearrange terms to obtain $\pi_i^c - \pi_i\left(\overline{q}\left(p_i^q\right), \overline{r}\left(p_i^q\right)\right) = \left[\left(\partial \pi_i / \partial q_i\right) f_i\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right) - \lambda_i\right] \Big/ \phi_i$. Since $\lambda_i \geq 0$ and $\lambda_i = 0$ when $\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right) > 0$, $\pi_i\left(\overline{q}\left(p_i^q\right), \overline{r}\left(p_i^q\right)\right) < \pi_i^c$ if and only if $\left(\partial \pi_i / \partial q_i\right) f_i\left(\overline{q}\left(p_i^q\right) - \overline{r}\left(p_i^q\right)\right) > 0$. Clearly, this requires that the regulator expects the firm to be noncompliant and that the probability of detection under p_i^q is a strictly increasing function of the firm's emissions.

We now compare that the detection probabilities under $p_i^c = \left[t_i^c, \pi_i^c \phi_i\right]$ and $p_i^{\overline{q}} = \left[t_i^{\overline{q}}, \pi_i\left(\overline{q}\left(p_i^{\overline{q}}\right), r_i\right) f_i(q_i - r_i)\right]$. Under $p_i^{\overline{q}}$ the regulator calculates $\overline{q}\left(p_i^{\overline{q}}\right)$ and commits to $\pi_i\left(\overline{q}\left(p_i^{\overline{q}}\right), r_i\right)$ at the outset. Consequently, the firm treats $\overline{q}\left(p_i^{\overline{q}}\right)$ as a constant, implying $\partial \pi_i / \partial q_i = 0$. Then, proceeding as above, it is easy to derive $\pi_i^c - \pi_i\left(\overline{q}\left(p_i^{\overline{q}}\right), \overline{r}\left(p_i^{\overline{q}}\right)\right) = -\lambda_i / \phi_i$.

Since $\lambda_i \geq 0$, $\pi_i^c \leq \pi_i\left(\overline{q}\left(p_i^{\overline{q}}\right), \overline{r}\left(p_i^{\overline{q}}\right)\right)$, which indicates that the probability of detection under $p_i^{\overline{q}}$ cannot be less than the probability of detection under p_i^c. QED.

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