The Cost-Effective Choice of Policy Instruments to Cap Aggregate Emissions with Costly Enforcement*

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Abstract

In this paper we first study the total-cost-effectiveness of inducing expected perfect compliance under a system of emissions standards when not only abating emissions but also monitoring and sanctioning are costly. We find that the cost-effective design of a program that caps aggregate emissions of a given pollutant from a set of firms based on emissions standards is one in which standards are firm-specific and perfectly enforced. We then compare the total (abatement, monitoring and sanctioning) expected costs of such an optimally designed program with that of an optimally designed program based on a perfectly competitive emission permits market, in the context of incomplete information. We find that the expected total costs of capping aggregate emissions to a certain level are minimized by the emission standards program. We conclude that, it is not in the name of cost-effectiveness *per se* that we economists are to argue in favor of tradable emission permits, but in the name of information advantages for the regulator.

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1 Introduction

The world witnesses discussions both in the US and abroad about the way and by how much to cap emissions of green-house gases. One of the most important arguments behind these discussions is the costs of the implied emission reductions. We environmental economists have been giving a clear policy recomendation for such an issue for a long time: whenever possible, a regulator should cap emissions by means of a competitive market on emission permits because this policy instrument minimizes the aggregate abatement costs of reaching any chosen cap with minimum information requirements for regulators. Based on this policy recommendation, the European Union has adopted an emissions trading scheme (the EU-ETS) as an important instrument to limit its GHG emissions. The Obama administration is also pushing a similar alternative in Congress. The Waxman-Markey´s American Clean Energy and Security Act has been approved in the House of Representatives and is now being discussed in the Senate. But climate change is not the only environmental issue in which environmental economists seem to have influenced policy decissions: until the appearance of the EU - ETS, the US was home of the major policy experiment with tradable permits; the SO_2 allowance market to control acid rain. **SUBSTANTIATE ALL THIS WITH CITES.**

This apparent success of the profession in the recomendation of this policy instrument mainly as a cost-effective way to attain a certain level of environmental quality may be seen as surprising. A tradable emissions permit system minimizes abatement costs, but these are not the only social costs of caping emissions. There are other important costs, such as the cost of monitoring compliance and sanctioning violations. The environmental economics literature has not yet given a definite answer on the relative cost-effectiveness of a tradable emission permits system with respect to one based on emission standards when enforcement costs are brought into the picture.[1] Malik (1992) compares the costs of reaching a given level of aggregate emissions by means of a perfectly enforced program based on uniform emission standards with that of a perfectly enforced program based on tradable permits, for a regulator with perfect information. He concludes that the enforcement costs under tradable permits may be higher than those under emission standards.

[1]Moreover, a recent paper surveying the literature on the choice of policy instruments completely ommits this issue (see Goulder and Parry, 2008).

Therefore, although the program based on tradable permits minimizes the aggregate abatement costs, the total costs of such a program could end up being higher than the total costs of a program based on emission standards. Nevertheless, he does not consider sanctioning costs. Hahn and Axtell (1995) compare the relative costs of a uniform emission standard instrument with that of a tradable permits system allowing non-compliance. But the costs in the alternatives are comprised of abatement costs and fines. These authors do not consider monitoring or sanctioning costs. More recently, Chávez, et al. (2009) repeat Malik's exercise for a regulator that, unlike Malik´s, cannot perfectly observe the abatement costs of the firms, but knows its distribution. With this information, he chooses to inspect all firms with a homogeneous probability that is high enough to assure compliance of the firms with higher abatement costs. The authors prove that emissions standards are more costly than tradable permits with this monitoring strategy.

One important aspect that all of the above papers share is that they do not consider the cost-effectiveness of inducing compliance. They simply assume that perfect compliance is the regulator's objective, as in Malik (1992) and Chavez, et al (2009), or it is simply non-attainable, as in Hahn and Axtell (1995). But inducing compliance is costly for the regulator. Stranlund (2007) seems to be the first to have adressed this issue of whether the regulator can use non-compliance as a way to reduce the costs of a program that cap aggregate emissions. To put it clearly, the question he addresses is the following: if a regulator wants to achieve a certain level of aggregate emissions from a set of firms at the least possible cost using tradable permits, does it have to design the program to allow a certain level of noncompliance or does it have to perfectly enforce such a program? The answer depends on the relative marginal cost of inspecting versus sanctioning, which in turn depends on the form of the fine structure. Taking into account abatement, monitoring and sanctioning costs, Stranlund concludes that the total-cost-effective design of a program based on tradable permits is one in which the marginal penalties are constant and the program is perfectly enforced. Arguedas (2008) replicates Stranlund´s analysis for the case of an emission standard system, a regulator with perfect information and one firm. She obtains an identical conclusion.

In this paper we first study the cost-effectiveness of inducing compliance in a system of emissions standards, with more than one firm and under the assumption of incomplete information. Considering the total program costs of an emissions standard system (abatement, monitoring, and sanctioning), and allowing the regulator to choose the fine structure to be increasing or linear in the level of violation, we characterize the total-cost-effective design of an emission standard system. Second, we compare the cost of such an optimally designed system of emissions standards with the costs an optimally designed transferable emissions permit system, as in Stranlund (2007), in the context of incomplete information.

We find that the cost-effective design of a program that caps aggregate emissions of a given pollutant from a set of firms based on emissions standards is one in which standards are firm-specific and perfectly enforced. In addition, such a system attains a certain level of aggregate emissions at lower expected costs than an optimally designed system of tradable permits. This is basically because the distribution of emissions generated by the latter differs from the distribution of emissions that minimizes the total costs of the program. Given that the distribution of emissions and monitoring efforts in the cost-effective design requires information that is private, and that the distribution of emissions and monitoring efforst in a cost-effective design of a tradable permits system does not reproduce the former, we conclude that it is not in the name of cost-effectiveness *per se* that we economists are to argue in favor of tradable emission permits, but in the name of information advantages for the regulator. In other words, the incomplete information on the actual marginal abatement costs functions of the firms could led the regulator to set a distribution of abatement responsibilities among firms (to set and perfectly enforce emission standards) that may result in lower expected costs but higher actual costs that those of a system of tradable permits. Clearly, more research is needed with respect to the factors affecting the balance of the costs of both instruments.

Our results also produce a clear policy recommendation for the design of environmental policy in developing countries. The environmental policy in these countries have been frequently described as poorly enforced (**CITAS**). Explanations of this situation frequently mention the budget constraints that regulators suffer in these countries. Our conclusion suggests that to design a regulation that sets a cap on emissions that is too costly for the regulator to enforce is of little justification in terms of the overall cost-effectiveness of the program. The regulator could attain the same level of aggregate emissions with less budget relaxing the non-enforced cap (letting the firms to pollute more) and perfectly enforcing the laxer regulation.

The paper is organized as follows. In section 2, we present the standard model of compliance behaviour of a risk-neutral polluter firm that faces an emission standard and, using this model we give the conditions under which it is cost-effective to induce perfect expected compliance for a regulator that wants to achieve a certain cap on the aggregate emissions of n firms using emissions standards. In Section 3 we characterize the cost-effective design of such a program when the exogenous structure of the penalty is such that it is cost effective to induce expected perfect compliance and when it is not. In Section 4 we let the regulator to choose the appropiate structure of penalties and we characterize the expected-cost-minimizing design based on emissions standards. Finally, in Section 5 we compare the costs of an optimally designed program based on standards and an optimally designed program based on tradable permits.

2 The Cost-Effectiveness of Inducing Perfect Compliance

In this section we answer the following question: when it is cost-effective for a regulator to induce perfect compliance? In order to do it, we first present the standard model of compliance behavior of a risk - neutral polluter firm under an emission standard (See Malik, 1992 or Harford, 1978). From this model we derive the emissions level with which the firm responds to the regulation. We then present the problem that a total cost minimizing regulator solves, taking into account the firms best reponses, when designing a program that caps aggregate emissions setting standards. From this model we derive the condition under which it is cost-effective for the regulator to induce perfect compliance.

¿DEBERÍAMOS DECIR ACÁ QUE ARGUEDAS YA HIZO ESTO PARA UNA FIRMA Y JOHN PARA PERMISOS, PERO QUE NOSOTROS LOS HACEMOS PARA VARIAS FIRMAS Y CON COSTOS DE MONITOREO Y SANCIONAMIENTO DIFERENTES?

2.1 A firm compliance behavior under an emission standard

Assume that reducing emissions of a given pollutant e is costly for a firm. The (minimum) abatement cost function for this firm, which we will call firm i, is $c_i(e_i)$, where e_i is the level of emissions of firm i. Firms' abatement costs can vary for many reasons, including differences in the type of the good being produced, the techniques and technologies of production and emissions control, input and output prices, and other more specific factors related to the corresponding industrial sector. The abatement cost function is assumed to be strictly decreasing and convex in the firm's emissions e $[c_i'(e_i) < 0$ and $c_i''(e_i) > 0]$.

The firm faces an emission standard (a maximum allowable level of emissions) s_i. An emissions violation v occurs when the firm's emissions exceed the emissions standard: $v_i = e_i - s_i > 0$. The firm is compliant otherwise. The firm faces a random probability of being audited π_i. An audit provides the regulator with perfect information about the firm's compliance status. If the firm is audited and found in violation, a penalty $f(v_i)$ is imposed. For the moment, we just assume that $f(v_i) = 0$ for all $e_i \leq s_i$, and $f'(v_i) > 0$ por all $e_i > s_i$.[2]

Under an emissions standard, a firm i chooses the level of emissions to minimize total expected compliance cost, which consists of its abatement costs plus the expected penalty. Thus, firm $i's$ problem is to choose the level of emissions to solve

$$\min_{e_i} c_i(e_i) + \pi_i f\left(e_i - s_i\right) \qquad (1)$$
$$\text{subject to } e_i - s_i \geq 0$$

The Lagrange equation for this problem is given by $\Gamma_i = c_i(e_i) + \pi_i f\left(e_i - s_i\right) - \eta_i\left(e_i - s_i\right)$, with η_i the Lagrange multiplier. The set of necessary Kuhn-Tucker conditions for a positive level of the standard an emissions is:

$$\begin{aligned}
\frac{\partial \Gamma_i}{\partial e_i} &= c_i'(e_i) + \pi_i f'\left(e_i - s_i\right) - \eta_i = 0 \\
\frac{\partial \Gamma_i}{\partial \eta_i} &= -e_i + s_i \leq 0; \eta_i \geq 0; \eta_i\left(e_i - s_i\right) = 0
\end{aligned}$$

Firm $i's$ choice of emissions: From the Kuhn-Tucker conditions it can be seen that

$$e_i = \begin{array}{l} s_i, \text{ if } -c_i'(s_i) \leq \pi_i f'(0) \\ e_i(s_i, \pi_i) > s_i, \text{ if } -c_i'(s_i) > \pi_i f'(0) \end{array}$$

[2] An alternative penalty function could be a two part penalty, i.e. $F(v) = F_0 + f(v)$, where F_0 is a fixed fee. Malik (1992), does not consider such type of penalty structure. Arguedas (2008) has already shown that it is not optimal to have a fixed penalty component when inducing compliance with an emissions standard.

The firm is going to comply with the standard if the expected marginal penalty is not lower than the marginal abatement cost associated with an emissions level equal to the emissions standard. Otherwise, the firm is going to choose a level of emissions $e_i(s_i, \pi_i) > s_i$, where $e_i(s_i, \pi_i)$ is the solution to $-c_i'(e_i) = \pi_i f'(e_i - s_i)$. Note that $c_i'(s_i)$, the marginal abatement costs evaluated at th standard, can vary among firms not only because they face a different standard, but also because of the firm's specific characteristics, possibly not perfectly observable for a regulatory authority.

2.2 The Condition under which it is Cost Effective for a Regulator to Induce Perfect Compliance

Now assume a regulator who is in charge of implementing a pollution control program based on emissions standards. The objective of the program is to cap the aggregate level of emissions of a given pollutant to a level E. The regulator wants to achieve this target at the least expected cost, including the abatement costs of the firms and his monitoring and sanctioning costs. Towards this objective he selects the probability of inspection π_i and the emission standard s_i, for every firm i. There are n firms that emit this pollutant. The firms differ in their abatement costs, but these are not perfectly observable for the regulator. Nevertheless, he can observe the type of each firm (he can observe whether the firm in question is a pulp and paper mill or a tannery, for example) and has a subjective probability distribution over the possible abatement cost functions of every type of firm. Based on this information, he constructs an expected abatement cost function for every type of firm and uses this as the proxy for the true level of abatement cost. The regulator's problem is:

$$\min_{\substack{(s_1,s_2,..,s_n)\\(\pi_1,\pi_2,..,\pi_n)}} E\left[\sum_{i=1}^{n} c_i(e_i) + \sum_{i=1}^{n} \mu_i \pi_i + \sum_{i=1}^{n} \beta_i \pi_i f(e_i - s_i)\right] \tag{2a}$$

subject to:

$$1) e_i = \bar{e}_i(s_i, \pi_i) \tag{2b}$$

$$2) \sum_{i=1}^{n} \bar{e}(s_i, \pi_i) = E \tag{2c}$$

$$3)\ s_i \leq e_i\ \forall i = 1, ...n \tag{2d}$$

The objective function is the total expected costs of the pollution control program, composed of the expected aggregate abatement costs, the total monitoring costs and the expected total sanctioning costs. The expected aggregate abatement costs are $E\left[\sum_{i=1}^{n} c_i(e_i)\right]$. Assuming the cost of inspecting plant i is given by μ_i, the aggregate monitoring or auditing costs are $\sum_{i=1}^{n} \mu_i \pi_i$. Assuming that sanctioning plant i has a cost of β_i per dollar of fine, the expected aggregate sanctioning costs are $\sum_{i=1}^{n} \beta_i \pi_i f(e_i - s_i)$.For the moment, we assume that the regulator has not the ability to change the structure of the penalty function $f(e_i - s_i)$. It is given for him. The regulator knows that the firm i will react to a standard s_i and a monitoring probability π_i according to its reaction function $e_i(s_i, \pi_i)$.Therefore, he incorporates this incentive compatibility constraint in the problem. Because he cannot observe the abatement cost functions of the firms, the regulator does not know the reaction function of each particular firm. Nevertheless, he uses his belief about what the expected abatement cost function for firm i is and the firm's problem to calculate $\bar{e}_i$, the level of emissions that he believes the firm will produce as a response to a certain level of the emission standard s_i and inspection probability $\pi_{i.}$ The second constraint summarizes the environmental objective of the program, namely, that the the expected aggregate level of emissions cannot exceed a predetermined target E. Finally, the third constraint ackowledges that it may be in the interest of the firms to violate the emission standard. The Lagrange of the regulator´s problem can be written as

$$L = E\left[\sum_{i=1}^{n} c_i(\bar{e}_i) + \sum_{i=1}^{n} \mu_i \pi_i + \sum_{i=1}^{n} \beta_i \pi_i f(\bar{e}_i - s_i)\right] + \lambda_1 \left[\sum_{i=1}^{n} \bar{e}_i - E\right] + \sum_{i=1}^{n} \lambda_2^i (s_i - \bar{e}_i)$$

with λ_1 and λ_2^i being the $n+1$ multipliers. The $n \times 2 + n + 1$ necessary Kuhn-Tucker for positive levels of the standard and the auditing probability are:

$$\frac{\partial L}{\partial s_i} = E\left[c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial s_i} + \beta_i \pi_i f'(\bar{e} - s_i)(\frac{\partial \bar{e}_i}{\partial s_i} - 1)\right] + \lambda_1 \frac{\partial \bar{e}_i}{\partial s_i} + \lambda_2^i (1 - \frac{\partial \bar{e}_i}{\partial s_i}) = 0, i = 1, ..., n \quad (3)$$

$$\frac{\partial L}{\partial \pi_i} = E\left\{c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial \pi_i} + \mu_i + \beta_i\left[f(\bar{e} - s_i) + \pi_i f'(\bar{e} - s_i)\frac{\partial \bar{e}_i}{\partial \pi_i}\right]\right\} \tag{4}$$

$$+\lambda_1 \frac{\partial \bar{e}_i}{\partial \pi_i} - \lambda_2^i \frac{\partial \bar{e}_i}{\partial \pi_i} = 0, i = 1, ..., n$$

$$\frac{\partial L}{\partial \lambda_1} = \sum_{i=1}^{n} \bar{e}_i - E \leq 0, \lambda_1 \geq 0; \left(\sum_{i=1}^{n} \bar{e}_i - E\right) \times \lambda_1 = 0 \tag{5}$$

$$\frac{\partial L}{\partial \lambda_2^i} = s_i - \bar{e}_i \leq 0, \lambda_2^i \geq 0, \lambda_2^i \times (s_i - \bar{e}_i) = 0 \tag{6}$$

If $\bar{e}_i = s_i$, from (6) we know that $\lambda_2^i \geq 0$.Because we have also that $\lambda_1 \geq 0$, we can re-write the first order conditions of the regulator's problem as:

$$\begin{aligned}
\frac{\partial L}{\partial s_i} &= \left\{E\left[c_i'(s_i)\right] + \beta_i \pi_i f'(0) + \left(\lambda_1 - \lambda_2^i\right)\right\} \frac{\partial \bar{e}_i}{\partial s_i} - \beta_i \pi_i f'(0) + \lambda_2^i = 0 \\
\frac{\partial L}{\partial \pi_i} &= \left\{E\left[c_i'(s_i)\right] + \beta_i \pi_i f'(0) + \left(\lambda_1 - \lambda_2^i\right)\right\} \frac{\partial \bar{e}_i}{\partial \pi_i} + \mu_i = 0
\end{aligned}$$

Re-arranging the expressions and dividing:

$$\frac{\partial \bar{e}_i / \partial s_i}{\partial \bar{e}_i / \partial \pi_i} = \frac{\beta_i \pi_i f'(0) - \lambda_2^i}{-\mu_i}$$

From the firm's optimal choice of emissions, we know that

$$-c_i'(e_i) = \pi_i f'(e_i - s_i)$$

From where,

$$\partial \bar{e}_i / \partial \pi_i = \frac{-f'}{c_i'' + \pi_i f''} < 0$$

and

$$1 > \partial \bar{e}_i / \partial s_i = \frac{\pi_i f''}{c_i'' + \pi_i f''} > 0 \tag{7}$$

Because a cost-minimizing regulator that wants to achieve $\bar{e}_i = s_i$ will set π_i such that $E\left[-c_i'(s_i)\right] = \pi_i f'(0)$ in order not to waste monitoring resources, we can write

$$\frac{\partial \bar{e}_i/\partial s_i}{\partial \bar{e}_i/\partial \pi_i}_{\bar{e}_i = s_i} = \frac{\pi_i f''(0)}{c_i''(s_i) + \pi_i f''(0)} \times \frac{c_i''(s_i) + \pi_i f''(0)}{-f'(0)} = \frac{\pi_i f''(0)}{-f'(0)} = \frac{\beta_i \pi_i f'(0) - \lambda_2^i}{-\mu_i}$$

or

$$\mu_i \frac{\pi_i f''(0)}{f'(0)} = \pi_i \beta_i f'(0) - \lambda_2^i$$

From where, using $\lambda_2^i \geq 0$,

$$\mu_i \frac{\pi_i f''(0)}{f'(0)} \leq \pi_i \beta_i f'(0) \tag{8}$$

We have proved that when a cost - minimizing regulator induces (expected) compliance, this condition is met. The reverse is also true. When this condition is met, it is cost effective for the regulator to induce firm i to comply with the emission standard. Why? The right-hand side of (8) is the marginal increase in the expected sanctioning costs when the regulator marginally decreases the standard. The left hand side is the marginal decrease in monitoring costs that the regulator can attain when he decreases the monitoring probability accordingly so as to leave the level of emissions unchanged. Therefore, what the condition is saying is the following: if the firm is complying with the standard and moving the standard and the monitoring probability so as to make the firm to marginally violate the standard increases the sanctioning costs more than it decreases the monitoring costs, it is not cost-effective to do so. The regulator should leave things as they are: set π_i and s_i so as to induce the firm to comply with the standard. Otherwise, allowing the firm to violate the standard will increase the costs of the program.

Dividing both sides of equation (8) by π_i we obtain

$$\mu_i \frac{f''(0)}{f'(0)} \leq \beta_i f'(0) \tag{9}$$

The above discussion is summarized in the following proposition:

Proposition 1 *When the penalty structure is given, the cost-effective design of a pollution control program that caps aggregate emissions using emissions* *standards, calls the regulator to induce compliance with the standards for all i if and only if $\mu_i \frac{f''(0)}{f'(0)} \leq \beta_i f'(0)$ for all i. If this condition is not met, if he wants to achieve the cap cost-effectively, the regulator should induce positive violations of the emission standards for all those plants for which $\mu_i \frac{f''(0)}{f'(0)} > \beta_i f'(0)$.*

This Proposition is the same as Proposition 1 in Arguedas (2008), except that we do not assume, as she does, that the cost of an inspection and the per dollar cost of sanctioning β is the same for all firms. Monitoring costs may vary for several reasons. One of these reasons may be the distance between the firm and the enforcing agency. Another may be the number of discharge points per plant. At the same time, sanctioning costs may differ between firms because of their differing propensity to litigate sanctions and challenge the legislation, which may be a function of their budget, their visibility, their environmental strategy, or other characteristics. Therefore, we could have that $\mu = \mu_i$ and $\beta = \beta_i$, $i = 1, ..n$, and $\mu_i \neq \mu_j$ and $\beta_i \neq \beta_j$, for at least some $i \neq j$. In this case, the condition in Proposition 1 may be valid for some firms but not for other ones. In other words, it could be cost-effective for the regulator to induce violations for some firms and compliance for the rest. Another fundamental difference, is that if one assumes that monitoring and sanctioning costs are the same for all firms, the condition under which it is cost effective for a regulator to induce compliance does not depend on any individual characteristic of the firms, but only on the penalty structure and the unit costs of monitoring and sanctioning. If one assumes the contrary, as we does, the contestability of firms with respect to the regulatory decisions, for example, may be a characteristic of firms on which the condition to fully enforce or not an emissions control program may depend.

Finally, also asumming that monitoring and sanctioning costs are the same among firms, Stranlund (2007) reaches the same result (exactly the same condition) for the case of transferable permits. The condition under which it is cost-effective for a cost-minimizing regulator to induce compliance is not instrument-dependent.

3 The cost minimizing design of a program based on emission standards

We now turn to characterize the expected cost minimizing design of a program that controls emissions with standards. We do this for the cases in which the penalty structure is out of the control of the environmental regulator, and when it is not.

3.1 A given penalty function

When the structure of the penalty function $f(.)$ is outside the tool-box that the regulator has to design a cost-effective program based on emissions standards, condition (9) eithers holds or not. In other words, when the penalty structure is exogenously given to the regulator, condition (9) dictates him whether it is cost-effective to induce perfect compliance or not. In the first case, it is easy to show that the optimal policy $(\pi_1^*, \pi_2^*, ...\pi_n^*, s_1^*, s_2^*, ...s_n^*)$ that induces expected compliance is characterized by:

$$E\left[c_i'(s_i^*)\right] + \mu_i \frac{d\pi_i^*}{ds_i} = E\left[c_j'(s_j^*)\right] + \mu_j \frac{d\pi_j^*}{ds_j}, \text{ for all } i \neq j, (i,j) = 1, ..., n, \quad (10)$$

$$\text{and } \pi_i^* = \frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}, \text{for all } i = 1, ..., n.$$

and (2) (See Proof 1 in the Appendix). When it is cost-effective to induce expected compliance, the regulator has to set emission standards such that the *sum* of marginal expected abatement and monitoring costs are equal between firms, a result obtained by Chávez, et. al (2009) and Malik (1992) in the context of perfect information on abtement costs and a given objective of perfect compliance. Note that allocating emissions responsibilities in this way does not imply perfect compliance with certainty. In the presence of incomplete information, the regulator could attain perfect compliance with certainty setting $\pi_i^* = \frac{-c_i'(s_i^*, \theta_L^i)}{f'(0)}$, with $c_i'(s_i^*, \theta_L^i)$ being the largest possible value of the marginal abatement cost of complying with the standard among all firms. It is easy to see that this monitoring probability is larger than the one that it has to choose to induce expected compliance. An immediate corollary that follows from this conclusion is that a program designed to induce perfect compliance with certainty in this fashion (as in Chávez, et. al (2009)) does not minimize the expected costs of the program.

When (9) does not hold, it is not cost-effective for the regulator to induce compliance for all firms. In other words, a regulator interested in implementing a program that caps aggregate emissions to a certain level, has to design such program (meaning to choose the auditing probability and the emission standard for each firm) so as to allow a certain level of non-compliance. In the context of incomplete information and given penalties, the characterization of the expected cost-effective program to control emissions with standards when it is cost-effective to induce non-compliance for all firms is given by Proposition 2.

Proposition 2 *If the optimal policy* $(\pi_1^*, \pi_2^*, ...\pi_n^*, s_1^*, s_2^*, ...s_n^*)$ *induces non-compliance for all firm* i *in expected terms, it is characterized by*

$$E\left[c_i'(\bar{e}_i)\right] + \beta_i \pi_i^* f'(\bar{e}_i - s_i^*) \left(\frac{\partial \bar{e}_i/\partial s_i - 1}{\partial \bar{e}_i/\partial s_i}\right) = -\lambda_1 \quad (11)$$

$$E\left[c_i'(\bar{e}_i)\right] + \frac{\mu_i}{\partial \bar{e}_i/\partial \pi_i} + \frac{\beta_i f(\bar{e}_i - s_i^*)}{\partial \bar{e}_i/\partial \pi_i} + \beta \pi_i^* f'(\bar{e}_i - s_i^*) = -\lambda_1 \quad (12)$$

for all $i = 1, ..., n$, *where* λ_1 *is the Lagrange multiplier of the cap of emissions constraint in the regulator's problem.*

See proof of Proposition 2 in the Appendix.

Proposition 2 is telling that when it is cost-effective to induce non-compliance for every firm, the regulator has to choose π_i and s_i such that: (1) the sum of the expected marginal abatement plus sanctioning costs of moving s_i is the same accross firms, and (2) the sum of the expected marginal abatement, monitoring and sanctioning costs of changing π_i is the same accross firms. Condition (11) is quite intuitive. The firm reacts to a change in s_i by adjusting e_i by the amount $\partial \bar{e}_i/\partial s_i$, in expected terms. This change in $\bar{e}_i$ has an effect on the abatement costs of the firm i, but also an effect on the sanctioning costs of the regulator. We know by (7) that $0 < \partial \bar{e}_i/\partial s_i < 1$. Thus, a change in s_i causes the level of violation to change, and therefore the level of the expected fines that the regulator is going to charge firm i with. This in turn means a change in the expected sanctioning costs for the regulator. The regulator sets s_i equating these two marginal costs among firms, and it does a similar thing when adjusting π_i (12). A marginal change in the inspection probability affects all costs of the program: it affects firm's i abatement costs *via* a change in the level of emissions, it affects the auditing costs directly, and also affects the sanctioning costs because it changes the number of violations being discovered and because it changes the amount of violation by firm i. The regulator sets π_i^* such that the sum of these three marginal costs, measured in units of expected emissions, are the same among all firms.

Furthermore, from (11) and (12), we can obtain the following

$$\frac{\mu_i}{\partial \bar{e}_i/\partial \pi_i} + \frac{\beta_i f(\bar{e}_i - s_i^*)}{\partial \bar{e}_i/\partial \pi_i} = -\frac{\beta_i \pi_i^* f'(\bar{e}_i - s_i^*)}{\partial \bar{e}_i/\partial s_i} \tag{13}$$

for all $i = 1, ..., n$. This condition says that in the cost minimizing solution the regulator equates the marginal costs of both the standard and the monitoring probability for every firm. More specifically, the sum of the marginal monitoring and sanctioning costs of moving π_i is equal to the marginal sanctioning costs of moving s_i for every firm i.

We have assumed that the unit cost of an inspection (μ) and the per dollar cost of a fine (β) can differ between firms. In the particular case when μ and β are the same for all firms, the conditions characterizing an expected cost-minimizing design of a regulatory program that controls emissions with standards are essentially the same, except that in this case the condition (9) either holds or not *for every firm*. Thus, the regulator must induce compliance or non-compliance for every firm in the program. On the other hand, if the monitoring and sanctioning costs differ between firms it could be the case that condition (9) holds for a group of firms and does not hold for another group of firms. In this case, the conditions caracterizing the expected cost minimizing design of the program would be a combination of conditions (10) and conditions (**??**), (**??**) and (**??**).

We can conclude from Proposition 2 that the cost-effective level of emission standards are firm-specific in any case. Assuming μ and β to be the same for all firms, it would be the heterogeneity in marginal abatement costs $c_i'(\bar{e}_i)$ that would call for firm-specific standards. Similarly, if marginal abatement costs were the same for all firms, differences in monitoring costs and sanctioning costs among firms ($\mu_i \neq \mu_{j,}$ $\beta_i \neq \beta_j$) could also call for differences in the cost-minimizing standards.

3.2 The regulator can choose the structure of the penalty function

Having characterized the optimal program when it is optimum to induce compliance and when it is optimum to induce non-compliance, we now allow the regulator to choose the structure of the penalty function, and therefore the optimality of inducing expected compliance or not. We consider only two fine structures: linear and increasing in the level of the violation. Consequently, the regulator has basically to compare four possible alternatives and choose the one that minimizes the expected cost of reaching the cap E on emissions. The four alternatives are (1) to induce expected compliance with linear penalties, (2) to induce expected compliance with increasing penalties, (3) to induce an expected level of violations with linear penalties, and (4) to induce an expected level of violations with increasing penalties. To induce expected compliance with linear or increasing penaties has the same minimum expected costs because under compliance there are no sanctioning costs. Also, to induce non-compliance with linear penalties is ruled out by Proposition 1: it is never cost-effective to induce non-compliance when the marginal fine is linear. Therefore, the choice for the regulator boils down to a comparison between the costs of two alternatives: to induce expected compliance (with linear or increasing marginal penalty) or not to induce expected compliance (with increasing penalties). The result of this comparison is given in the next Proposition:

Proposition 3 *The optimal policy* $(s_1^*, s_2^*, ..., s_n^*, \pi_1^*, \pi_2^*, ...\pi_n^*, f^*)$ *induces compliance and it is characterized by (1)* $E\left[c_i'(s_i^*)\right] + \mu_i \frac{d\pi_i^*}{ds_i} = E\left[c_j'(s_j^*)\right] + \mu_j \frac{d\pi_j^*}{ds_j}$ *for all* $i = 1, ...n$*,* $i \neq j$*, (2)* $\pi_i^* = \frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}$*, and (3)* $f(e_i - s_i) = \phi(e_i - s_i) + \frac{\gamma}{2}(e_i - s_i)^2$ *for all* i*, with* ϕ *set as high as possible and* $0 \leq \gamma \leq \min\left[\frac{\beta_i}{\mu_i}\right] \times \phi^2$*.*

See the proof of Proposition 3 in the Appendix.

The expected cost minimizing policy when a regulator wants to cap aggregate emissions of a given pollutant to a certain level E through emission standards will be one that induces expected compliance. The structure of the fine does not play any role in equilibrium. Expected compliance could be induced with a constant marginal penalty or an increasing marginal penalty, as long as $\mu_i \gamma \leq \beta_i \phi^2$ for all i (otherwise the regulator mistakenly increases the cost of the program by making cost-effective not to induce perfect compliance).

Proposition 3 has important implications for the real-world policy design. The first and most obvious one is that there is no justification in terms of the costs of the program to design it to allow violations if the fine structure is under the control of the environmetal policy administrator. It is not difficult though to think of emission control programs in the real world that were designed or are being designed by different agencies or offices inside a regulatory agency. Think for example of ....**PONER EJEMPLOS**. If this is the case, one agency or office may set first the environmental objective (the aggregate level of emissions E in our case) and the abatement responsibilities among firms (the standards) while another agency or office may be in charge of designing the monitoring and enforcing strategy, for which it could be using fine structures defined by the general civil or criminal law. Proposition 3 suggests that the resulting regulatory design will be probably sub-optimum, except for the cases in which the penalty structure is the appropriate to induce expected perfect compliance and the offices are coordinated so as to set standards and monitoring probabilities according to Proposition 3.

Proposition 3 does not give a clear rule for setting ϕ "as high as possible". In the real world ϕ will be given be bounded upward by things such as the possibility that firms may go bankrupt, ... **VER LITERATURE** Wasserman (1992), Segerson and Tietenberg (1991), Becker (1968). Note that if this upper bound of ϕ is combined with a binding monitoring budget, the environmental regulator may not be capable of assuring expected compliance for all i and by this way minimize the total expected costs of the emissions control program.

4 Comparing costs of emission standards and tradable permits

4.1 Optimally designed programs

We have seen that the optimal design of a program based on emissions standards is one in which standards are firm-specific (set according to Proposition 3) and perfectly enforced (with the fine structure playing no role in equilibrium). We know from Stranlund (2007) that the optimal design of a program based on tradable permits is also one in which the program is perfectly enforced. Stranlund (2007) concludes that this has to be done using a constant marginal penalty. Instead, we argue that, as in the case of emission standards, the structure of the penalty does not play any role in equilibrium. According to Stranlund (2007), a cost minimizer regulator who wants to achieve expected perfect compliance in a system of tradable permits must set the monitoring probability for firm i (π_i^*) such that $\pi_i^* = \pi^* = \frac{\bar{p}}{\phi}$ for all i, where $\bar{p}$ is the expected full-compliance equilibrium price of the permits market and $\phi = f'(0)$. It is easy to see from this condition that the structure of the penalty function (whether it is increasing at a constant or an increasing rate) plays no role in the (minimimum) costs of the program. As in the case of emission standards, what affects these costs is $\phi = f'(0)$. The value of γ could take any positive value as long as $\mu_i \gamma \leq \beta_i \phi^2$ (it is cost-effective to induce perfect compliance).

Notwithstanding, the question remains whether a regulator interested in controlling emissions of a given pollutant by setting a cap on aggregate emissions in an expected cost minimizing manner should implement a perfectly enforced program based on firm-specific standards as in Proposition 3 above or a perfectly enforced program based on tradable permits as in Stranlund (2007). That is, once we know the optimal design of the programs based on the two instruments, what instrument should a regulator use if it wants to minimize the total expected costs of the program? The answer is given in the following Proposition:

Proposition 4 *If a regulator wants to control the emissions of a given pollutant by setting a cap on the aggregate level of emissions of this pollutant it will not minimize the total costs of doing so by implementing a system of tradable permits. On the contrary, expected total costs of such a pollution control program will be minimized by: (a) implementing firm-specific emissions standards and (b) perfectly enforcing this program.*

See proof of Proposition (4) in the Appendix.

Proposition (4) states that an optimally designed program based on firm-specific emissions standards, not one based on tradable permits, minimizes the expected total costs of a pollution control program that caps aggregate emissions to a certain level. This result may be surprising because it seems to contradict what we environmental economists have been advocating over the last forty years. Nevertheless, the reason why we have been advocating tradable permits is because they minimize aggregate abatement costs. Monitoring and enforcement costs were not part of the anlysis that led to this policy recomendation. Also, we have been advocating tradable permits as cost-effective policy instrument when compared to *uniform* (i.e: not firm-specific) emission standards. We know that in a world of perfect information there is no relative advantage of one instrument over the other in terms of abatement cost-effectiveness (Weitzman, 1974). Proposition (4) tells that when enforcement costs are brought into the picture this conclusion changes: firm specific standards are to be implemented because the functioning of a tradable permits market cannot by itself exploit the differences in abatement *and* monitoring costs. This conclusion can be extended to the setting of incomplete information if we talk about *expected* costs, not actual costs. Of course, when the regulator cannot observe firms' marginal abatement costs, it may commit relevant mistakes in the estimation of the abatement costs functions. (**PONER EJEMPLOS DE ESTIMACIONES DE COSTOS DE ABATIMIENTO VIA PRECIO DE EQUILIBRIO EN EL SO2 MARKET DE EEUU Y EN EL EUETS**). If this is the case, the realized social costs of setting and enforcing a global cap on emissions via firm-specific standards could end up being more expensive than doing it via an emissions trading scheme. This is the reason we are cautious about deriving policy recomendations from Proposition (4). More research is needed in this area before this can be done. (The same caveat is valid for Proposition (5) below).

In any case, what Proposition (4) tells is that it is not in the name of cost-effectiveness *per se* that we economists are to argue in favor of tradable emission permits, but in the name of information advantages: the regulator needs to know nothing about abatement costs when designing and enforcing an emissions trading scheme, and by this way it *may* be a cheaper instrument than emissions standards in terms of the realized social costs of setting a global cap on emissions.

(Comparar con Weitzman (1974) y Montero (2002)?) ?????

NOS QUEDA ESTUDIAR O COMENTAR SOBRE LOS FACTORES DE LOS QUE DEPENDE QUE EL REGULADOR TERMINE COMETIENDO ERRORES TAL QUE LA ASIGNACIÓN DE ESTANDARES SEA TAL QUE (EL COSTO """REAL""" del $\mathbf{P}^{ES}$ termine siendo superior a al costo del $\mathbf{P}^{TEP}$.

4.2 Comparing costs when it is cost - effective to induce non-compliance

As discussed above, it may be a common situation in the real world that the fine structure is given to the environmental authority. Assume that this is the case and that $\gamma > 0$. In this setting, whether the regulator has to perfectly enforce the program or not depends on the relative size of the monitoring and sanctioning parameters (i.e: whether $\mu_i \gamma \leq \beta_i \phi^2$ for all i or not). Assume that $\mu_i \gamma > \beta_i \phi^2$ for all i. Then it is cost-effective to design a program that induce a given expected level of non-compliance. In this case, how do the cost of a program based on emission standards compare with one based on tradable permits?

In order to answer this question, we first characterize the cost-effective design of a pollution capping program based on tradable permits when it is cost-effective to induce a given expected level of aggregate non-compliance. The we see if this optimally design program minimizes the total expected costs of reaching the cap E.

4.2.1 Characterization of the cost-effective design of a program based on tradable permits when is is cost-effective to induce non-compliance

When it is optimum not to induce perfect compliance for all i ($v_i > 0$ for all i), equations (21) and (22) can be re-written, assuming $\pi_i > 0$ for all i, as:

$$\frac{\partial \Lambda}{\partial \pi_i} = c_i'(\cdot) + \frac{\mu_i + \beta_i f(v_i)}{\frac{\partial l_i}{\partial p}\frac{\partial p}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}} + \lambda = 0;\ i = 1, .., n \tag{14}$$

$$\frac{\partial \Lambda}{\partial v_i} = c_i'(\cdot) + \pi_i \beta_i f'(v_i) + \lambda = 0,\ i = 1, .., n \tag{15}$$

These equations characterize the optimal design of a tradable permits program when it is cost - effective to induce all firms to violate their permit holdings ($e_i - l_i > 0$). In a similar fashion to the emission standards program, in the optimally designed tradable permits program the regulator sets π_i and v_i for all i such that: (a) the sum the marginal abatement, monitoring and sanctioning costs of changing π_i are equal across firms (equation 14) and (b) the sum of marginal abetement and sanctioning costs of changing v_i are equal across firms (equation 15). From equations (14) and (15) we can obtain

$$\frac{\mu_i + \beta_i f(v_i)}{\frac{\partial l_i}{\partial p}\frac{\partial p}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}} = \pi_i \beta_i f'(v_i),\ i = 1, .., n \tag{16}$$

Therefore, in the optimal design of a tradable permits program when it is cost - effective to induce all firms to violate their permit holdings the regulator also has to set the sum of the marginal monitoring and sanctioning costs of changing π_i equal to the marginal sanctioning costs of moving v_i for every firm i.

4.2.2 Comparison of Costs

Having characterized the optimal emissions trading program, we now show that this program does not minimize the total expected costs of capping aggregate emissions to E. In order to do this, we recall from the proof of Proposition (4) that every firm i that violates their permits holdings in a competitive emission permits market chooses its level of emissions such that $-c_i'(\cdot) = p$ and the quantity of permits to demand such that $p = \pi_i f'(v_i)$. Using both expressions, we can write (15) as

$$(-1 + \beta_i)\, p = -\lambda, \text{ for all } i = 1, .., n$$

or

$$\beta_i = 1 - \frac{\lambda}{p}, \text{ for all } i = 1, .., n$$

It is clear from the above equation that if sanctioning costs differ among firms ($\beta_i \neq \beta_j$ for some $i \neq j$, $(i, j) = 1, .., n$), a competitive permits market (one that generates a unique equilibrium price p for all firms) will not minimize the total expected costs of capping aggregate emissions to a level E, while allowing some degree of noncompliance. We express this result more formally in the Proposition below.

Proposition 5 *If a regulator wants set a cap on the aggregate level of emissions of a pollutant and it is not cost-effective to induce all firms to comply with the regulation ($\mu_i \gamma > \beta_i \phi^2$ for all i), it will minimize the total expected costs of such a regulatory program by implementing a system of firm-specific emissions standards, not a system of tradable permits.*

Proposition (5) is robust to the case when μ and β do not differ between firms. If $\mu_i = \mu_j$ and $\beta_i = \beta_j$ for all $i \neq j$, and we assume that the permits market is perfectly competitive, so that $\frac{\partial p}{\partial \pi_i} = 0$, then equation (16) can be written as

$$\frac{\mu + \beta f(v_i)}{\partial l_i / \partial \pi_i} = \pi_i \beta f'(v_i) \text{ for all } i = 1, .., n$$

But we know from Stranlund (2007) that if μ and β do not differ between firms, the regulator must induce a uniform violation across firms and monitor all firms with a uniform probability. Thus, the above equation can be written as

$$\frac{\mu+\beta f(v)}{\partial l_i/\partial \pi_i}=\pi\beta f'(v) \text{ for all } i=1,..,n$$

Using $p=\pi f'(v)$ and $\partial l_i/\partial \pi = f'(v)/\pi f''(v)$,

$$(\mu+\beta f(v))\frac{f''(v)}{(f'(v))^2}=\beta \text{ for all } i=1,..,n$$

This condition will not be met except in the special case where $\mu=0$ and $f(v)\frac{f''(v)}{(f'(v))^2}=1$. Therefore, in the general case where μ and β do not differ between firms it is also true that a system of tradable emission permits does not minimize the expected costs of capping aggregate emissions.

5 Conclusion

6 Appendix

Proof 1. When $\bar{e}_i=s_i$, expected violations are zero and therefore there are only two types of expected costs; monitoring and abatement. Moreover, if the regulator wants to achieve $\bar{e}_i=s_i$ it has to set π_i such that $E\left[-c_i'(s_i^*)\right]\leq \pi_i^* f'(0)$, or $\pi_i^*\geq \frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}$. Furthermore, if the regulator can induce $\bar{e}_i=s_i$ with $\pi_i^*=\frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}$ it would not be cost-effective to select $\pi_i^*>\frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}$.Therefore, $\pi_i^*=\frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}$. In this case, the Lagrange of the regulator´s problem can be re-written as ■

$$L=E\left[\sum_{i=1}^{n}c_i(s_i)+\sum_{i=1}^{n}\mu_i\pi_i^*\right]+\lambda_1\left[\sum_{i=1}^{n}s_i-E\right]$$

Therefore, the n +1 necessary conditions defining the n interior solutions for the standards are

$$\begin{aligned}\frac{\partial L}{\partial s_i} &= E\left[c_i'(s_i^*)\right]+\mu\frac{d\pi_i^*}{ds_i}+\lambda_1=0 \qquad\qquad i=1,2,...n\\ \frac{\partial L}{\partial \lambda_1} &= \sum_{i=1}^{n}s_i-E=0\end{aligned}$$

It follows directly from this condition that when it is cost-effective to induce expected compliance for all i, the optimal policy is to set s_i such that $E\left[c_i'(s_i^*)\right] + \mu \frac{d\pi_i^*}{ds_i} = E\left[c_j'(s_j^*)\right] + \mu \frac{d\pi_j^*}{ds_j}$ for all $i \neq j$, $(i,j) = 1, ..., n$.

Proof 2 (Proof of Proposition 2). When it is cost-effective to induce non-compliance for all firms, the expected cost-minimizing standards must be set such that $\bar{e}_i > s_i^*$. From Kuhn-Tucker condition (6), this implies that $\lambda_2^i = 0$. It is easy to see that the relevant Kuhn Tucker conditions in this case are

$$\frac{\partial L}{\partial s_i} = E\left[c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial s_i} + \beta_i \pi_i f'(\bar{e}_i - s_i)(\frac{\partial \bar{e}_i}{\partial s_i} - 1)\right] + \lambda_1 \frac{\partial \bar{e}_i}{\partial s_i} = 0, i = 1, ..., n \tag{17}$$

■

$$\frac{\partial L}{\partial \pi_i} = E\left\{c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial \pi_i} + \mu_i + \beta_i\left[f(\bar{e}_i - s_i) + \pi_i f'(\bar{e} - s_i)\frac{\partial \bar{e}_i}{\partial \pi_i}\right]\right\} + \lambda_1 \frac{\partial \bar{e}_i}{\partial \pi_i} = 0, i = 1, ..., n \tag{18}$$

Dividing (17) and (18) by $\frac{\partial \bar{e}_i}{\partial s_i}$ and $\frac{\partial \bar{e}_i}{\partial \pi_i}$ respectively, we obtain (**??**) and (**??**):

$$E\left[c_i'(\bar{e}_i)\right] + \beta_i \pi_i f'(\bar{e}_i - s_i)\left(\frac{\partial \bar{e}_i/\partial s_i - 1}{\partial \bar{e}_i/\partial s_i}\right) = -\lambda_1 \text{ for all } i = 1, ..., n$$

$$E\left[c_i'(\bar{e}_i)\right] + \frac{\mu_i}{\partial \bar{e}_i/\partial \pi_i} + \frac{\beta_i f(\bar{e}_i - s_i)}{\partial \bar{e}_i/\partial \pi_i} + \beta \pi_i f'(\bar{e}_i - s_i) = -\lambda_1 \text{ for all } i = 1, ..., n$$

Finally, from these two equalities we obtain (**??**):$\frac{\mu_i}{\partial \bar{e}_i/\partial \pi_i} + \frac{\beta_i f(\bar{e}_i - s_i)}{\partial \bar{e}_i/\partial \pi_i} = -\frac{\beta_i \pi_i f'(\bar{e}_i - s_i)}{\partial \bar{e}_i/\partial s_i}$ for all $i = 1, ..., n$. **Q.E.D.**

Note that the equation (13) is the first orden condition of the regulator's problem when $\pi_i^* = \frac{E\left[-c_i'(\bar{e}_i)\right]}{f'(\bar{e}_i - s_i)}$.

In this case, the relevant first order condition is:

$$\frac{\partial L}{\partial s_i} = E\left[c_i'(\bar{e}_i)\left(\frac{\partial \bar{e}_i}{\partial \pi_i}\frac{\partial \pi_i^*}{\partial s_i} + \frac{\partial \bar{e}_i}{\partial s_i}\right)\right] + \mu_i \frac{\partial \pi_i^*}{\partial s_i} + \beta_i \frac{\partial \pi_i^*}{\partial s_i} f(\bar{e} - s_i)$$
$$+\beta_i \pi_i^* f'(\bar{e} - s_i)\left(\frac{\partial \bar{e}_i}{\partial \pi_i}\frac{\partial \pi_i^*}{\partial s_i} + \frac{\partial \bar{e}_i}{\partial s_i} - 1\right) + \lambda_1\left(\frac{\partial \bar{e}_i}{\partial \pi_i}\frac{\partial \pi_i^*}{\partial s_i} + \frac{\partial \bar{e}_i}{\partial s_i}\right)$$
$$+\lambda_2^i(1 - \frac{\partial \bar{e}_i}{\partial \pi_i}\frac{\partial \pi_i^*}{\partial s_i} + \frac{\partial \bar{e}_i}{\partial s_i}) = 0, i = 1, ..., n$$

Using $\partial \pi_i^*/\partial s_i = -\frac{\partial \bar{e}_i/\partial s_i}{\partial \bar{e}_i/\partial \pi_i}$and $\lambda_2^i = 0$ when $s_i < \bar{e}_i$ $\forall i = 1, ...n$, this equation collapses to

$$\frac{\partial L}{\partial s_i} = \mu_i \frac{\partial \pi_i^*}{\partial s_i} + \beta_i\left[\frac{\partial \pi_i^*}{\partial s_i} f(\bar{e} - s_i) - \pi_i^* f'(\bar{e} - s_i)\right] = 0, i = 1, ..., n$$

from which we obtain (**??**) by using again $\partial \pi_i^*/\partial s_i = -\frac{\partial \bar{e}_i/\partial s_i}{\partial \bar{e}_i/\partial \pi_i}$.

Proof 3 (Proof of Proposition 3). In order to prove Proposition 3, we need first to answer a previous question: what is the cost-minimizing structure of the fine when it is optimum to induce compliance and when it is not. We consider only two fine structure: linear and increasing. The general fine structure can be writen as $f(e - s) = \phi(e - s) + \frac{\gamma}{2}(e - s)^2$, where ϕ is a positive constant and $\gamma \geq 0$.

If the optimal policy is going to induce compliance for all i, condition (9) requires that

$$\mu_i \gamma \leq \beta_i \phi^2 \text{ for all } i = 1, ..., n$$

We also know from Section 3 that in this case the characterization of the cost-effective design of a program based on standards calls for the following monitoring probability:

$$\pi_i^* = \frac{E\left[-c_i'(s_i^*)\right]}{f'(0)} = \frac{E\left[-c_i'(s_i^*)\right]}{\phi}$$

From here we can conclude:

(1) The regulator must choose the linear component ϕ of the fine structure as high as possible because this will decrease the optimum level of the inspection probability, π_i^*, and by this way the monitoring costs. Conceptually, this calls for $\phi = \infty$ because this will make the monitoring costs equal to

zero. But in the real world there may be limits to the upper value of ϕ. These limits may be given by...**CITATIONS FROM THE LITERATURE.**

(2) If we call $\bar{\phi}$ the highest possible value of ϕ, any value of $\gamma : 0 \leq \gamma \leq \min\left[\frac{\beta_i}{\mu_i}\right] \times \bar{\phi}^2$, will still make cost-efective to induce compliance for every firm and will not hav an effect on the minimum expected costs of the program, namely $\sum_{i=1}^{n} c_i(s_i^*) + \mu \sum_{i=1}^{n} \pi_i^*$.

Our conclusions in this respect differ from Arguedas' (2008). She concludes: "the larger the linear gravity component the lower the minimum probability to achieve compliance and therefore the social costs. Therefore, the optimal fine is one on which $f'(0)$ is as high as possible and $f''(0)$ is as low as possible, since only the first component affects the probability." On the contrary, we conclude that γ ($f''(0)$) plays no role (it does not affect the costs of the program). The penalty function can be linear ($\gamma = 0$) or increasing ($\gamma > 0$), as long as $\gamma \leq \min\left[\frac{\beta_i}{\mu_i}\right] \times \bar{\phi}^2$. This is because there are no sanctioning costs and all that the penalty function affects are the monitoring costs, through ϕ. Therefore, our conclusion: *If the optimal policy induces compliance for all i, the cost-minimizing shape of the fine must be such that the linear component ϕ is set as high as possible. The value of the progressive component γ is irrelevant in equilibrium as long as* $0 \leq \gamma \leq \min\left[\frac{\beta_i}{\mu_i}\right] \times \bar{\phi}^2$, where $\bar{\phi}$ is the chosen level of ϕ.

If the regulator is going to induce non-compliance, how does it have *to* choose ϕ and γ in order to minimize the costs of a program that produces E? In other words, can the regulator decrease the expected costs of the program by altering the fine structure (the value of ϕ and γ), once the optimal standards, inspections probabilities and emissions have been chosen? Notice that to choose the appropriate fine structure the regulator should optimize in the values of ϕ and γ keeping violations, and fines, constant. If $f(e-s) = \phi(e-s) + \frac{\gamma}{2}(e-s)^2$, changing ϕ and γ so as to keep f constant requires $\frac{e-s}{2} = -\frac{d\phi}{d\gamma}$. But with n firms, it is impossible to move ϕ and γ such that $\frac{e_i - s_i}{2} = -\frac{d\phi}{d\gamma}$ for all i. Keeping f contant for all i requires a firm-specific fine parameters. We assume that this is the case and we show that the optimal design of the program calls for a uniform fine structure.

If the fine structure is firm-specific, we have $f_i(\bar{e}_i - s_i) = \phi_i(\bar{e}_i - s_i) + \frac{\gamma_i}{2}(\bar{e}_i - s_i)^2$, and $f_i'(\bar{e}_i - s_i) = \phi_i + \gamma_i(\bar{e}_i - s_i)$ for each i. Now we ask how to choose ϕ_i and γ_i in order to minimize the costs of a program that produces E

when it is optimal to induce expected violations. Following Arguedas (2008), we ask ourselves whether we can decrease the costs of a program that induces a certain expected level of violation for each firm changing the fine structure (changing the values of ϕ_i and γ_i) while choosing π_i optimally. In order to answer this question, we evaluate the Lagrangean of the regulator's problem at $\pi_i = \pi_i^* = \frac{E\left[-c_i'(\bar{e}_i)\right]}{f'(\bar{e}_i - s_i)}$ when $\bar{e}_i > s_i$ and $\sum_i \bar{e}_i = E$ and change ϕ_i and γ_i such that $df_i = 0$, that is $-\frac{d\phi_i}{d\gamma_i} = \frac{\bar{e}_i - s_i}{2}$.

$$L = E\left[\sum_{i=1}^{n} c_i(\bar{e}_i)\right] + \sum_{i=1}^{n} \mu_i \pi_i^* + \sum_{i=1}^{n} \beta_i \pi_i^* f_i(\bar{e}_i - s_i)$$

$$dL = \frac{\partial L}{\partial \phi_i} d\phi_i + \frac{\partial L}{\partial \gamma_i} d\gamma_i$$

$$\begin{aligned} dL &= \left[\mu_i \frac{\partial \pi_i^*}{\partial \phi_i} + \beta_i \left[\frac{\partial \pi_i^*}{\partial \phi_i} f_i(\bar{e}_i - s_i) + \pi_i^*(\bar{e}_i - s_i)\right]\right] d\phi_i \\ &\quad + \left[\mu_i \frac{\partial \pi_i^*}{\partial \gamma_i} + \beta_i \left[\frac{\partial \pi_i^*}{\partial \gamma_i} f_i(\bar{e}_i - s_i) + \pi_i^* \frac{(\bar{e}_i - s_i)^2}{2}\right]\right] d\gamma_i \end{aligned}$$

Dividing both sides by $d\phi_i$ and substituting $\frac{d\gamma_i}{d\phi_i}$ for $\frac{2}{\bar{e}_i - s_i}$ we obtain

$$\begin{aligned} \frac{dL}{d\phi_i} &= \mu_i \frac{\partial \pi_i^*}{\partial \phi_i} + \beta_i \left[\frac{\partial \pi_i^*}{\partial \phi_i}\left(\phi_i(\bar{e}_i - s_i) + \frac{\gamma_i}{2}(\bar{e}_i - s_i)^2\right)\right] \\ &\quad - \frac{2\mu_i}{\bar{e}_i - s_i} \frac{\partial \pi_i^*}{\partial \gamma_i} - \beta \left[\frac{\partial \pi_i^*}{\partial \gamma_i}\left(2\phi_i + \gamma_i(\bar{e}_i - s_i)\right)\right] \end{aligned}$$

We know that $\frac{\partial \pi_i^*}{\partial \phi_i} = \frac{-E\left[-c_i'(\bar{e}_i)\right]}{\left[\phi_i + \gamma_i(\bar{e}_i - s_i)\right]^2}$ and $\frac{\partial \pi_i^*}{\partial \gamma_i} = \frac{-E\left[-c_i'(\bar{e}_i)\right]}{\left[\phi_i + \gamma_i(\bar{e}_i - s_i)\right]^2} \times (\bar{e}_i - s_i)$. Substituting,

$$\begin{aligned} \frac{dL}{d\phi_i} &= -\frac{E\left[-c_i'(\bar{e}_i)\right]}{\left[\phi_i + \gamma_i(\bar{e}_i - s_i)\right]^2}\left[\mu_i + \beta_i\left(\phi_i(\bar{e}_i - s_i) + \frac{\gamma_i}{2}(\bar{e}_i - s_i)^2\right)\right] \\ &\quad + \frac{E\left[-c_i'(\bar{e}_i)\right]}{\left[\phi_i + \gamma_i(\bar{e}_i - s_i)\right]^2} \times (\bar{e}_i - s_i)\left[\frac{2\mu_i}{\bar{e}_i - s_i} + \beta_i\left(2\phi_i + \gamma_i(\bar{e}_i - s_i)\right)\right] \end{aligned} \quad (20)$$

And after some operations we obtain

$$\frac{dL}{d\phi_i} = \frac{E\left[-c_i'(\bar{e}_i)\right]}{\left[\phi_i + \gamma_i(\bar{e}_i - s_i)\right]^2}\left[\mu_i + \beta_i\left(\phi_i(\bar{e}_i - s_i) + \frac{\gamma_i}{2}(\bar{e}_i - s_i)^2\right)\right] > 0$$

This means that the regulator can decrease the costs of a program that induces a violation $(\bar{e}_i - s_i)$ for each firm by decreasing ϕ_i (and increasing γ_i accordingly so as to keep the equilibrium fine constant). The intuition behind this result follows form two observations. First, by increasing the marginal equilibrium penalty the regulator decreases the equilibrium inspection probability π_i^* needed to induce a given expected level of violation $(\bar{e}_i - s_i)$. This decreases monitoring costs while keeps the rest of the costs constant. Second, the marginal equilibrium penalty increases more if the regulator increases γ_i than if it increases ϕ_i. The first term in the right-hand side of (20) is the marginal effect of a change in ϕ_i on the expected costs of the program. The second term is the marginal effect of a change in γ_i. These two effects act in opposed directions because keeping the fine constant requires increasing one parameter and decreasing the other. Decreasing ϕ_i increases the expected monitoring costs by $\frac{-E\left[-c_i'(\bar{e}_i)\right]}{[f(\bar{e}_i - s_i)]^2} \times \mu_i$ and by this way increases also the expected sanctioning costs by $\frac{E\left[-c_i'(\bar{e}_i)\right]}{[f(\bar{e}_i - s_i)]^2}\left[\beta_i f(\bar{e}_i - s_i)\right]$. Ii is easy to see from (**??**) that increasing γ_i by the quantity that keeps $f(\bar{e}_i - s_i)$ constant decreases both costs by more than this. Therefore the final effect is to decrease the total expected costs of the program (expected abatement costs do not change).

Now, decreasing ϕ_i has a limit and this limit is $\phi_i = 0$. Under a negative value of ϕ_i it will always exist a (sufficiently small) level of violation that makes the fine negative. But a negative fine violates our assumption that $f \geq 0$ for all levels of violations. On the other hand, there is no theoretical maximum value for γ_i. In theory this value is infinite, and therefore it is not firm-specific. Therefore, the expected cost minimizing design of a program based on standards calls for a uniform penalty structure for all firms: $f(\bar{e}_i - s_i) = \frac{\gamma}{2}(\bar{e}_i - s_i)^2$ for all i.The regulator always decreases monitoring costs by increasing γ, for the same level of violation. This is true for all firms and therefore it must set γ as high as possible for all firms. Because we are in the case where the regulator induces non-compliance, condition $\mu_i\gamma > \beta_i\phi^2$ for all $i = 1, ..., n$ must hold. Because we have just said that the cost minimizing shape of the penalty function requires $\phi_i = 0$ for all $i = 1, ..., n$, the above condition only requires $\gamma > 0$. Therefore, there is no positive lower limit to γ. In conclusion, *if the optimal policy induces expected non-compliance, the best shape of the penalty function is one in which the linear component $\phi = 0$ and the progressive component is set "as high as possible" for all firms.*

Having answered what is the cost-minimizing structure of the fine when it is optimum to induce compliance and when it is not, we now prove Proposition 3. Following Arguedas (2008), assume that it is optimum to induce expected non-compliance, and call the optimal policy $P^n = (s_1^n, s_2^n, ..., s_n^n, \pi_1^n, \pi_2^n, ...\pi_n^n, f^n)$, with $f^n = \frac{\gamma}{2}(e_i - s_i)^2$ for all i (with γ as high as possible following the results above), $\pi_i^n = \frac{E\left[-c_i'(\bar{e}_i^n)\right]}{\gamma(\bar{e}_i^n - s_i^n)}$ and $\sum_{i=1}^{n} \bar{e}_i^n = E$. Now consider an alternative policy $P^c = (s_1^c, s_2^c, ..., s_n^c, \pi_1^c, \pi_2^c, ...\pi_n^c, f^c)$ such that $s_i^c = \bar{e}_i^n$ and $\pi_i^c = \pi_i^n$ for all i, and $f^c = \phi(e_i - s_i)$ for all i with $\phi = \gamma \times \max_i \left[\bar{e}_i^n - s_i^n\right]$. By construction, this policy induces expected compliance because $\pi_i^c f^{c\prime} = \pi_i^c \phi = \pi_i^c \gamma \times \max_i \left[\bar{e}_i^n - s_i^n\right] \geq E\left[-c_i'(\bar{e}_i^n)\right] = E\left[-c_i'(s_i^c)\right]$ for all i. Moreover, P^c is cheaper than P^n in expected terms because expected abatement costs are the same under both programs ($s_i^c = \bar{e}_i^n$ for all i), expected monitoring costs are the same under both programs ($\pi_i^c = \pi_i^n$ for all i), but under policy P^c there are no expected sanctioning costs because there are no expected violations. **QED.** ■

Proof 4 (Proof of Proposition 4). The total expected costs of a program that sets a cap on aggregate emissions is given by the expected abatement costs of the regulated firms and the expected monitoring and sanctioning costs of the regulator. That is,

$$ETC^k = EAC^k + EMC^k + ESC^k$$

where ETC^k is the total expected costs of the program k, EAC^k is the expected abatement costs of the program k, EMC^k is the expected monitoring costs of the program k, ESC^k is the expected sanctioning costs of the program k and k = emission standards or tradable permits. We know from Proposition 3 that the optimally designed program based on emission standards must induce expected compliance. We also know from Stranlund (2007) that an optimally designed program based on tradable permits must also induce expected compliance. As a result, our comparison of the programs does not need to take into account ESC because these are zero in both programs when they are optimally designed. Taking this into account, and assuming that the emission standards program is enforced with a constant marginal penalty function, we know from Proposition 2 that $\pi_i^* = \frac{E\left[-c_i'(s_i^*)\right]}{\phi}$ in the optimally designed program based on standards and from Stranlund (2007) that $\pi_i^* = \pi^* = \frac{\bar{p}}{\phi}$ for all i in the case of the optimally designed program based on tradable permits. Consequently we can write

$$\begin{aligned} ETC^{TEP} &= E\left(\sum_{i=1}^{n} c_i\left(e_i\left(\bar{p}\right)\right)\right) + \frac{\bar{p}}{\phi}\sum_{i=1}^{n}\mu_i \\ ETC^{ES} &= E\left(\sum_{i=1}^{n} c_i\left(s_i^*\right)\right) + \frac{1}{\phi}E\left(\sum_{i=1}^{n} -\mu_i c_i'\left(s_i^*\right)\right) \end{aligned}$$

where ETC^{TEP} is the expected total cost of an optimally designed program based on tradable emission permits and ETC^{ES} is the expected total cost of an optimally designed program based on emission standards.

The proof that $ETC^{ES} < ETC^{TEP}$ is trivial. By definition, in the optimally designed ES program, which has to induce perfect compliance, the emission responsibilities (standards) and monitoring probabilities are allocated so as to minimize the total expected costs of a program that caps aggregate emissions at E. Therefore, the total expected costs of the ES program must be lower than the total expected costs of an optimally designed program based on tradable permits, which produces a different allocation of emissions and monitoring probablities. Put it differently, an optimally designed tradable permits program does not minimze the expected total costs of capping aggregate emissions at a certain level E. We provide a proof of this latter assertion below.

In order to make the regulator's problem under a system of tradable permits comparable to the regulator's problem under a system of emission standards, assume that under a system of tradable permits, a cost minimizing regulator chooses the level of violation v_i and the level of monitoring π_i for each firm i, $i = 1, ..., n$, where $v_i = e_i - l_i$, and l_i is the quantity of permits demanded by firm i. More formally, the regulator's problem is:

$$\min_{\substack{(v_1,...,v_n)\\(\pi_1,...,\pi_n)}} E\left[\sum_{i=1}^{n} c_i\left(v_i + l_i\left(p, \pi_i\right)\right)\right] + \sum_{i=1}^{n}\mu_i\pi_i + \sum_{i=1}^{n}\pi_i\beta_i f(v_i)$$

subjet to

$$\sum_{i=1}^{n} v_i + l_i\left(p, L\right) = E$$

and

$$v_i \geq 0$$

where $l_i(p)$ is firm's i demand function for permits, with p the equilibrium price of permits, and L the total number of permits issued, such that $\sum_{i=1}^{n} l_i(p, \pi_i) \equiv L$.

The Lagreangean of this problem is

$$\Lambda = E\left[\sum_{i=1}^{n} c_i\left(v_i + l_i(p, \pi_i)\right)\right] + \sum_{i=1}^{n} \mu_i \pi_i + \sum_{i=1}^{n} \pi_i \beta_i f(v_i) + \lambda\left(\sum_{i=1}^{n} v_i + l_i(p, L) - E\right)$$

The Kuhn - Tucker conditions of this problem are:

$$\frac{\partial \Lambda}{\partial \pi_i} = c_i'(\cdot)\left(\frac{\partial l_i}{\partial p}\frac{\partial p}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}\right) + \mu_i + \beta_i f(v_i) + \lambda\left(\frac{\partial l_i}{\partial p}\frac{\partial p}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}\right) \geq 0; \tag{21}$$

$$\pi_i \geq 0; \frac{\partial \Lambda}{\partial \pi_i}\pi_i = 0,\ i = 1, .., n$$

$$\frac{\partial \Lambda}{\partial v_i} = c_i'(\cdot) + \pi_i \beta_i f'(v_i) + \lambda \geq 0; v_i \geq 0; \frac{\partial \Lambda}{\partial v_i} v_i = 0,\ \ i = 1, .., n \tag{22}$$

$$\frac{\partial \Lambda}{\partial \lambda} = \sum_{i=1}^{n} v_i + l_i(p, L) - E = 0$$

When it is optimum to induce perfect compliance for all i ($v_i = 0$), (21) and (22) can be re-written, assuming $\pi_i > 0$ for all i, as:

$$\frac{\partial \Lambda}{\partial \pi_i} = c_i'(\cdot) + \frac{\mu_i}{\frac{\partial l_i}{\partial p}\frac{\partial p}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}} + \lambda = 0;\ \ i = 1, .., n \tag{23}$$

$$\frac{\partial \Lambda}{\partial v_i} = c_i'(\cdot) + \pi_i \beta_i f'(0) + \lambda \geq 0, i = 1, .., n$$

We know from Stranlund and Dhanda (1999) that, independently of its compliance status, in a competitive permits market, every firm i decides its level of emissions such that $-c_i'(\cdot) = p$. Using this, and assuming $\frac{\partial p}{\partial \pi_i} = 0$ (perfect competition in the permits market), (23) can be written as

$$p + \frac{\mu_i}{\partial l_i / \partial \pi_i} = -\lambda \text{ for all } i = 1, .., n$$

This implies, for any given two firms i and j, $i \neq j$, that the following identity must hold in the cost-minimizing design of perfectly enforced tradable permits market:

$$p + \frac{\mu_i}{\partial l_i / \partial \pi_i} = p + \frac{\mu_j}{\partial l_j / \partial \pi_j} \text{ for all } i \neq j, (i, j) = 1, .., n$$

Now, we also know from Stranlund and Dhanda (1999) that every firm is demanding permits so that $p = \pi_i f'(v_i)$. Using this condition, we can see that

$$\frac{\partial l_i}{\partial \pi_i} = \frac{f'(v_i)}{\pi_i f''(v_i)} \text{ for all } i = 1, .., n$$

So, when $v_i = 0$, we can write

$$p + \mu_i \frac{\pi_i f''(0)}{f'(0)} = p + \mu_j \frac{\pi_j f''(0)}{f'(0)} \text{ for all } i \neq j, (i, j) = 1, .., n$$

Cost-effective monitoring requires $\pi_i = p/f'(0)$ for all $i = 1, .., n$. Substituting this expression for π_i and π_j :

$$p + \mu_i \frac{pf''(0)}{(f'(0))^2} = p + \mu_j \frac{pf''(0)}{(f'(0))^2} \text{ for all } i \neq j, (i, j) = 1, .., n$$

It is easy to see that, in a competitive market for emission permits (i.e: one that generates a unique equilibrium price p), the above equality holds if and only if $\mu_i = \mu_j$. Thus, we can conclude that, if $\mu_i \neq \mu_j$ for any two firms i and j, $i \neq j$, a competitive system of tradable permits will not minimize the total costs of program that caps aggregate emissions to a certain level.QED.
■

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