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

Abstract

We study the cost-effectiveness of inducing expected perfect compliance considering the abatement, monitoring and sanctioning costs in a program that caps aggregate emissions of a given pollutant from a set of heterogeneous firms based on emissions standards. We find that the total cost-effective design of such a program is one in which standards are firm-specific and perfectly enforced. We then compare the expected costs of such an optimally designed program with that of an optimally designed program based on a perfectly competitive transferable emission permits system. We find that the latter minimizes the total expected costs of attaining a certain level of aggregate emissions only under some unlikely conditions. This result holds also in the case when it is cost effective to induce violations.

JEL Codes: L51, Q28, K32, K42

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1 Introduction

One of the most important features behind any emissions control policy, national or international, is the total cost of the implied emissions reduction. 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. This policy recomendation has had its impact: the European Union adopted an emissions trading scheme, the European Union Emissions Trading Scheme (EU-ETS), as an important instrument to limit its emissions of greenhouse gases. The Obama administration is also pushing a similar alternative in the U.S. Congress (The Waxman-Markey´s American Clean Energy and Security Act). Until the appearance of the EU - ETS, the US was home of the major policy experience with tradable permits; the SO_2 allowance market to control acid rain.

The apparent success of this policy recommendation may be seen as surprising, though, because abatement costs are not the only social costs of caping emissions. There are other relevant costs, such as the cost of monitoring compliance and sanctioning violations. Interestingly, the 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. Therefore, although the program based on tradable permits minimizes the aggregate abatement costs,

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

the total costs of such a program could end up being higher than the total costs of a program based on emission standards. Malik does not consider sanctioning costs because he focuses on perfectly enforced programs. 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 considering only abatement costs and fines. These authors do not consider monitoring or sanctioning costs. More recently, Chávez, et al. (2009) extend Malik's contribution for a regulator that, unlike Malik´s, cannot perfectly observe the abatement costs of the firms, but instead 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 the existing work 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). Stranlund (2007) seems to be the first to have adressed the issue of whether the regulator can use non-compliance as a way to reduce the costs of a program that caps 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 structure of the penalty function. 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.[2] Arguedas (2008) replicates Stranlund´s analysis for the case of an emission standard, a regulator with complete information and one firm. She obtains an identical conclusion. The analysis of one firm fails nevertheless to illustrate a central aspect of the design of cost-effective regulation in the real world; namely, how does the regulator have to allocate emissions responsibilities and monitoring and sanctioning efforts among different firms in order to minimize the total cost of the pollution control program.

In this paper we first derive the condition under which it is cost-effective to induce compliance in a system of emissions standards, with more than one firm, possibly firm-specific monitoring and sanctioning costs and incomplete information. Considering the total costs of the program (abatement, monitoring, and sanctioning), we then characterize the total expected cost effective design of an emission standard system and compare it to the costs an optimally designed transferable emissions permit system, as in Stranlund (2007), under different assumptions of the penalty structure.

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, we find that an optimally designed system of tradable permits never minimizes the total expected costs of attaining a certain level of aggregate emissions. This is basically because the distribution of emissions generated by the market for permits and its corresponding cost-effective monitoring differ from the distribution of emissions and monitoring efforts that minimizes the total costs of the program. This result holds both in the case when it is cost-effective to induce compliance and when it is cost-effective to induce violations.

The paper is organized as follows. In section 2, we present the standard model of

[2] In another paper, Stranlund et al (2009) analyze the optimality of perfect compliance for the case of emission taxes.

compliance behaviour of a risk-neutral polluter firm that faces an emission standard. We use this model to derive the condition under which it is cost-effective for a regulator to induce perfect expected compliance in a system of emissions standards that caps the aggregate emissions of n firms. In Section 3 we characterize the cost-effective design of such a program both when it is cost effective to induce expected perfect compliance, and when the opposite is true. We then let the regulator to choose the structure of penalties and we characterize the expected-cost-minimizing design of a program based on emissions standards in this case. In Section 4 we compare the costs of a program based on standards with that of a program based on tradable permits. Finally, in section 5 we present our conclusions.

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; 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 firm‘s 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. The model we present here extends Arguedas' (2008) by including more than one firm and Stranlund's (2007) by differentiating monitoring and sanctioning costs among firms.

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.[3] 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 $e_i > s_i$.

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

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

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 and emissions is:

$$\frac{\partial \Gamma_i}{\partial e_i} = c_i'(e_i) + \pi_i f'\left(e_i - s_i\right) - \eta_i = 0 \tag{2a}$$
$$\frac{\partial \Gamma_i}{\partial \eta_i} = -e_i + s_i \leq 0; \eta_i \geq 0; \eta_i\left(e_i - s_i\right) = 0 \tag{2b}$$

[3]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.

From the above Kuhn-Tucker conditions it can be seen that 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. That is, $e_i = s_i$ if $-c_i'(s_i) \leq \pi_i f'(0)$. 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 the standard, can vary among firms not only because they face a different standard, but also because of the firm's specific characteristics, possibly not completely observable for a regulator.

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 completely 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:

$$\min_{\substack{(s_1,s_2,..,s_n)\\(\pi_1,\pi_2,..,\pi_n)}} E\left[\sum_{i=1}^{n} c_i(e_i) + \sum_{i=1}^{n} \mu_i \pi_i + \sum_{i=1}^{n} \beta_i \pi_i f(e_i - s_i)\right] \tag{3a}$$

subject to:

$$e_i = \bar{e}_i(s_i, \pi_i) \tag{3b}$$

$$\sum_{i=1}^{n} \bar{e}(s_i, \pi_i) = E \tag{3c}$$

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

where $E[\cdot]$ denotes the regulator's subjective expected value of the program costs. These are comprised 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 structure of the penalty function $f(e_i - s_i)$ is given for the environmental regulator. 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 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 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:

$$\frac{\partial L}{\partial s_i} = E\left[c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial s_i} + \beta_i\pi_i f'(\bar{e} - s_i)(\frac{\partial \bar{e}_i}{\partial s_i} - 1)\right] + \lambda_1\frac{\partial \bar{e}_i}{\partial s_i} + \lambda_2^i(1 - \frac{\partial \bar{e}_i}{\partial s_i}) = 0, i = 1, ..., n \tag{4}$$

$$\frac{\partial L}{\partial \pi_i} = E\left[c_i'(\bar{e}_i)\frac{\partial \bar{e}_i}{\partial \pi_i} + \mu_i + \beta_i\left(f(\bar{e} - s_i) + \pi_i f'(\bar{e} - s_i)\frac{\partial \bar{e}_i}{\partial \pi_i}\right)\right] + \lambda_1\frac{\partial \bar{e}_i}{\partial \pi_i} - \lambda_2^i\frac{\partial \bar{e}_i}{\partial \pi_i} = 0, i = 1, ..., n \tag{5}$$

$$\frac{\partial L}{\partial \lambda_1} = \sum_{i=1}^{n} \bar{e}_i - E = 0 \tag{6}$$

$$\frac{\partial L}{\partial \lambda_2^i} = s_i - \bar{e}_i \leq 0, \lambda_2^i \geq 0, \lambda_2^i \times (s_i - \bar{e}_i) = 0 \tag{7}$$

We assume that these conditions are sufficient to characterize the optimal solution of the problem. Using these conditions, we derive 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*

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

for all i. If this condition is not met and the regulator wants to achieve the cap cost-effectively, it should induce violations of the emission standards for all those plants for which $\mu_i\frac{f''(0)}{f'(0)} > \beta_i f'(0)$.

Proof of Proposition 1: see Appendix.

Our Proposition 1 is an extension of Arguedas' (2008) Proposition 1 to the case of n firms and heterogeneous monitoring and sanctioning costs ($\mu_i \neq \mu_j$ and $\beta_i \neq \beta_j$, for at least some $i \neq j$, $i, j = 1, ..n$). It is also analogous to the condition derived by Stranlund (2007) for the case of transferable permits, but with homogeneous monitoring and sanctioning costs. Therefore, a first conclusion is that the condition under which it is cost-effective for a regulator to induce compliance is not instrument-dependent. Proposition 1 is also telling that when monitoring and sanctioning costs differ among firms, it could be cost-effective for the regulator to induce violations for some firms and compliance for the rest. This result cannot be observed when one assumes that monitoring and sanctioning costs are the same for all firms. In this case, the condition under which it is cost effective for a regulator to induce compliance does not depend on any individual characteristic of the firms, only on the penalty structure and the homogeneous costs of monitoring and sanctioning. But there are several reasons why auditing different firms may imply different costs for the regulator. Stranlund et al (2009) mention the distance between the firm and the enforcing agency, the variation in the production technologies within and between industry sectors and the number of discharge points per plant. The latter could be an example of a firm investment to conceal noncompliance (Heyes 2000). At the same time, sanctioning costs may differ between firms because of their differing propensity to litigate sanctions and challenge the legislation (Kambhu 1989).

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 pollution with emission 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 penalty structure is exogenously given to the regulator, condition (8) 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:

$$E\left[c_i'(s_i^*)\right] + \mu_i \frac{d\pi_i^*}{ds_i} = E\left[c_j'(s_j^*)\right] + \mu_j \frac{d\pi_j^*}{ds_j}, \text{ for all } i \neq j, (i,j) = 1, ..., n, \qquad (9)$$
$$\text{and } \pi_i^* = \frac{E\left[-c_i'(s_i^*)\right]}{f'(0)}, \text{for all } i = 1, ..., n.$$

(See Proof 2 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 complete 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 (8) does not hold, a regulator interested in minimizing the social costs of 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 other words, the expected cost-minimizing standards must be set such that $\bar{e}_i > s_i^*$. From Kuhn-Tucker condition (7), this implies that $\lambda_2^i = 0$. It is easy to see that the relevant

Kuhn Tucker conditions in this case are

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

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

both for $i = 1, ..n$. Dividing the above two equations by $\frac{\partial \bar{e}_i}{\partial s_i}$ and $\frac{\partial \bar{e}_i}{\partial \pi_i}$ respectively, we obtain:

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

for all $i, j = 1, ..., n$. Based on these, we can characterize the expected cost minimizing program to control emissions with standards when it is cost-effective to induce non-compliance in the context of incomplete information and given penalties. This is done in Proposition 2 below.

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

$$E\left[c_i'(\bar{e}_i)\right] + \beta_i \pi_i^* f'(\bar{e}_i - s_i^*)\left(\frac{\partial \bar{e}_i/\partial s_i - 1}{\partial \bar{e}_i/\partial s_i}\right) = \quad (11)$$
$$E\left[c_j'(\bar{e}_j)\right] + \beta_j \pi_j^* f'(\bar{e}_j - s_j^*)\left(\frac{\partial \bar{e}_j/\partial s_j - 1}{\partial \bar{e}_j/\partial s_j}\right)$$
$$E\left[c_i'(\bar{e}_i)\right] + \frac{\mu_i}{\partial \bar{e}_i/\partial \pi_i} + \frac{\beta_i f(\bar{e}_i - s_i^*)}{\partial \bar{e}_i/\partial \pi_i} + \beta \pi_i^* f'(\bar{e}_i - s_i^*) = \quad (12)$$
$$E\left[c_j'(\bar{e}_j)\right] + \frac{\mu_j}{\partial \bar{e}_j/\partial \pi_j} + \frac{\beta_j f(\bar{e}_j - s_j^*)}{\partial \bar{e}_j/\partial \pi_j} + \beta \pi_j^* f'(\bar{e}_j - s_j^*)$$

for all $i \neq j$, $(i, j) = 1, ..., n$.

Proof of Proposition 2: it follows from the previous dicussion.

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 that $0 < \partial \bar{e}_i / \partial s_i < 1$.[4] 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 (condition 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 (20), 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 moving the standard with that of moving 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.

[4] This result was obtained as parto of the proof of Proposition 1.

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 (8) 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 (8) 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 (9) , (11) and (12).

We can conclude from Proposition 2 that the cost-effective level of emission standards are firm-specific whenever abatement and/or enforcement costs differ among firms. 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* $0 \leq \gamma \leq \min\left[\frac{\beta_i}{\mu_i}\right] \times \phi^2$.

Proof of Proposition 3: see 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. 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-optimal, 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 bounded upward by things such as the possibility that firms may have insufficient assets to cover the fines (Segerson and Tietenberg 1991) or the unwillingness of judges or juries to impose very high penalties (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 implementing firm-specific emissions standards and perfectly enforcing this program according to Proposition 3.*

Proof of Proposition 4 The proof that the expected total costs of an emission standards program is lower than the expected total costs of a transferable emission permits system is trivial. By definition, in the optimally designed emission standards 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 emission standards 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 minimize 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:

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

subjet to

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

and

$$v_i \geq 0$$

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

The Lagreangean of this problem is

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

The Kuhn - Tucker conditions of this problem are:

$$\frac{\partial \Lambda}{\partial \pi_i} = c_i'\left(\cdot\right)\left(\frac{\partial l_i}{\partial \bar{p}}\frac{\partial \bar{p}}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}\right) + \mu_i + \beta_i f(v_i) + \lambda\left(\frac{\partial l_i}{\partial \bar{p}}\frac{\partial \bar{p}}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}\right) \geq 0; \qquad (14a)$$

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

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

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

When it is optimum to induce perfect compliance for all i ($v_i = 0$), (14a) and (14b) can be re-written, assuming $\pi_i > 0$ for all i, as:

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

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

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 $-c_i'(\cdot) = \bar{p}$. Using this, and assuming $\frac{\partial \bar{p}}{\partial \pi_i} = 0$ (perfect competition in the permits market), (14c) can be written as

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

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:

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

Now, we also know from Stranlund and Dhanda (1999) that every firm is demanding permits so that $\bar{p} = \pi_i f'(v_i)$. 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

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

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

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

It is easy to see that, in a competitive market for emission permits (i.e: one that generates a unique equilibrium price $\bar{p}$), 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, Q.E.D.

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 environmental economists have been advocating for over the last forty years. But monitoring and enforcement costs were not taken into account in the analysis that led to this policy recomendation; only aggregate abatement costs, which tradable permits certainly minimize. 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. 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) that follows).

In spite of this cautiousness, we do want to emphasize that, according to Proposition (4), it is not in the name of cost-effectiveness that we are to argue in favor of tradable emission permits. Moreover, tradable permits do not emerge from this analysis either with an advantage over emission standards as clear as in the case of costless and perfect enforcement with respect to the amount of information needed by the regulator to design the program: in order to set the appropriate inspection probability the regulator has to predict the equilibrium price of the permits market, which depends on the unknown abatement costs of the firms.

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 for all i. 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. Then 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 (14a) and (14b) can be re-written, assuming $\pi_i > 0$ for all i, as:

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

$$\frac{\partial \Lambda}{\partial v_i} = c_i'(\cdot) + \pi_i \beta_i f'(v_i) + \lambda = 0,\ i = 1, .., n \tag{16}$$

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 15) and (b) the sum of marginal abetement and sanctioning costs of changing v_i are equal across firms (equation 16). From equations (15) and (16) we can obtain

$$\frac{\mu_i + \beta_i f(v_i)}{\frac{\partial l_i}{\partial \bar{p}} \frac{\partial \bar{p}}{\partial \pi_i} + \frac{\partial l_i}{\partial \pi_i}} = \pi_i \beta_i f'(v_i),\ i = 1, .., n \tag{17}$$

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 $-c_i'(\cdot) = \bar{p}$ and the quantity of permits to demand such that $\bar{p} = \pi_i f'(v_i)$. Using both expressions, we can write (16) as

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

or

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

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 $\bar{p}$ 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 cost-effective to induce all firms to violate 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 as characterized by Proposition 2, 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 $\frac{\partial \bar{p}}{\partial \pi_i} = 0$, then equation (17) 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 $\bar{p} = \pi f'(v)$ 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 when it is cost-effective to induce violations.

5 Conclusion

In this paper we first derive the condition under which it is cost effective for a regulator to induce perfect compliance in an emissions control program. This condition depends on the cost of monitoring and sanctioning a firm, as well as on the structure of the penalty for violations. Therefore, it is not instrument-dependent. If the condition is met, the regulator has to induce perfect compliance independently of whether it is implementing emission standards or transferable permits. Because we assume that the regulator's monitoring and sanctioning costs are firm-specific, the condition itself is firm-specific. In other words, it is possible that cost-effectiveness calls the regulator to induce some firms to comply with the legislation while at the same time let others violate the legislation. This cannot happen when one assumes that the regulator's monitoring and sanctioning costs are the same for all firms. In this case, the regulator has either to induce compliance on all firms or to induce violations on all firms.

Second, we characterize the total-cost minimizing design of a program that caps aggregate emissions of a given pollutant from a set of heterogeneous firms based on emissions standards when it is cost effective to induce perfect compliance and when it is not. We then allow the regulator to choose the optimality of inducing compliance or not assuming that it can choose the structure of the penalty function. Doing this we find that the total cost-effective design of such a program is one in which standards are firm-specific and perfectly enforced.

Third, we compare the expected costs of such an optimally designed program with that of an optimally designed program based on a perfectly competitive emission permits market, which also calls for perfect enforcement according to Stranlund

(2007). This comparison allows us to conclude that the latter never minimizes the total expected costs of attaining a certain level of aggregate emissions. Moreover, this result holds also in the case when it is cost effective to induce violations. The reason behind these results is that a tradable permits market cannot by itself exploit the differences in abatement *and* monitoring costs, only the former. Consequently, the allocation of emission responsibilities that results from a tradable permits market and its corresponding cost-effective monitoring differ from the ones that minimize the total expected costs; namely, that of the optimally designed emission standards program.

Because the distribution of emissions and monitoring efforts in a cost-effective design of a tradable permits system does not reproduce the distribution of emissions and monitoring efforts in the cost-effective design of a program that caps aggregate emissions of a pollutant, we argue that it is not in the name of cost-effectiveness that we are to argue in favor of tradable emission permits. Nevertheless, we are cautious in deriving policiy recommendations. 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 than those of a system of tradable permits. Clearly, more research is needed concerning this issue.

Finally, our results produce a clear policy recommendation for the design of environmental policy in developing countries, as our own. The environmental policy in these countries has been frequently described as poorly enforced (see, for example, Russell and Powell 1996; Eskeland and Jimenez 1992; O'Connor 1998; Seroa da Motta et al. 1999). 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 and perfectly enforcing the laxer regulation.

Appendix

Proof of Proposition 1 If $\bar{e}_i = s_i$, from (7) 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 (4) and (5) of the regulator's problem as:

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

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

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

From where,

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

and

$$0 < \partial \bar{e}_i / \partial s_i = \frac{\pi_i f''}{c_i'' + \pi_i f''} < 1 \tag{18}$$

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

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

or

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

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

$$\mu_i \frac{\pi_i f''(0)}{f'(0)} \leq \pi_i \beta_i f'(0) \tag{19}$$

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 (19) 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 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 (19) by π_i we obtain $\mu_i \frac{f''(0)}{f'(0)} \leq \beta_i f'(0)$ *for all* i, Q.E.D.

Proof 2 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

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

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 structures: 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 (8) 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, of course.

(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 minimum 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 in equilibrium 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 $-\frac{d\phi_i}{d\gamma_i} = \frac{\bar{e}_i - s_i}{2}$.

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

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

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

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

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

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

$$\begin{aligned}\frac{dL}{d\phi_i} &= -\frac{E[-c_i'(\bar{e}_i)]}{[\phi_i + \gamma_i(\bar{e}_i - s_i)]^2} \left[\mu_i + \beta_i \left(\phi_i(\bar{e}_i - s_i) + \frac{\gamma_i}{2}(\bar{e}_i - s_i)^2 \right) \right] \\ &\quad + \frac{E[-c_i'(\bar{e}_i)]}{[\phi_i + \gamma_i(\bar{e}_i - s_i)]^2} \times (\bar{e}_i - s_i) \left[\frac{2\mu_i}{\bar{e}_i - s_i} + \beta_i (2\phi_i + \gamma_i(\bar{e}_i - s_i)) \right]\end{aligned} \tag{21}$$

And after some operations we obtain

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

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 (21) 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 $\frac{-E[-c_i'(\bar{e}_i)]}{[f(\bar{e}_i - s_i)]^2} \times \mu_i$ and by this way increases also the expected sanctioning costs by $\frac{E[-c_i'(\bar{e}_i)]}{[f(\bar{e}_i - s_i)]^2} [\beta_i f(\bar{e}_i - s_i)]$. Ii is easy to see from (21) that increasing γ_i by the quantity that keeps $f(\bar{e}_i - s_i)$ constant decreases both costs by more than this (The second term is larger that the first term). 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. And 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, **Q.E.D**.

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