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THE CHOICE OF POLICY INSTRUMENTS TO CONTROL POLLUTION UNDER COSTLY ENFORCEMENT AND INCOMPLETE INFORMATION

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We analyze the cost of enforcing a system of firm specific emissions standards vis a vis a transferable emissions permit system in the context of complete and incomplete information. We also examine the optimality of a transferable emissions permit system when abatement costs and enforcement costs are considered. We show that under incomplete information, regulation based on each firm-specific emissions standards cannot be less costly than a transferable emissions permit system. In addition, we find that the distribution of emissions that minimize aggregate program costs differ from the distribution of emissions generated by a competitive transferable emissions permit system.

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Key words: environmental policy, cost-effectiveness, enforcement costs, incomplete information

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I. Introduction

Environmental improvements can be achieved through different regulatory strategies. Traditional environmental policy, especially in developing countries, has been based on the use of command and control policies; however, economic incentives –a major innovation in this policy arena– are gaining support among policymakers.[1] Among economic incentives to control pollution is the transferable emission permit system (Dales 1968, Crocker 1966, Montgomery 1972), which is based and critically depends on the creation and appropriate functioning of a market. The growing interest in economic incentives is related to the conceptual promise of these policies to improve environmental quality at lower costs than alternative, more traditional regulatory tools (Bohm and Russell 1985, Tietenberg 2006). The existing literature provides fairly convincing evidence about the potential cost savings to be achieved by regulating firms through a transferable emissions permit system as compared to alternative command and control policies (Arimura 2002, Burtraw 1996 and 1999, McLean 1997, Schmalensee et al. 1998, Stavins 1998).

The conceptual analysis of environmental policy considers two alternative criteria for the selection of policy instruments; namely, efficiency and cost-effectiveness. Both criteria, widely used in economics, have usually focused on aggregate abatement costs on the costs side; thus, society must allocate resources to reduce emissions to achieve an environmental target. However, there is still much to be done in terms of the economic analysis of the explicit consideration for the need of enforcement to induce compliance and its related costs for the comparison of alternative environmental policy options. Some contributions to this topic are the works of Keeler (1991), Malik (1992), Garvie and Keeler (1994), and Hahn and Axtell (1995).

Unfortunately, in the current literature, the advantages of transferable emissions permit systems over command and control regulations are not that clear when both abatement costs and enforcement costs are considered. The literature on compliance and enforcement in transferable emissions permit systems has rapidly increased

[1] Examples of economic incentive policies in developing countries include Santiago's Emissions Compensation (EC) Program, implemented in Chile's capital city in 1992 and the Discharge Fee (DF) Program applied in Colombia since 1997. An analysis of the design of the EC Program and the functioning of the emission capacity permit market is presented in Montero et al. (2001, 2002). For a description of the EC Program and details of the enforcement design and compliance results, see Palacios and Chávez (2005, 2002). A description of the legal foundation, implementation, and evaluation of Colombia's DF Program is provided by Blackman (2009).

and is still growing. See, for example, Malik (1990), Keeler (1992), Van Egteren and Weber (1996), Stranlund and Dhanda (1999), Stranlund and Chávez (2000), Malik (2002), Montero (2002), Chávez and Stranlund (2003), and Stranlund (2007). A small portion of the works on compliance in market-based systems is specifically devoted to comparing outcomes with those of command and control systems. The primary message that emerges from this analysis is that the often-claimed superiority of market-based policies over command and control cannot be guaranteed when firms may be non-compliant and resources must be expended to enforce compliance.

In particular, by considering feasible enforcement strategies that are sufficient to induce perfect compliance in a least costs manner from both regulatory schemes (specific firm emissions standards and transferable emissions permit systems), Malik (1992) was able to show that it is possible for total program costs –aggregate abatement costs plus enforcement costs– under an emissions trading program to exceed the cost of achieving a given environmental target when using an emissions standards system. Since, according to the cost-effectiveness property, aggregate abatement costs will be lower under transferable emissions permit systems, higher aggregate policy costs must be due to higher enforcement costs, suggesting that a conventional emissions trading program might not be cost-effective.[2]

The objective of this paper is to analyze the cost of enforcing a system of firm specific emissions standards *vis a vis* a transferable emissions permit system. We consider scenarios of complete as well as incomplete information. Furthermore, we also examine the optimality of a transferable emissions permit system when both abatement and enforcement costs are taken into account. To our knowledge, there is no work squarely dealing with these specific issues.

We find that asymmetric information about firms' abatement costs implies that a regulation based on a system of firm-specific emissions standards cannot be less costly than a transferable emissions permit system when both aggregate abatement costs and aggregate monitoring costs are considered.

This result is a contribution to the literature on the choice of policy instruments for controlling pollution, since the recommendations stemming from previous works that only consider the case a regulator with complete information are different and ambiguous. Particularly, Malik (1992: 714) concludes that "enforcement costs can

[2] This research question was put forward by Russell and Powel (1996), pointing out that command and control policy can be superior to transferable emissions permit systems when enforcement and implementation costs are considered, especially for developing countries at the early stages of designing and implementing environmental policies.

be higher for incentive-based policies than for policies based on direct controls, depending on the characteristics of the firms' abatement cost functions". We show that, except for a very special case, Malik's result only holds when the regulator has complete information regarding the firms' abatement costs. If a firm knows more about its marginal abatement costs than the regulatory agency and can exploit this informational advantage to its benefit, it will always be cheaper to induce compliance through a perfectly competitive transferable emissions permit system than using a system of emissions standards. This is so since, under a competitive transferable emissions permit system, there is no need to target different types of firms and the uniform monitoring effort should be tied to the observable equilibrium permit prices.[3]

The second contribution of this paper is the finding that the distribution of emissions that minimize aggregate program costs differ from the distribution of emissions generated by a competitive transferable emissions permit system. Although our result is not entirely new, we extend Malik's (1992) work by characterizing an optimal (cost-effective) distribution of emissions among regulated firms when aggregate abatement costs as well as enforcement costs are relevant to the society. We have been able to show that cost-effectiveness in this case requires equal marginal abatement costs plus marginal monitoring costs among firms. The result suggests that a transferable emissions permit system that generates a uniform equilibrium permit price might not be cost-effective. Another way to put it is that cost-effectiveness in the context of an emission trading program called for discriminatory prices among firms. The fundamental reason for that result is that, because enforcement is costly, a regulator can exploit differences in the costs of monitoring firms, thereby reducing total program costs.

The paper is organized in five sections. In section II, we briefly present an individual compliance behaviour model under a system of a firm-specific emissions standards and a transferable emissions permit system. Section III discusses

[3] Others in the literature on compliance in transferable emission permits systems compared outcomes in these systems to those in command-and-control systems. Considering a fixed enforcement program, Hahn and Axtell (1995) found inconclusive results comparing aggregate abatement and aggregate control cost between market-based and command-and-control policies. With a somewhat different model, but under fixed enforcement, Keeler (1991) shows that the aggregate level of emissions and the number of firms violating their legal rights to emit might be larger under a transferable emission permits system than under a command and control type of regulation, except for the case of a linear penalty function. Because in these papers enforcement is fixed, they do not address the issues that are important to us, namely, whether or not enforcing a set of emissions standards is more costly than enforcing a competitive transferable emissions permit system when there is incomplete information, and how to characterize an optimal distribution of emissions when enforcement is costly.

enforcement strategies under both regulatory systems, considering cases of complete and incomplete information between the enforcement authority and the firms. In particular, we focus on perfect compliance and determine the related enforcement costs considering a regulator with incomplete information about each individual firm's enforcement costs. In section IV, we present the main results of the paper, tackling the issue of minimizing aggregate program costs, which include aggregate abatement and enforcement costs. We show that a system of specific emissions standards for different firms cannot be less costly than a competitive transferable emissions permit system. In addition, we also characterize the cost-effective distribution of emissions among regulated firms when enforcement is costly. Finally, in section V, we put forward some concluding remarks and implications that can be inferred from our work.

II. A model of compliance under a system of firm specific emissions standards and a transferable emissions permit system

The purpose of this section is to present a conceptual model of the individual firm's behaviour and choices under both command and control regulation and a competitive transferable emissions permit system. The model we present follows previous work by Malik (1990), Stranlund and Dhanda (1999), and Stranlund and Chávez (2000).

A. A model of a firm's behaviour

To analyze the individual firm's compliance behaviour throughout, we consider a risk-neutral firm operating either under an emissions standard or a competitive transferable permits system, along with a fixed number of other heterogeneous firms. The firm's abatement cost function is $c(e, \theta)$, which is strictly decreasing and convex in the firm's emissions e [$c_e(e, \theta) < 0$ and $c_{ee}(e, \theta) > 0$]. A firm is distinguished from others by the shift parameter θ.[4] We assume that both the firm's abatement costs and its marginal abatement costs are increasing in θ, that is, $c_\theta(e, \theta) > 0$ and $c_{e\theta}(e, \theta) > 0$. We index firms by i and denote the total number of firms as n (whenever possible, we avoid the use of a specific firm index for simplicity). The environmental

[4] Firms' abatement costs can vary for many reasons, including differences in production and emissions control technologies, input and output prices, and specific factors related to the corresponding industrial sector.

target is a fixed aggregate level of emissions E, exogenously determined by the regulatory authority.

Let us first consider the case of a command and control environmental policy in which each firm faces an emissions standard s. Under this policy the regulator defines for each firm the maximum allowable (legal) level of emissions, which is common knowledge to all firms. Emissions standards for all firms satisfy $\sum_i s_i = E$. In this context, an emissions violation v occurs when the firm's emissions exceed the emissions standard: $v = e - s > 0$. The firm is compliant otherwise.

As for enforcement, the firm faces a random probability of being audited π. We assume that an audit provides the regulator perfect information about firms' compliance status. If the firm is audited and found in violation, a penalty $f(v)$ is imposed. The penalty is assumed to be zero for a zero violation, but the marginal penalty for a zero violation is greater than zero $[f(0) = 0, f'(0) > 0]$. For a positive violation, the penalty increases at an increasing rate $[f''(v) > 0]$.

To ensure that perfect compliance is a possible outcome, we assume $-c_e(s,\theta) \leq f'(0)$; that is, the firm's marginal abatement cost evaluated at the standard is not greater than the marginal penalty for a slight violation. If the inequality was reversed, then the firm would choose to be noncompliant even if it was monitored with certainty, because the marginal benefit of violating the standard would be greater than the expected penalty for some level of violation.[5]

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

$$\min c(e, \theta) + \pi f(e - s), \quad (1)$$
$$\text{s.t. } e - s \geq 0.$$

The Lagrange equation for the problem in (1) is given by $\Lambda = c(e,\theta) + \pi f(e - s) - \beta(e - s)$, which gives the set of necessary Kuhn-Tucker conditions:

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[5] An alternative penalty function could be a two part penalty, i.e. $F(v) = F_o + f(v)$, where F_o is a fixed fee. However, we choose to focus only on variable penalties for several reasons. First, we want to be able to directly compare our results to that of Malik (1992), so it was natural to us to set enforcement considering the same penalty function. Second, two part penalties are not very common in the literature that address the enforcement of environmental policies. Third, our analysis of the enforcement costs between the policy instruments requires keeping constant the penalty structure, so we decided to specify a commonly used penalty function. Fourth, Arguedas (2008) has recently shown that is not optimal to have a fixed penalty component when inducing compliance with an emissions standard.

$$\frac{\partial \Lambda}{\partial e} = c_e(e,\theta) + \pi f'(e-s) - \beta = 0, \tag{2a}$$

$$\frac{\partial \Lambda}{\partial \beta} = s - e \leq 0; \beta \geq 0; \beta(e-s) = 0. \tag{2b}$$

On the other hand, under a transferable emissions permit system, a total of $L = E$ licenses are issued by a regulatory authority, each of which confers the legal right to release one unit of emissions. Each individual firm is a perfect competitor in the license market, so the license market generates an equilibrium license price p. Let l_0 be the initial allocation of licenses to the firm, and let l be the number of licenses that the firm holds after trade. When a firm is non-compliant, its emissions exceed the number of licenses it holds and the level of its violation (v) is $v = e - l > 0$, for $e > l$.

Enforcement, from the firm's point of view, remains the same as under a system of emissions standards, which implies an audit probability and a penalty if audited and found in violation. As for the case of emissions standards, to allow for perfect compliance as a possible outcome under a transferable emissions permit system, we assume $p \leq f'(0)$. For a transferable emissions permit system, a firm chooses its emissions and permit demand to minimize compliance costs –abatement costs, receipts or expenditures from buying or selling permits, and the expected penalty– taking the enforcement strategy to be given.

Thus, the firm's problem is to choose emissions and licenses to solve

$$\min c(e,\theta) + p(l - l_0) + \pi f(e - l), \tag{3}$$
$$\text{s.t. } e - l \geq 0.$$

Let λ be the multiplier attached to the constraint $e - l \geq 0$. Then, the Lagrange equation for (3) becomes: $\mathrm{K} = c(e,\theta) + p(l - l_0) + \pi f(e-l) - \lambda(e-l)$; and the set of necessary Kuhn-Tucker conditions are:

$$\frac{\partial \mathrm{K}}{\partial e} = c_e(e,\theta) + \pi f'(e-l) - \lambda = 0, \tag{4a}$$

$$\frac{\partial \mathrm{K}}{\partial l} = p - \pi f'(e-l) + \lambda = 0, \tag{4b}$$

$$\frac{\partial \mathrm{K}}{\partial \lambda} = l - e \leq 0; \lambda \geq 0; \lambda(l-e) = 0. \tag{4c}$$

We assume that the conditions presented in equations (2a), (2b), (4a), (4b), and (4c) are necessary and sufficient to uniquely determine the firm's optimal choices of emissions, permit demand, and violation.

B. Individual firm's choices

In terms of an emissions standard, from equations (2a) and (2b), we have that a firm will be compliant whenever it chooses a level of emissions consistent with $-c_e(s,\theta) \leq \pi f'(0)$, see for instance, Heyes (2000). Thus, an individual firm's compliance choice requires the expected marginal penalty to be no lower than the marginal abatement cost associated with an emissions level equivalent to the emissions standard. We note that the marginal abatement costs at the level of the standard can vary among firms, not only because they face a different standard, but also because of the firm's specific, possibly imperfectly observable characteristics for a regulatory authority.

In the case of a transferable emissions permit system, from equations (4a) and (4c), we know that a firm is compliant if and only if: $-c_e(l,\theta) \leq \pi f'(0)$. (For details, see for example, Malik 1990 and Stranlund and Dhanda 1999). We also know, from equations (4a) and (4b), that the optimal choice of emissions requires $-c_e(e,\theta) = p$, which implicitly defines $e(p, \theta)$. If compliant, the choice of emissions for firm i equals its demand of permits, that is $e_i(p, \theta)) = l_i(p, \theta)$. The permit market equilibrium condition is $\sum_{i=1}^{n} l_i(p,\theta_i) = L = E$, which implicitly defines the equilibrium permit price as a function of the firms' abatement cost shift parameters, and the total number of licenses; that is, $p(\overline{\theta},E)$, where $\overline{\theta} = (\theta_1,\ldots,\theta_n)$.Hence, under a transferable emissions permitsystem, a firm will be compliant whenever $p(\overline{\theta},L) \leq \pi f'(0)$; suggesting that a firm will comply with the regulation when the expected marginal penalty is not lower than the equilibrium price obtained in a competitive permits market.[6]

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[6] Similar to others in this literature (Malik 1990, Stranlund and Chávez 2000), we choose to focus on perfect compliance. In part, we use this assumption to be able to compare our results to Malik (1992). However, we acknowledge that others have focused on less than perfect compliance (see, for example, Montero 2002). In this literature, only Stranlund (2007) has considered the regulatory choice of optimal compliance in the context of an emissions trading program.

III. Enforcement strategies and enforcement costs

We are ready to explore enforcement strategies under command and control regulation and a transferable emissions permit system to induce compliance. We choose to focus on perfect compliance and to determine the related enforcement costs.

A. Cost-effective enforcement under complete information

Our analysis in Section II about individual compliance behaviour suggests that cost-effective enforcement of emissions standards should involve targeted monitoring. Specifically, minimum required monitoring to induce compliance by each firm is given by:

$$\pi^{\min}(s,\theta) = \frac{-c_e(s,\theta)}{f'(0)}. \tag{5}$$

Similarly, an enforcer that wants to achieve perfect compliance while conserving monitoring costs under a competitive transferable emissions permit system should audit each firm with probability:

$$\pi^{\min} = \frac{p(\bar{\theta},E)}{f'(0)}. \tag{6}$$

Thus, given that penalties are applied uniformly, monitoring should also be uniform; that is, there is no need to target different types of firms (see Stranlund and Dhanda 1999, and Stranlund and Chávez 2000).

The fundamental lack of any firm characteristic in the specification of the minimum audit probability is due to the equilibrating nature of frictionless and competitive transferable emissions permit systems. This suggests further that firm-specific information is not valuable in this context (see Stranlund and Dhanda 1999). In contrast, for the case of emissions standards, according to equation (5), cost-effective enforcement calls for a monitoring effort that varies across firms (see also Malik 1992).[7]

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[7] Consider, for example, that firms face a uniform emissions standard. In this case, according to (5), cost effective enforcement requires, $\pi_1^{\min}(\theta_1) < \pi_2^{\min}(\theta_2) < \ldots < \pi_n^{\min}(\theta_n)$. However, to target monitoring perfectly, a regulator must have complete knowledge of the marginal abatement costs of all regulated firms. Acquiring this knowledge will be very difficult because it requires detailed information about each firm's operations.

B. Enforcing emissions standards under incomplete information

We now consider the problem faced by a regulatory authority when designing enforcement strategies to induce perfect compliance under command and control regulation with incomplete information. The regulatory authority wishes to induce the firms to comply with a given set of emissions standards. The problem is that each firm knows more about its abatement costs than the regulatory agency and, therefore, can try to exploit this informational advantage to its benefit. To simplify matters, we assume that there are only two types of firms operating under the emissions standard system: low-cost and high-cost firms. The system contains n_k identical firms of type k, with k = 1,2. We use the shift parameter θ to define both types of firms, assuming that a low-cost firm is characterized by θ_1 and a high-cost firm by θ_2, with $\theta_2 > \theta_1$. This implies that, given emissions standard s, the low-cost firm will face lower abatement costs than the high-cost firm, formally $c(s,\theta_2) > c(s,\theta_1)$.[8] Because of the incomplete information, the regulator is unable to recognize the true type of a firm.

Given the results found in the complete information scenario regarding a targeted monitoring effort, it is obvious that there is space for strategic behaviour on the part of the firms. Specifically, with emissions standards, the optimal monitoring probability for a low-cost firm should be lower than that for a high-cost firm, the high-cost firm faces economic incentives to be "selected" as a low-cost firm by the regulator, which could imply lower expected monitoring costs.

In this context, the regulator should anticipate the strategic response of a firm and design enforcement accordingly. Let us consider two possible emissions standards, one for each firm type, denoting these standards as s_1 and s_2 for firm types 1 and 2, respectively. If the regulator wants to ensure perfect compliance and is unable to discover the firm type, from our discussion in Section II, the following set of restrictions must hold:

$$\pi_1 f'(0) \geq -c_{e1}(s_1,\theta_1), \tag{7a}$$

$$\pi_2 f'(0) \geq -c_{e2}(s_2,\theta_2), \tag{7b}$$

$$\pi_1 f'(0) \geq -c_{e2}(s_2,\theta_2), \tag{7c}$$

[8] We are analyzing the case in which enforcement and emissions standards are chosen separately. We explore the problem of cost-effective emissions distribution with costly enforcement in the next section.

$$\pi_2 f'(0) \geq -c_{e1}(s_1,\theta_1), \tag{7d}$$

$$\pi_1 \in [0,1], \tag{7e}$$

$$\pi_2 \in [0,1], \tag{7f}$$

Restrictions (7a) and (7b) represent the compliance constraints that ensure that each firm type is interested in complying with the abatement standard set for its type. Constraints (7c) and (7d) represent the self-selection/compliance constraints, which ensure that expected marginal penalties are sufficient to induce each firm type to be interested in complying with the abatement standard for its type. Finally, (7e) and (7f) are the monitoring probabilities constraints.

Given that the cost of conducting an audit is independent of the type of firm, minimizing enforcement costs requires choosing enforcement strategies at a minimum level subject to the constraints (7a-f).

Considering the set of emissions standards and the firms' heterogeneity, three cases are possible. In the first, the environmental regulatory authority sets uniform emissions standards; in our context, that is $s_1 = s_2 = s = E/(n_1 + n_2)$. In this situation, given marginal abatement cost functions, we see that $-c_{e2}(s,\theta_2) > -c_{e1}(s,\theta_1)$, suggesting that $\pi_2 > \pi_1$. To satisfy restrictions (7 a-d) with minimum monitoring effort (least enforcement cost), the regulator should monitor type 1 and type 2 firms according to:

$$\pi_1 = \pi_2 = \frac{-c_{e2}(s,\theta_2)}{f'(0)}. \tag{8}$$

The second case considers emissions standards that were chosen such that $s_1 > s_2$. Considering the marginal abatement cost functions, we have $-c_{e2}(s_2,\theta_2) > -c_{e1}(s_1,\theta_1)$, suggesting that $\pi_2 > \pi_1$. In this case, to satisfy restrictions (7 a-d) in the least-cost manner, the regulator should monitor type 1 and type 2 firms according to:

$$\pi_1 = \pi_2 = \frac{-c_{e2}(s_2,\theta_2)}{f'(0)} > \frac{-c_{e1}(s_1,\theta_1)}{f'(0)}. \tag{9}$$

In the third case, emissions standards were chosen such that $s_1 < s_2$. Considering the marginal abatement cost functions, two cases are possible: namely, either $-c_{e2}(s_2,\theta_2) > -c_{e1}(s_1,\theta_1)$ or $-c_{e2}(s_2,\theta_2) < -c_{e1}(s_1,\theta_1)$. To satisfy restrictions (7a-d) in a least-cost manner for this case, the regulator should monitor type 1 and type 2 firms according to:

$$\pi_1 = \pi_2 = \max\left(\frac{-c_{e1}(s_1,\theta_1)}{f'(0)}, \frac{-c_{e2}(s_2,\theta_2)}{f'(0)}\right). \tag{10}$$

The results of equations (8) to (10) suggest that inducing compliance with an emissions standards system under incomplete information requires that the regulator monitor both types of firms with the same probability. Furthermore, the (uniform) enforcement effort should be tied to the firm with the highest marginal abatement cost. As we have shown, monitoring effort under incomplete information must be higher for one type of firm than under complete information, regardless of how the emissions standards are set.

IV. Enforcement costs and program costs

Aggregate program costs or compliance costs (*CC*) includes aggregate abatement costs (*A*) and enforcement costs (*M*). To simplify the analysis, we consider as enforcement costs only the cost of monitoring firms. Enforcement costs depend upon the enforcement effort (audit probability for each firm) and the cost of conducting an audit, which we denote by w.[9] We notice that equations (5), (6), and (8)-(10) show compliance costs might vary across regulatory systems. Furthermore, the level of the expected enforcement costs depends on the enforcers' available information.

Let us first analyze the case of an emissions standards system. According to our discussion in Section III, the following lemma holds:

Lemma 1 *Given the objective of perfect compliance and a set of heterogenous firms facing a system of individual emissions standards, the expected enforcement costs under incomplete information* (M^*) *can not be lower than the expected enforcement costs under complete information* (M).

[9] Of course, enforcement costs might include more than monitoring costs. For example, enforcement actions might involve perhaps costly warning activities, costly litigation, and even costly imposition of sanctions once a violation is detected. Sanctioning and litigation costs are not common in the analysis of enforcement of environmental policies; however they are more common in the general literature on optimal enforcement of the law. In the enforcement of environmental regulation literature, only Stranlund (2007) has considered costly collection of sanctions in the context of a transferable emissions permit system. More recently, Stranlund et al. (2009) assume that imposing sanctions in the context of emissions taxes is costly. Sanctioning costs have been considered in the context of the enforcement of emission standards, see for example Malik (1993) and more recently Arguedas (2008).

Proof of Lemma 1: Consider any given set of emissions standards (s_1, s_2) consistent with the environmental target E. Then, under complete information, least cost enforcement to induce perfect compliance requires to monitor each type of firms according to $\pi_1 = -c_{e1}(s_1,\theta_1)/f'(0)$ and $\pi_2 = -c_{e2}(s_2,\theta_2)/f'(0)$; thus, expected enforcement cost is given by $M = (w/f'(0)) \times [n_1 \times (-c_{e1}(s_1,\theta_1)) + n_2 \times (-c_{e2}(s_2,\theta_2))]$. From equations (8)-(10), least cost enforcement under incomplete information requires uniform monitoring. Furthermore, monitoring effort should be set according to the firm type with the highest possible marginal abatement cost, that is $\pi_1 = \pi_2 = \max(-c_{e1}(s_1,\theta_1)/f'(0), -c_{e2}(s_2,\theta_2)/f'(0))$, thus, expected enforcement cost under incomplete information is given by $M^* = (w/f'(0)) \times [(n_1 + n_2) \times (-c_{ek}(s_k,\theta_k))]$, where $-c_{ek}(s_k,\theta_k) = \max\{(-c_{e1}(s_1,\theta_1), -c_{e2}(s_2,\theta_k)\}$. By inspection of these expressions, we conclude that $M^* > M$. Finally, for the special case in which s_1 and s_2 are such that $-c_{e1}(s_1,\theta_1) = -c_{e2}(s_2,\theta_2)$, $M^* = M$ holds, so we conclude that $M^* \geq M$. QED.

Lemma 1 suggests the critical role incomplete information plays on monitoring costs when considering a system of emissions standards to improve environmental quality. Furthermore, the result also suggests that enforcement costs are a function of the distribution of the abatement responsibilities. Specifically, changes in the distribution of abatement responsibilities (emissions standards) can generate changes in enforcement costs because they will change the marginal benefit of non-compliance, which is fully represented by the marginal abatement cost at the standard. We will explore this later to characterize an efficient distribution of emissions with costly enforcement.

For the case of a transferable emissions permit system, enforcement costs of inducing perfect compliance are given by $M = w \times (n_1 + n_2) \times p(\theta_1,\theta_2,E)/f'(0)$. We notice that, for the case of a competitive transferable emissions permit system, the equilibrium permit price can affect monitoring costs. Since this variable can be easily known by the regulator and does not vary across firms, it can be argued that the informational requirements for authorities in order to minimize enforcement costs are lower with transferable emissions permits than with emissions standards, in which enforcement costs depend upon the marginal abatement costs of all regulated firms. Using Lemma 1, we are ready to offer our first Proposition regarding monitoring costs to induce compliance among policy instruments.

Proposition 1 *Suppose a regulator has incomplete information on firms' abatement costs, then, for any given environmental target E, inducing compliance of a perfectly competitive transferable emissions permit system can not be more costly than inducing compliance for a system of emissions standards.*

Proof of Proposition 1: Suppose the regulator implements a transferable emissions permit system to achieve the environmental target E. Assuming enforcement is sufficient to induce perfect compliance, for any arbitrary allocation of permits a competitive transferable emissions permit system generates a distribution of emissions that minimizes aggregate abatement cost. Denote the equilibrium price of permits as $p(\theta_1,\theta_2,E)$ and the equilibrium distribution of emissions $(\bar{s}_1 = \bar{e}_1(p(\theta_1,\theta_2,E));$ $\bar{s}_2 = \bar{e}_2(p(\theta_1,\theta_2,E)))$, for firms type 1 and 2, respectively. According to equation (6), to induce compliance in a least cost-manner, each type of firm should be monitored with probability $\pi_1 = \pi_2 = \pi = p(\theta_1,\theta_2,E)/f'(0)$. Further, in equilibrium it must be the case that $-c_{e1}(\bar{s}_1(p(\theta_1,\theta_2,E),\theta_1) = -c_{e2}(\bar{s}_2(p(\theta_1,\theta_2,E),\theta_2) = p(\theta_1,\theta_2,E)$. Then, enforcement costs are given by $\bar{M} = w \times (n_1 + n_2) \times p(\theta_1,\theta_2,E)/f'(0)$. Consider now any alternative distribution of emissions (s_1, s_2) such that $s_1 + s_2 = E$. Let us to suppose that $s_1 \neq \bar{s}_1$ and $s_2 \neq \bar{s}_2$, inducing compliance of any of these alternative distributions of emissions under a system of emissions standards with incomplete information, require uniform monitoring effort tied to the type of firm with the highest marginal abatement cost, that is $\pi_1 = \pi_2 = \max(-c_{e1}(s_1,\theta_1)/f'(0), -c_{e2}(s_2,\theta_2)/f'(0))$; from Lemma 1, expected enforcement costs are given by M^*, and consequently it follows that $\bar{M} = M < M^*$. Finally, for the special case in which $s_1 = \bar{s}_1$ and $s_2 = \bar{s}_2$, $\bar{M} = M^*$ holds, so we conclude that $\bar{M} \leq M^*$. QED.

Considering a regulator implementing enforcement strategies that induce perfect compliance under incomplete information, we use our previous results to write an expression for total expected compliance costs under an emissions standards system:

$$CC^{ES} = A^{ES} + M^{ES}, \tag{11}$$

where $A^{ES} = n_1 c_1(s_1,\theta_1) + n_2 c_2(s_2,\theta_2)$, and $M^{ES} = M^{ES}(n_1,n_2,s_1,s_2,\theta_1,\theta_2)$, with $s_k = e_k$ for $k = 1,2$, and $n_1 s_1 + n_2 s_2 = E$.

For the total compliance costs of a transferable emissions permit (*TEP*) system, we write:

$$CC^{TEP} = A^{TEP} + M^{TEP}, \tag{12}$$

$$CC^{TEP} = n_1 c_1(e_1(p(\bar{\theta},L),\theta_1),\theta_1) + n_2 c_2(e_2(p(\bar{\theta},L),\theta_2),\theta_2) + w \times (n_1 + n_2) \times \frac{p(\bar{\theta},L)}{f'(0)}, \tag{13}$$

where $e_k = l_k$ for $k = 1,2$, $\bar{\theta} = (\theta_1, \theta_2)$, and $n_1 e_1 + n_2 e_2 = n_1 l_1 + n_2 l_2 = E = L$.

Among the most important results in the literature on transferable emissions permit systems is that these allow environmental regulators to achieve environmental targets at the least abatement costs. From that result, we already know that:

$A^{ES} = \sum_{i=1}^{n} c_{ei}(s_i, \theta_i) \geq \sum_{i=1}^{n} c_i(e_i(p(\bar{\theta}), \theta_i), \theta_i) = A^{TEP}$; hence, sign $(A^{ES} - A^{TEP}) \geq 0$.

In terms of enforcement costs, and considering Proposition 1, we know that: sign $(M^{ES} - M^{TEP}) \geq 0$. The previous analysis allows us to state our next Proposition.

Proposition 2 *Considering costly enforcement and regulator's incomplete information on firms' abatement costs, a system of emissions standards can not be less costly than a perfectly competitive transferable emissions permit system.*

Proof of Proposition 2: Follows directly from the previous analysis.

Propositions 1 and 2 differ from the existing literature on the choice of policy instruments to control pollution. Since previous works have considered only the case of regulator's complete information on firm's abatement costs, a different and ambiguous recommendation has been suggested. In particular, Malik (1992: 720) indicates that depending on the characteristics of firm's abatement cost functions, economic incentives can be more costly to enforce than direct controls. Here we have shown that this result only holds when a regulator has complete information regarding the firms' abatement costs or for a very specific allocation of emissions standards; namely, the one that would be generated by the market of permits. If firms know more about their marginal abatement costs than the regulatory agency and can exploit this informational advantage to their benefit, inducing compliance through a perfectly competitive transferable emissions permit system is likely to be cheaper than inducing compliance with an emissions standards system. This is so because, under a transferable emissions permit system there is no need to target different types of firms.

These results are particularly relevant for developing countries where environmental agencies are typically under funded and monitoring costs are, therefore, quite relevant. The results presented in Propositions 1 and 2 suggest an additional argument for implementing economic incentive-based policies in developing countries, since the informational requirements for regulators to minimize enforcement costs are always lower under a transferable emissions permit system than under an emissions standards system.

Whereas Proposition 2 does suggest that, except for a very special case, aggregate compliance costs are always higher for an emissions standard system than for a transferable emissions permit system, this does not imply that a transferable emissions permit system is cost-effective in the sense that it minimizes aggregate compliance costs. The following Proposition characterizes the cost-effective distribution of emissions among regulated sources when enforcement is costly.

Proposition 3 *To minimize aggregate compliance costs, firms should choose their level of emissions such that:*

$$-c_{ei}\left(s_i\right)+\frac{w}{f'(0)}c_{eei}\left(s_i\right)=-c_{ej}\left(s_j\right)+\frac{w}{f'(0)}c_{eej}\left(s_j\right) \quad \forall i\neq j, \quad i,j=1,...,n \tag{14}$$

Proof of Proposition 3: In order to minimize aggregate compliance costs, we must solve the following optimization problem:

$$\begin{aligned} &\min_{s_i} \quad CC=\sum_{i=1}^{n}c_i\left(s_i\right)+\frac{w}{f'(0)}\left[\sum_{i=1}^{n}-c_{ei}\left(s_i\right)\right] \\ &\text{s.t.} \quad \sum_{i=1}^{n}s_i=E \end{aligned} \tag{15}$$

The second term of the objective function in (15) represents the aggregate enforcement costs of inducing perfect compliance by every firm. It considers monitoring costs and the minimum monitoring effort required to induce full compliance. The Lagrange equation for (15) is given by the following expression: $\Gamma=\sum_{i=1}^{n}c_i\left(s_i\right)+\frac{w}{f'(0)}\left[\sum_{i=1}^{n}-c_{ei}\left(s_i\right)\right]+\lambda\left(\sum_{i=1}^{n}s_i-E\right)$ and the set of Kuhn-Tucker conditions are:

$$\frac{\partial\Gamma}{\partial s_i}=c_{ei}\left(s_i\right)-\frac{w}{f'(0)}c_{eei}\left(s_i\right)+\lambda=0 \quad \forall\, i=1,...,n, \tag{16}$$

$$\frac{\partial\Gamma}{\partial\lambda}=\sum_{i=1}^{n}s_i-E=0 \quad \forall\, i=1,...,n. \tag{17}$$

Equation (16) implies that the following must hold:

$$\lambda=-c_{ei}\left(s_i\right)+\frac{w}{f'(0)}c_{eei}\left(s_i\right)=-c_{ej}\left(s_j\right)+\frac{w}{f'(0)}c_{eej}\left(s_j\right)\ \forall i\neq j,\ i,j=1,...,n. \text{ Q.E.D.}$$

Proposition 3 implies that, in order to achieve cost-effectiveness considering enforcement costs as well as abatement costs, the distribution of emissions should be such that the sum of marginal abatement costs and marginal monitoring costs are equal across firms. This condition represents a trade-off for the regulator in terms of the optimal allocation of emissions, since changes in emissions that tend to minimize aggregate abatement costs will also change aggregate enforcement costs.

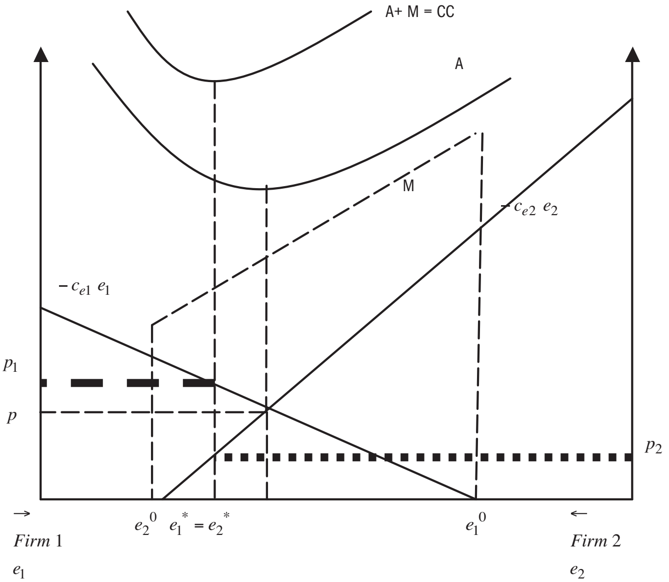
Our result in Proposition 3 has several new implications for the proper design of environmental policies based on transferable emissions permit systems. First, the distribution of emissions that minimize aggregate compliance costs will differ from the distribution of emissions that minimize only aggregate abatement costs. In order to minimize aggregate abatement costs, firms should choose their emissions level such that $-c_{ei}(e_i) = -c_{ej}(e_j)$ for all $i \neq j$. This implies that a competitive transferable emissions permit system that generates a uniform price will not be cost-effective, and so the environmental policy will not produce an efficient outcome. We notice that the result in Proposition 3 holds when the costs of conducting an audit are the same across firms ($w_i = w$, $i = 1,\ldots n$) ; it also holds when such costs vary across firms ($w_i \neq w_j$, $i,j = 1,\ldots,n$).

Second, our result recovers the cost-effectiveness property of a transferable emissions permit system as a *very special case*: set $c_{eei}(e_i) = c_{eej}(e_j)$ to obtain $-c_{ei}(e_i) = -c_{ej}(e_j)$. That is, recognizing that monitoring to induce compliance is costly overturns the cost-effectiveness property of a perfectly competitive transferable emissions permit system.

Third, our results suggest that permit prices should be discriminatory; that is, each firm should face a different price per emissions permit. However, a competitive transferable emissions permit system generates a single, non-discriminatory price for emissions permits. We conclude, then, *that a conventional tradable permits program cannot be cost-effective*. In effect, a competitive transferable emissions permit system will generate an emissions distribution that does not minimize total program costs. This is so, since the individual firms under a transferable emissions permit system do not internalize the monitoring costs required to induce perfect compliance. This is obvious since the aggregate compliance cost differs from the aggregate abatement cost. A graphic representation of this situation is presented in Figure 1.

In order to simplify the diagram, Figure 1 presents the case of just two firms. The total cost of the program, represented by the curve *CC*, is given by the sum of abatement costs (curve *A*) and enforcement costs (curve *M*). This figure clearly indicates that, when the equilibrium level of emissions achieved in a competitive permit market coincides with the level that minimizes abatement costs (curve A),

Figure 1. Graphical example for the case where $e_i^0 = \overline{e}, \quad \forall\ i$



it is different from the one that minimizes the sum of abatement and enforcement costs (curve $CC = A + M$) given by $e_1^* = e_2^*$. Figure 1 also allows a more intuitive vision showing that, whereas abatement costs are given by the slope of the abatement cost functions, $-c_{e1}(e_1)$ and $-c_{e2}(e_2)$, enforcement costs are given by the slope of the marginal abatement cost functions, $-c_{ee1}(e_1)$ and $-c_{ee2}(e_2)$.[10]

Proposition 3 and our previous discussion suggest that the emissions distribution that minimizes aggregate abatement costs, achieved by implementing a competitive transferable emissions permit system, will not guarantee that total program costs will be at the minimum. This is because, under a transferable emissions permit system, to reduce enforcement costs, minimum monitoring calls for uniform enforcement efforts among regulated sources. However, this does not allow the

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[10] Consider the case of two firms, and quadratic abatement costs functions. Using Proposition 3, we can write $c_{e2}(e_2) - c_{e1}(e_1) = (w / f'(0))\left[c_{ee2} - c_{ee1}\right]$ with c_{ee1} and c_{ee2} positive constants. From which follows that $-c_{e1}(e_1) = (w / f'(0))\left[c_{ee2} - c_{ee1}\right] - c_{e2}(e_2)$. Let us consider the case in which $c_{ee2} > c_{ee1}$. Strict convexity of abatement costs functions implies that $p_1 = -c_{e1}(e_1) > p_2 = -c_{e2}(e_2)$ and that $p_1 - p_2 = (w / f'(0)\left[c_{ee2} - c_{ee1}\right] > 0$.

regulator to exploit potential savings in enforcement costs associated with alternative distributions of abatement responsibilities. Nonetheless, the cost-effective property of a transferable emissions permit system, when considering total program costs, can be recovered by making each regulated firm face a different, perhaps firm-specific, price. How to implement this is beyond the scope of this paper, but for sure, uniform prices are problematic.

V. Conclusions

The results presented in this paper are important for designing environmental regulations. We have shown that, under the realistic assumption of incomplete information that allows regulated firms to exploit information asymmetries regarding their incentives to be non-compliant, an emissions standards system cannot be less costly than a transferable emissions permit system.

Moreover, we have also shown that the emissions distribution that minimizes aggregate program costs differs from the emissions allocation of a transferable emission permit system. Thus, a competitive transferable emissions permit system will not guarantee a cost-effective outcome.

Our results and discussion also suggest that an optimal transferable emissions permit system, considering enforcement costs, may be implemented by making the individual firms face discriminatory permit prices. This sort of environmental policy can be implemented by the authorities by charging firms with the enforcement costs they impose on the environmental regulator. Although, in practice, an environmental policy of this line could be formulated, its political feasibility, which requires a clear technical justification, is key to its implementation. This topic should be further analyzed and, therefore, provides an interesting avenue for future research.

References

Arguedas, Carmen (2008), To comply or not to comply? Pollution standard setting under costly monitoring and sanctioning, *Environmental and Resource Economics* **41**: 155-168.

Arimura, Toshi (2002), An empirical study of the SO2 Allowance Market: Effects of PUC regulations, *Journal of Environmental Economics and Management* **44**: 271-289.

Blackman, Allen (2009), Colombia's Discharge Fee Program: Incentives for polluters or regulators?, *Journal of Environmental Management* **90**: 101-119.

Bohm, Peter, and Clifford S. Russell (1985), Comparative analysis of alternative policy instruments, in A. V. Kneese & J. L. Sweeney, eds., *Handbook of natural resource and energy economics* (Vol. 1), Amsterdam, Elsevier

Burtraw, Dallas (1996), The SO2 Emissions Trading Program: Cost savings without allowance trades, *Contemporary Economic Policy* **14**: 79-94.

Burtraw, Dallas (1999), Cost savings, market performance and economic benefits of the US Acid Rain Program, in S. Sorrell and J. Skea, eds., *Pollution for sale: Emissions trading and joint implementation*, Cheltenham, Edward Elgar Publishing.

Chávez, Carlos, and John Stranlund (2003), Enforcing transferable emission permit systems in the presence of market power, *Environmental and Resource Economics* **25**: 65-78.

Cohen, Mark (1999), Monitoring and enforcement of environmental policy, in H. Folmer and T. Tietemberg, eds., *International yearbook of environmental and resource economics* 1999/2000, Cheltenham - Northampton, Edward Elgar Publishing.

Crocker, Tom (1966), Structuring of atmospheric pollution control systems, in H. Wolozin, ed., *The economics of air pollution*, New York, W.W. Norton.

Dales, John (1968), *Pollution, property and prices*, Toronto, University of Toronto Press.

Garvie, Devon, and Andrew Keeler (1994), Incomplete enforcement with endogenous regulatory choice, *Journal of Public Economics* **55**: 141-162.

Hahn, Robert, and Robert Axtell (1995), Reevaluating the relationship between transferable property rights and command and control regulations, *Journal of Regulatory Economics* **8**: 125-148.

Heyes, Anthony (2000), Implementing environmental regulation: Enforcement and compliance, *Journal of Regulatory Economics* **17**: 107-129.

Keeler, Andrew (1991), Noncompliant firms in transferable discharge permit markets: Some extensions, *Journal of Environmental Economics and Management* **21**: 180-189.

McLean, Brian (1997), Evolution of marketable permits: The US Experience with Sulfur Dioxide Allowance Trading, *International Journal of Environment and Pollution* **8**: 19-36.

Malik, Arun (1993), Self reporting and the design of policies for regulating stochastic pollution, *Journal of Environmental Economics and Management* **24**: 241-257.

Malik, Arun (1992), Enforcement cost and the choice of policy instruments for controlling pollution, *Economic Inquiry* **30**: 714-721.

Malik, Arun (1990), Markets for pollution control when firms are noncompliant, *Journal of Environmental Economics and Management* **18**: 97-106.

Montero, Juan Pablo, José Miguel Sánchez, and Ricardo Katz (2002), A market-based environmental policy experiment in Chile, *Journal of Law and Economics* **45**: 267-287.

Montero, Juan Pablo (2002), Prices vs. quantities with incomplete enforcement, *Journal of Public Economics* Vol. **85**, 435-454.

Montero, Juan Pablo, José Miguel Sánchez, and Ricardo Katz (2001), Análisis del mercado de emisiones de material particulado en Santiago, *Estudios Públicos* **81**: 177-203.

Montgomery, W. David (1972), Markets in licenses and efficient pollution control programs, *Journal of Economic Theory*: 395-418.

Palacios, Milagros, and Carlos Chávez (2005), Determinants of compliance in the Emissions Compensation Program in Santiago, Chile, *Environment and Development Economics* **10**: 453-483.

Palacios, Milagros, and Carlos Chávez (2002), Programa de compensación de emisiones: evaluación de su diseño de fiscalización y cumplimiento, *Estudios Públicos* **88**: 97-126.

Russell, Clifford S., and Philip T. Powell (1996), Choosing environmental policy tools: Theoretical cautions and practical considerations, in M. L. Livingston, ed, *Environmental policy for economies in transition: Lessons learned and future directions*, Washington, D.C., Proceedings of the Resource Policy Consortium Symposium.

Schmalensee, Richard, Paul Joskow, A. Denny Ellerman, Juan Pablo Montero, and Elizabeth Bailey (1998), An interim evaluation of sulfur dioxide emissions trading, *Journal of Economic Perspectives* **12**: 53-68.

Stavins, Robert (1998), What can we learn from the Grand Policy Experiment? Lessons from the SO_2 Allowance Trading, *Journal of Economic Perspectives* **12**: 69-88.

Stranlund, John, Carlos Chávez, and Mauricio Villena (2009), The optimal pricing of pollution when enforcement is costly, *Journal of Environmental Economics and Management* **58**: 183-191.

Stranlund, John K (2007), The regulatory choice of noncompliance in emissions trading programs, *Environmental and Resource Economics* **38**: 99-117.

Stranlund, John, Carlos Chávez and Barry Field (2002), Enforcing emissions trading programs: Theory, practice and performance, *Policy Studies Journal* **30**: 343-361.

Stranlund, John, and Carlos Chávez (2000), Effective enforcement of a transferable emissions permit system with a self-reporting requirement, *Journal of Regulatory Economics*, **18**: 113-131.

Stranlund, John, and Kanwalroop K. Dhanda (1999), Endogenous monitoring and enforcement of a transferable emissions permit system, *Journal of Environmental Economics and Management* **38**: 267-282.

Tietenberg, Tom (2006) *Emissions trading: Principles and practice*, 2nd ed., Washington, DC: Resources for the Future.

Van Egteren, Henry, and Marian Weber (1996), Marketable permits, market power, and cheating, *Journal of Environmental Economics and Management*, **30**: 161-173.