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JK Stranlund

CA Chavez

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JOHN K. STRANLUND
University of Massachusetts-Amherst,
Department of Resource Economics, University of Massachusetts, Amherst, MA 01003

CARLOS A. CHAVEZ
Universidad de Concepcion, Chile
Departamento de Economia, Universidad de Concepcion, Casilla 1987, Concepcion, Chile

Abstract
We propose an enforcement strategy to achieve complete compliance in a transferable emissions permit system when firms are required to provide reports of their own emissions. Like the literature on self-reporting in the enforcement of standards, we find that self-reporting can conserve monitoring costs, but for a different reason. In addition, we show that targeted monitoring—the practice of monitoring some firms more closely than others—is not necessary in a competitive permit system. Furthermore, tying penalties to the equilibrium permit price can stabilize the monitoring effort necessary to maintain full compliance in the face of permit price fluctuations.

1. Introduction

Although market-based environmental policies are quickly gaining support among policy-makers, a key component of these systems has not been adequately addressed; namely, how they should be enforced to achieve acceptable levels of compliance in a cost-effective manner. While there is a small literature concerning the consequences of non-compliance in transferable emissions permit systems, most of it does not deal squarely with the problem of how to design enforcement strategies for market-based policies. For example, Malik's (1990) work is primarily a positive analysis of firm behavior in a transferable permit system when they face a fixed enforcement strategy. In addition, Keeler (1991), Malik (1992), and Hahn and Axtell (1995) all chose to focus on comparing the performance of transferable permit systems to command-and-control policies when firms may be non-compliant.[1]

This paper proposes an enforcement strategy for a competitive transferable emissions

1 We are aware of only two attempts to construct enforcement strategies for transferable permit systems. Beavis and Walker (1984) characterize a uniform monitoring strategy with fixed penalties to achieve an

permit system in which firms are required to provide reports of their own emissions. The addition of a self-reporting requirement implies that an enforcement strategy must address two types of possible violations: emissions violations, where firms do not hold enough permits to cover their emissions, and reporting violations, where firms do not give an accurate report of their emissions. Like a large portion of all environmental policies in the United States, the current generation of market-based initiatives—the Sulfur Dioxide (SO_2) Allowance Trading program and the Regional Clean Air Incentives Market (RECLAIM) program—require firms to provide regulators with reports of their emissions. However, to our knowledge, no one has examined the role of self-reporting in the enforcement of market-based environmental policies. Because self-reporting is an important component of existing market-based policies, and will likely to be important for future initiatives, we incorporate a self-reporting requirement into our analysis.[2]

We also assume that the regulatory objective is what we choose to call *effective enforcement*: the enforcement strategy is designed to achieve complete emissions compliance (each firm holds enough permits to cover its emissions) in a cost-effective manner. We focus on achieving complete emissions compliance because a great deal of effort has been devoted to achieving very high rates of compliance in the Sulfur Dioxide Allowance Trading and RECLAIM programs, and thus far these efforts have been quite successful. [We provide a brief sketch of the enforcement components of the SO_2 Trading and RECLAIM programs in the first half of section 2.] Since its inception, firms in the SO_2 Trading program have been perfectly compliant (U.S. EPA 1996, 1997 and 1998a). There have been a small number of violations in the RECLAIM program, but authorities attribute these to a few firms that lacked sufficient understanding of the required protocols, rather than deliberate attempts to evade their legal obligations (South Coast Air Quality Management District 1998).

After presenting the basic model of the paper in the second half of section 2, section 3 is devoted to deriving an effective enforcement strategy for a transferable emissions permit system with self-reporting. We begin by presenting a necessary and sufficient condition for an enforcement strategy to be incentive-compatible; that is, to elicit truthful emissions reports. We go on to show that an enforcement strategy for a market-based policy with a self-reporting requirement that does not elicit truthful emissions reports cannot achieve complete emissions compliance. Although incentive-compatible enforcement is necessary to achieve complete emissions compliance, it is not sufficient. An additional condition that

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aggregate emissions target in a cost-effective manner. They do not consider any of the issues that are important in this paper; in particular, self-reporting, targeted monitoring and setting penalties. Stranlund and Dhanda (1999) only consider the desirability of targeted monitoring, but they do so from the perspective of maximizing aggregate compliance with a fixed enforcement budget.

2 A few authors have examined the role of self-reporting, but all have done so in the context of enforcing standards. Harford (1987) provides a positive analysis of firm behavior in this setting, while Malik (1993), Kaplow and Shavell (1994), and Livernois and McKenna (1999) provide normative analyses. Although our analysis is also best characterized as normative, our modeling approach is closer to Harford's, particularly in the way penalties are applied, and that we allow for continuous choices. The later papers in this literature assume that compliance is simply an either/or choice.

relates the equilibrium permit price to the marginal penalty for a small emissions violation is required.

In section 4 we explore a number of implications of the strategy we propose in section 3. We begin by considering the value of the self-reporting requirement. The normative analyses of self-reporting in the enforcement of standards (Malik 1993; Kaplow and Shavell 1994; Livernois and McKenna 1999) all conclude that self-reporting can conserve monitoring costs because it allows a strong form of targeted monitoring.[3] In our context, targeted monitoring—the practice of auditing some firms with a higher probability than others—cannot be used to lower monitoring costs. However, we find that a self-reporting requirement can conserve monitoring costs if a regulator can apply penalties for reporting violations in addition to penalties for emissions violations.

In section 4 we elaborate on the theme that in a frictionless and competitive permit market, targeted monitoring is not necessary; that is, effective enforcement implies a uniform monitoring strategy. However, we argue that uniform monitoring will not be cost-effective in the presence of significant transaction costs or market power. We also propose that marginal penalties in a transferable permit system be tied to the equilibrium permit price to stabilize the amount of monitoring necessary to achieve complete emissions compliance in the face of permit price fluctuations.

2. A Model of Compliance in a Transferable Emissions Permit System

The primary purpose of this section is to present the model of this paper. To set the stage, let us first consider briefly the enforcement strategies used in the Sulfur Dioxide Allowance Trading and RECLAIM programs.[4]

2.1. Monitoring and Enforcement in Existing Transferable Permit Programs

In both the SO_2 Allowance Trading and RECLAIM programs, a system is in place to keep track of emissions permits so that, at any point in time, program authorities know how many permits a firm holds. All sources in the SO_2 Trading program and most sources in the RECLAIM program are required to install a continuous emissions monitoring system (CEMS), or an equivalent technology, on each emitting stack. These systems provide a continuous and very accurate measure of emissions leaving a stack. All sources

3 In particular, firms that report that they are non-compliant need not be monitored so audits are conducted (with some probability) only on the firms that report being compliant. No doubt this strong result is due, in large part, to the common assumption in these models that compliance is only an either/or choice. If a firm knows that it will not be audited if it reports that it is non-compliant and can choose among varying levels of non-compliance, it will have an incentive to submit a report of non-compliance but misrepresent the extent of its violation. We thank two referees for bringing this characteristic of these models to our attention.

4 The EPA maintains a website with a wealth of information about the SO_2 Allowance Trading Program (*http://www.epa.gov/acidrain/trading.html*). The South Coast Air Quality Management District's website on RECLAIM (*http://www.aqmd.gov/reclaim/reclaim.html*) provides only a brief sketch of the program.

in both programs are also required to submit emissions reports, as well as periodic quality control tests of monitoring devices to maintain the accuracy of emissions data. The requirements for reporting emissions data are quite demanding, usually specifying an automated system for receiving emissions data from monitoring devices, formatting data into emissions reports, and submitting the reports to the agencies.

In the SO_2 Trading program the EPA subjects *every single emissions report* to a series of reviews to verify the accuracy of each report. These audits appear to be primarily of the sources' reports rather than site visits. However, the EPA may conduct site audits to inspect monitoring devices and review on-site operation and quality assurance records (U.S. EPA 1998b). RECLAIM authorities claimed to have also reviewed each emissions report in the first three years of the program (1994–1996). Apparently these reviews also included site visits to inspect equipment, monitoring devices and operation records (South Coast Air Quality Management District 1998). Although the requirements for obtaining and reporting emissions data in both programs are rather substantial, it is not clear to what extent firms can be penalized for filing false reports.

Because of the level of agency-monitoring and the stringency of the self-monitoring and self-reporting requirements, it is widely believed that sources have little opportunity to manipulate data files to under-report their emissions; hence, there is a high degree of confidence in the accuracy of the emissions reports in both programs. We should note here that the enforcement strategy that we propose will also generate accurate emissions reporting, but in a very different way. While the SO_2 and RECLAIM programs rely primarily on very stringent technological and process standards to generate accurate emissions reports, our strategy relies on choosing audit probabilities and penalties to provide firms with the proper incentives for truthful reporting.

As for penalties for emissions violations, the SO_2 Allowance Trading program is unique among environmental policies in that these penalties are explicit and are intended to be assessed automatically. The monetary penalty was set at $2000 per ton of excess emissions in 1990, and is indexed to inflation. [In 1998 the penalty was $2581 per ton of excess emissions]. In addition, any excess emissions are deducted from the source's allocation in the following year. Our analysis will make it obvious why these stiff penalties and the effort devoted to monitoring emissions in the SO_2 program have induced the perfect compliance record the program has achieved thus far. Non-compliant RECLAIM sources may face monetary penalties and must offset excess emissions in the following year as well, but the penalties are not automatic and are not specified as clearly as those in the SO_2 program.

2.2. A Model of a Self-Reporting Firm

The analysis of this paper is based on a static model of a risk-neutral firm that operates under a competitive transferable emissions permit system. The firm's emissions-control cost function, $c(e)$, is strictly decreasing and convex in its actual emissions e; that is, $c'(e) < 0$ and $c''(e) > 0$.[5] In general, a firm has a number of options for reducing its

5 The standard interpretation of $c(e)$ is as follows: Let e^0 be the firm's unconstrained level of emissions and let $\pi(e^0)$ be the firm's maximal profit in this setting. The cost of holding its emissions to $e < e^0$ is $c(e) =$

emissions including reducing output, using cleaner inputs, and installing end-of-pipe control technologies. Therefore, its emissions-control costs will depend on a host of factors including prices of inputs and outputs, and characteristics of available production and the emissions-control technologies.[6] We expect that in actual settings the abatement costs of firms in a transferable permit system are likely to vary substantially and that regulators, including enforcement authorities, will have to make design decisions without complete information about these costs.

The firm is required to provide a report of its emissions to the enforcement authority. Denote an emissions report as r and assume that submission of a report is costless.[7] Let l_0 be the number of permits that are initially allocated to the firm, and let l be the number of permits that the firm holds after trade. Possession of a permit confers the legal right to emit one unit of emissions. We assume that the aggregate issuance of permits is fixed, and that permits trade at a competitive price p.

Two types of violation may occur: an emissions violation occurs when a firm's emissions exceed the number of permits it holds $(e - l > 0)$, and a reporting violation occurs when its actual emissions exceed its reported emissions $(e - r > 0)$. We assume that a firm never reports that its emissions violation is greater than it actually is, and it never reports that it is over-compliant; that is, we shall restrict our analysis by $e - l \geq r - l \geq 0$. Of course, this implies that a firm never reports that its emissions are greater than they actually are $(e \geq r)$, nor that its emissions are less than the number of permits it holds $(r \geq l)$. Furthermore, if a firm holds enough permits to cover its emissions, it will also provide an accurate report of its emissions; that is, for a compliant firm, $e = r = l$.[8]

Like the Sulfur Dioxide Allowance Trading and RECLAIM programs, we assume that a system is in place to track emissions permits so that the regulator has perfect information on the number of permits a firm holds. Thus, when choosing a monitoring strategy, the enforcement authority has two pieces of information about a firm, its emissions report and the number of permits it holds. We assume that the regulator bases its audit strategy on the

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$\pi(e^0) - \pi(e)$. Montgomery (1972) showed that $c(e)$ is decreasing and convex when the firm is a price-taker in input and output markets, but since the formulation of $c(e)$ is quite general it will have these characteristics in many non-competitive settings as well.

6 A firm's abatement costs may also be affected by other regulations it faces besides the transferable permit system it operates under. For example, all of the firms in the SO_2 Allowance Trading program are public electric utilities, whose emissions-control costs are likely to be affected by state public utility regulations (Coggins and Smith 1993).

7 However, the firm may incur substantial costs if it is forced to obtain an accurate account of its emissions. Since it seems unlikely that these costs will affect the firm's choices of emissions and emissions report, we shall ignore them.

8 Since the model is static, we do not allow firms to save emissions permits for future use or sale, nor do we allow firms to borrow permits against future allocations. The RECLAIM program does not allow any sort of permit banking, while the SO_2 Trading program only allows firms to save allowances for future use or sale. In fact, firms in the SO_2 program are saving a significant proportion of their allowances (Schmalensee et. al. 1998). A few authors have constructed dynamic models to examine the role of permit banking in transferable permit systems (Kling and Rubin 1997; Cronshaw and Cruse 1996; Rubin 1996), but no one has considered enforcement in a dynamic setting. We feel that this is an important area for future research.

firm's reported violation; that is, the regulator will audit a firm that reports its emissions to be r and holds l permits with probability $\pi(r-l)$. A firm that reports being compliant is audited with probability $\pi(0)$. For simplicity we assume that an audit of the firm reveals its true violation.[9]

We follow Harford's (1987) approach to modeling penalties. If a firm reports an emissions violation, a penalty of $f(r-l)$ is imposed automatically. If a firm is audited and found to have under-reported its emissions, a penalty for the reporting violation, $g(e-r)$, is imposed, as well as the incremental penalty for its emissions violation, $f(e-l)-f(r-l)$. We assume that these penalties are zero for zero reporting and emissions violations $[g(0)=f(0)=0]$, but that the marginal penalties for zero reporting and emissions violations are greater than zero $[g'(0)>0, f'(0)>0]$. For positive reporting and emissions violations, the penalty functions are strictly increasing and convex. Strict convexity of the penalty functions is not necessary for our analysis—all of our results hold as well under constant marginal penalties, but the analysis is a bit more complicated.

As is standard in the literature, we assume that an enforcement authority commits itself to a strategy at the outset and communicates this strategy to all firms. A firm chooses its emissions, its emissions report, and permit demand to solve (1), taking the enforcement strategy as given.

$$\min\ c(e)+p(l-l_0)+f(r-l)+\pi(r-l)[g(e-r)+f(e-l)-f(r-l)] \tag{1}$$
$$s.t.\ e \geq r \geq l>0.$$

Notice that we are not interested in the unrealistic case in which the firm holds no permits. The Lagrange equation for (1) is $\theta = c(e)+p(l-l_0)+f(r-l)+\pi(r-l)[g(e-r)+f(e-l)-f(r-l)]-\beta(e-r)-\mu(r-l)$, and the Kuhn-Tucker conditions are:

$$\theta_e = c'(e)+\pi(r-l)[g'(e-r)+f'(e-l)]-\beta = 0; \tag{2a}$$
$$\theta_l = p-f'(r-l)-\pi'(r-l)[g(e-r)+f(e-l)-f(r-l)] - \pi(r-l)[f'(e-l)-f'(r-l)]+\mu = 0; \tag{2b}$$
$$\theta_r = f'(r-l)+\pi'(r-l)[g(e-r)+f(e-l)-f(r-l)] - \pi(r-l)[g'(e-r)+f'(r-l)]+\beta-\mu = 0; \tag{2c}$$

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9 A more general monitoring strategy would base the audit probability on the firm's reported emissions and the number of permits it holds separately; that is, $\pi(r,l)$. All of the results of this paper hold as long as $\pi_r = -\pi_l$, but cannot be guaranteed to hold otherwise. Because it is not clear to us that an enforcement authority can do better with an audit strategy such that $\pi_r \neq -\pi_l$, we have chosen $\pi(r,l)=\pi(r-l)$. We recognize, however, that this assumption may be restrictive.

$$\theta_\beta = r - e \leq 0, \beta \geq 0, \beta \times (r - e) = 0; \tag{2d}$$

$$\theta_\mu = l - r \leq 0, \mu \geq 0, \mu \times (l - r) = 0. \tag{2e}$$

We assume that (2a–e) are necessary and sufficient to determine the firm's optimal choices of emissions, emissions report, and permit demand uniquely.

3. Effective Enforcement of a Transferable Permit System with Self-Reporting

Assume that the objective of an enforcement authority is to induce complete emissions compliance at least cost. In this section we derive the appropriate enforcement strategy. To begin, we consider a firm's choice of emissions.

3.1. A Firm's Choice of Emissions

A number of authors have noted the rather surprising result that under incentive-based policies, the emissions-choices of firms may be independent of a regulator's enforcement strategy [e.g., Malik (1990) in the case of transferable permits, and Harford (1978) in the case of an emissions tax]. This independence result also obtains in our context.

Proposition 1: *Given an optimal choice of permit demand and emissions report, a firm chooses its emissions so that* $c'(e) + p = 0$*, regardless of its compliance status.*

Proof of Proposition 1: *Combine (2b) and (2c) to obtain*

$$p - \pi(r - l)[g'(e - r) + f'(e - l)] + \beta = 0. \tag{3}$$

From (2a), $c'(e) = -\pi(r - l)[g'(e - r) + f'(e - l)] + \beta$*. Substitute this into (3) to obtain* $c'(e) + p = 0$*. Q.E.D.*

Proposition 1 has important implications for our analysis. First, since a firm's choice of emissions is independent of the enforcement strategy it faces, we can ignore this choice (i.e., the first-order condition (2a)) when we focus on the firm's emissions report and permit demand. Second, Proposition 1 implies that, given the goal of complete emissions compliance, the choice of enforcement strategy will have no impact on the equilibrium permit price.[10] Therefore, we can derive the appropriate enforcement strategy from a single firm's choices without providing a complete analysis of the permit market.

Proposition 1 also implies that, regardless of the particular enforcement strategy, in any

10 To see this, index firms by i and note that equilibrium in the permit market requires $\sum l_i = L$, where the summation is over the entire set of firms in the program and L denotes the aggregate number of permits in circulation. From Proposition 1, firm i's choice of emissions can be written as $e_i(p)$, which is the implicit solution to $c_i'(e_i) + p = 0$. Achieving complete compliance requires $e_i(p) = l_i$ for every firm i; hence, the permit market clears when $\sum e_i(p) = L$. This market-clearing condition implicitly defines the

equilibrium the firms' marginal abatement costs are equal to the permit price and, since all firms face the same price, marginal abatement costs are equal across firms. We shall see that this equilibrating characteristic of competitive transferable permit systems has important implications for the design of enforcement strategies for transferable permit systems.[11]

3.2. An Incentive-Compatible Enforcement Strategy

Whether a firm provides a truthful report of its emissions or not depends on the regulator's enforcement strategy. In their analyses of self-reporting of violations of standards, Kaplow and Shavell (1994) and Malik (1993) focused on incentive-compatible enforcement strategies; that is, strategies that induce agents to report any violation truthfully. We shall do the same.

Proposition 2: *Given some choice of emissions and an optimal choice of emissions permits, a firm reports a violation truthfully if and only if*

$$p \leq \pi(r-l)[g'(0) + f'(e-l)], \forall r-l \in [0, e-l]. \tag{4}$$

Proof of Proposition 2: *From (2b), an optimal choice of permits implies*

$$\begin{aligned} p - \pi(r-l)[f'(e-l) - f'(r-l)] \\ = f'(r-l) + \pi'(r-l)[g(e-r) + f(e-l) - f(r-l)] - \mu. \end{aligned} \tag{5}$$

Substitute the right-hand-side of (5) into (2c) to obtain

$$\begin{aligned} \theta_r &= p - \pi(r-l)[f'(e-l) - f'(r-l)] - \pi(r-l)[g'(e-r) + f'(r-l)] + \beta \\ &= p - \pi(r-l)[g'(e-r) + f'(e-l)] + \beta = 0. \end{aligned} \tag{6}$$

For some e and an optimal choice of l, an optimal choice of r must satisfy (6).

Suppose first that $r = e$. Then, if this report is optimal, $\theta_r = p - \pi(r-l)[g'(0) + f'(e-l)] + \beta = 0$. Since, from (2d), $e = r$ implies $\beta \geq 0$, (4) is clearly necessary for $r = e$ to be an optimal report. To show that (4) is also sufficient, suppose to the contrary that (4) holds but $e > r \geq l$. From (2d) the first inequality implies $\beta = 0$. Then, $\theta_r = p - \pi(r-l)[g'(e-r) + f'(e-l)] < 0$, the sign of which follows from the fact that

equilibrium permit price and indicates that, since every firm's choice of emissions is independent of the enforcement strategy, the equilibrium permit price is independent of the choice of enforcement strategy as well.

11 We should note that Proposition 1 holds only if $\pi_r = -\pi_l$. Therefore, if an enforcement authority chooses a monitoring strategy that does not satisfy $\pi_r = -\pi_l$, the equilibrium distribution of emissions will deviate from that in which all marginal abatement costs are equal to the equilibrium permit price.

$e > r$ implies $g'(e - r) > g'(0)$. Since $\theta_r < 0$ contradicts (6), we have established the sufficiency of (4) for inducing truthful reporting. Q.E.D.

The reason that (4) guarantees truthful reports is straightforward. Imagine a non-compliant firm that considers under-reporting its violation $(e > r \geq l)$. Given that its choice of emissions is fixed at the solution to $c'(e) + p = 0$ (Proposition 1) and that it has chosen its permits optimally, (6) indicates that the marginal expected cost of its report is $\theta_r = p - \pi(r - l)[g'(e - r) + f'(e - l)]$. If (4) is satisfied, then $\theta_r < 0$ whenever $e > r \geq l$, implying that the firm can reduce its expected costs by increasing its reported emissions to the level of its actual emissions.

Choosing $\pi(r - l)$ so that (4) holds is somewhat problematic because it requires knowledge of an actual violation $(e - l)$, which can only be determined with an audit. However, using a firm's reported violation in place of its actual violation suggests that the regulator choose its enforcement strategy so that

$$p \leq \pi(r - l)[g'(0) + f'(r - l)], \forall r - l \geq 0. \tag{7}$$

Using the fact that $r - l \leq e - l$ implies $f'(r - l) \leq f'(e - l)$, it is easy to see that if (7) holds, (4) also holds; hence, (7) characterizes an incentive-compatible enforcement strategy that is based upon information available to a regulator. Furthermore, equation (7) suggests that an incentive-compatible enforcement strategy should satisfy $p \leq \pi(0)[g'(0) + f'(0)]$ for a report of a zero violation (i.e., $r - l = 0$). Since $f'(r - l)$ is assumed to be increasing in $r - l$, choosing $\pi(0)$ so that it is exactly equal to $p/[g'(0) + f'(0)]$ guarantees that every firm will report its true violation, even if it is non-compliant.

A couple of immediate implications follow from the choice of an enforcement strategy to elicit accurate emissions reporting; that is, one that satisfies $p = \pi(0)[g'(0) + f'(0)]$. Notice first that it does not require a penalty for a reporting violation. However, given the marginal penalty for a slight emissions violation, $f'(0)$, the application of a penalty for a reporting violation allows the regulator to reduce the amount of monitoring necessary to induce truthful reporting by every firm. We shall return to this idea in section 4 where we examine the value of a self-reporting requirement in market-based policies.

More importantly, note that there is nothing in the condition, $p = \pi(0)[g'(0) + f'(0)]$, that is specific to particular firms. This is due to Proposition 1—regardless of the enforcement strategy, each firm chooses its emissions so that its marginal abatement costs are equal to the equilibrium permit price. This fact allows the enforcement strategy to be tied to the equilibrium permit price rather than to individual marginal control costs. Consequently, to elicit accurate emissions reports the regulator need only observe the equilibrium permit price, not hard-to-obtain information on firms' control costs. Furthermore, since all firms face the same permit price, as long as penalties are applied uniformly, uniform monitoring with probability $\pi(0)$ guarantees that all firms will provide truthful reports of their emissions. Thus, from the perspective of inducing accurate emissions reporting, the equilibrating nature of competitive transferable permit systems implies that an enforcement authority need not use fundamental differences among firms to target its enforcement strategy. We shall see that this extends to inducing complete emissions compliance as well.

3.3. Effective Enforcement with Self-Reporting

The focus on incentive-compatible policy mechanisms is usually justified by appealing to the Revelation Principle (Myerson 1979)—loosely, for a wide range of policy objectives, a policy that elicits truthful reports of key pieces of information cannot be dominated by one that does not. We have a more pressing reason for focusing on incentive-compatibility. As the following proposition indicates, a regulator cannot hope to achieve complete emissions compliance unless $p \leq \pi(0)[g'(0) + f'(0)]$.

Proposition 3: *If $p > \pi(0)[g'(0) + f'(0)]$, each firm is non-compliant; that is, $e > l$ for every firm.*

Proof of Proposition 3: *Toward a contradiction, suppose that $p > \pi(0)[g'(0) + f'(0)]$, but a firm is compliant (i.e., $e = l$). Using (2b) and (2c), if emissions compliance is optimal,*

$$\theta_l = p - f'(0) + \mu = 0, \tag{8}$$

and

$$\theta_r = f'(0) - \pi(0)[g'(0) + f'(0)] + \beta - \mu = 0. \tag{9}$$

Substitute (9) into (8) to obtain

$$\theta_l = p - \pi(0)[g'(0) + f'(0)] + \beta > 0. \tag{10}$$

The sign of (10) follows because $p > \pi(0)[g'(0) + f'(0)]$ and $\beta \geq 0$, and contradicts (8). Therefore, if $p > \pi(0)[g'(0) + f'(0)]$, a firm chooses to be non-compliant. Since there is nothing specific to a particular firm in equations (8), (9) and (10), the conclusion applies to all firms. Q.E.D.

Equation (10) indicates that a firm that contemplates full emissions compliance in the absence of incentive-compatible enforcement will find that at $e = l$ the marginal expected cost of its permit demand is strictly positive ($\theta_l > 0$). Thus, because its choice of emissions is fixed at the solution to $c'(e) + p = 0$ (Proposition 1), the firm is motivated to hold fewer permits, thereby choosing to be non-compliant. Furthermore, it does not provide a truthful report of its resulting emissions violation because it does not have the proper incentive to do so.

Although an incentive-compatible enforcement strategy is necessary to achieve full emissions compliance, it is not sufficient. An additional condition is needed.

Proposition 4: *Full emissions compliance is achieved if and only if*

$$(A)\ p \leq \pi(0)[g'(0) + f'(0)],$$

and

$$(B)\ p \leq f'(0).$$

Proof Proposition 4: *We have already established the necessity of (A) to induce full emissions compliance. Given (A), we first show that* $p - f'(0) \leq 0$ *is also necessary. Given truthful reporting, (2b) reveals that a firm's optimal demand for permits must satisfy*

$$\theta_l = p - f'(e - l) + \mu = 0. \tag{11}$$

If a firm is compliant, $e = r = l$*, which, from (2e), implies* $\mu \geq 0$*. Clearly,* $p - f'(0) \leq 0$ *is therefore necessary to satisfy (11) when a firm is compliant. To establish sufficiency, suppose that* $e = r > l$ *while* $p - f'(0) \leq 0$*. From (2e),* $r > l$ *implies* $\mu = 0$*. Then, since* $e > l$ *implies* $f'(e - l) > f'(0)$, $\theta_l = p - f'(e - l) < 0$*. However,* $\theta_l < 0$ *contradicts (11). Again, since the proof of the proposition for a single firm does not rely on anything specific to that firm, the proposition applies to all firms. Q.E.D.*

Proposition 4 is the primary result of this paper and we shall discuss its significance and limitations at length in the next section. Before we move on, however, let us make a few observations. First, given an incentive-compatible enforcement strategy [part (A) of the proposition], a non-compliant firm reports its emissions violation truthfully and pays the certain penalty $f(e - l)$. Thus, if $p \leq f'(0)$ so that part (B) of the proposition holds, the permit price is less than the marginal penalty of any emissions violation; therefore, every firm chooses their emissions and permits to be compliant because non-compliance is more costly than purchasing enough permits to cover their emissions. However, if $p > f'(0)$, equation (11) implies that a firm chooses its emissions violation so that $p = f'(e - l)$. Perhaps surprisingly, since every firm faces the same permit price, as long as they face the same penalties for emissions violations as well, they all choose the same emissions violation.

Notice that Becker's (1968) seminal insight about the tradeoff between monitoring and penalties can be applied to the enforcement strategy proposed in Proposition 4. If monitoring is costly but setting penalties is not, the enforcement cost of maintaining full emissions compliance can be minimized by setting the marginal penalties at arbitrarily high levels so that the audit probability can be made arbitrarily small. There are very sound theoretical and ethical reasons for why this strategy is not very practical and, perhaps for these reasons, the strategy is not observed in actual practice.[12]

However, relative to going prices for SO_2 allowances, the marginal penalty for emissions violations in the SO_2 Trading program is quite high, implying that the audit

12 See Cohen (1999, section 3) and Macauley and Brennan (1998, section 3.3.2) for discussions of the limits to setting arbitrarily high penalties, both with particular reference to enforcing environmental policies.

probability necessary to achieve complete emissions compliance can be very low. In 1998, prices for allowances ranged between $100 and $200 per allowance. In the same year the monetary penalty for excess emissions was $2581 per unit. In addition, any excess emissions would have been offset in 1999, suggesting an additional per unit penalty for forfeited 1999 allowances equal to the present value of these allowances. Assuming that this value is roughly equal to 1998 permit prices, the effective marginal penalty for an emissions violation would have been in the neighborhood of $2650 to $2750. Note that part (B) of Proposition 4 is easily satisfied and, with a probability of detecting a violation as low as 0.08, part (A) would be satisfied as well. Given the effort expended on monitoring and the stringency of the reporting requirements in the SO_2 program, the actual probability of detecting emissions violations is probably much higher. It is therefore quite clear why firms in the SO_2 program have chosen full emissions compliance.

4. Implications for Designing Enforcement Strategies for Transferable Permit Systems

Proposition 4 reveals that effective enforcement of a transferable permit system with self-reporting has two requirements. Firms should be audited with probability $\pi(0)$, and marginal penalties for slight emissions and reporting violations, $f'(0)$ and $g'(0)$, should be chosen so that $p = \pi(0)[g'(0) + f'(0)]$. Furthermore, the marginal penalty for a slight emissions violation should not be less than the equilibrium permit price; that is, $p \leq f'(0)$. The first condition guarantees a truthful report of any emissions violation [Proposition 2 and the discussion that follows], which is necessary for firms to have the proper incentive to choose complete emissions compliance [Proposition 3]. Given incentive-compatible enforcement, the second condition guarantees complete emissions compliance [Proposition 4]. These conditions have strong implications for the value of self-reporting, the desirability of targeted monitoring, and useful criteria for setting penalties in transferable permit systems.[13]

4.1. The Value of Self-Reporting in Enforcing Transferable Permit Systems

Each of the normative analyses of the consequences of self-reporting in the enforcement of standards (Malik 1993; Kaplow and Shavell 1994; Livernois and McKenna 1999) have found that self-reporting can reduce monitoring costs because the report provides information to the enforcement agency that it can use to target its monitoring effort. However, targeted monitoring is not appropriate in our context because, as indicated by the discussion immediately following Proposition 4, with incentive-compatible enforcement, all firms choose the same emissions violation, whether it is a zero violation when $p \leq f'(0)$, or the same positive violation when this condition does not hold.

13 Our discussions of the implications for targeted monitoring and setting penalties apply as well to enforcement without self-reporting. However, the suggestions that we make in subsections 4.2 and 4.3 have not, to our knowledge, been presented elsewhere.

Therefore, in cases when a regulator can ensure truthful reports, there is no variation in violations, and hence, there is no role for differentiated monitoring effort.

Let us now consider perfect enforcement of a transferable permit system without self-reporting to see if we can identify other potential benefits of the self-reporting requirement. Assume that in the absence of a self-reporting requirement, an enforcement authority bases its choice of audit probability on the number of permits a firm holds; thus a firm is audited with probability $\pi(I)$. Presuming perhaps that a firm with fewer permits is more likely to be non-compliant, let us assume that $\pi(I)$ is non-increasing. Then:

Proposition 5: *In a transferable emissions permit system without a self-reporting requirement, a firm is compliant if and only if* $p \leq \pi(l)f'(0)$.

Versions of this result have been presented elsewhere (Malik 1990; vanEgteren and Weber 1995; Stranlund and Dhanda 1999) so we have relegated its proof to the appendix.

As in the case of a self-reporting requirement, complete emissions compliance without self-reporting can be achieved only if $p \leq f'(0)$. Assume satisfaction of this condition under both regimes. From Proposition 4, define $\pi^r = \pi(0) = p/[g'(0) + f'(0)]$ as the minimum audit probability necessary to achieve complete emissions compliance with a self-reporting requirement, given fixed marginal penalties. From Proposition 5, the corresponding audit probability without self-reporting is $\pi^{nr} = p/f'(0)$. In both cases, if penalties are applied uniformly across firms, audit probabilities should also apply uniformly across firms—there is no role for targeting monitoring effort at different firms.

Since π^r and π^{nr} differ only in the application of a marginal penalty for a slight reporting violation, $g'(0)$, without this penalty the monitoring requirement under both regimes is the same. Therefore, the self-reporting requirement does not affect monitoring costs in the absence of a penalty for reporting violations. On the other hand, if a penalty for reporting violations is available, the minimum audit probability necessary to achieve full emissions compliance is less with a self-reporting requirement. Therefore, assuming that the cost of an audit is the same with and without the self-reporting requirement, the application of a penalty for reporting violations in addition to a penalty for emissions violations implies that a self-reporting requirement can lower the costs of monitoring for complete emissions compliance.

Let us briefly examine how the monitoring expenditure saved by the self-reporting requirement varies with key parameters. Let the number of firms under a transferable permit system be n, and suppose for simplicity that the cost of an audit under both regimes is w. The value of the self-reporting requirement that is due to lower monitoring costs is then $wn(\pi^{nr} - \pi^r)$. Substituting $\pi^r = p/[g'(0) + f'(0)]$ and $\pi^{nr} = p/f'(0)$ yields

$$wn(\pi^{nr} - \pi^r) = wpn\left[\frac{g'(0)}{f'(0) * [g'(0) + f'(0)]}\right] \tag{12}$$

as the value of the self-reporting requirement.

Because fewer firms need to be audited with a self-reporting requirement, the value of the requirement is increasing in the cost of an audit. Equation (12) also indicates that the value of the self-reporting requirement is increasing in the equilibrium permit price. Since the equilibrium permit price is an indicator of the difficulty of meeting an aggregate emissions standard, the value of a self-reporting requirement is increasing in the stringency of the aggregate emissions standard, and the difficulty with which firms reduce their emissions (i.e., their marginal abatement costs).

The value of the self-reporting requirement is also increasing in the number of firms, in part because the additional number of firms that need to be audited in the absence of a self-reporting requirement, $n\pi^{nr} - n\pi^{r}$, is increasing in the number of firms. In addition, as long as the aggregate number of permits in circulation remains constant, there is an indirect price effect because more firms put upward pressure on the equilibrium permit price, which in turn increases the relative value of a self-reporting requirement.

Finally, it is easy to show that (12) is increasing in $g'(0)$ and decreasing in $f'(0)$. Since the value of a self-reporting requirement stems from the regulator's ability to apply penalties for reporting violations in addition to penalties for emissions violations, the value of the self-reporting requirement is increasing in the marginal penalty for a small reporting violation. On the other hand, because penalties for emissions violations are applied under both regimes, the value of the self-reporting requirement is decreasing in the marginal penalty for a slight emissions violation.

4.2. Targeting Monitoring Effort in Transferable Emissions Permit Systems

We have indicated at a number of points in the analysis that the requirements for effective enforcement do not depend on anything specific to particular firms. The enforcement strategy that we propose is tied to the equilibrium permit price rather than to individual marginal control costs. This is due to the equilibrating nature of frictionless and competitive transferable permit systems: in any equilibrium, each firm equates its marginal abatement cost to the permit price, and hence, the firms' marginal abatement costs are all equal. In equilibrium, there is simply no heterogeneity in the firms' marginal abatement costs that a regulator can use to target its monitoring effort. This implies that as long as firms face the same permit price and penalties are fixed and applied uniformly, monitoring should also be uniform; each firm should be audited with the same probability. This suggests further that knowledge of the firms' marginal abatement costs is not relevant for the design of an effective enforcement strategy. Thus, the fact that firms are likely to be better informed about their control costs than a regulator has no bearing on the regulator's choice of enforcement strategy.

The same is not true of enforcing emissions standards. When faced with an emissions standard, the benefit to a firm of non-compliance is the emissions-control costs it would have to incur to be compliant; therefore, a firm's marginal abatement cost function indicates exactly its marginal benefit of non-compliance. In fact, given fixed penalties that are applied uniformly, a firm with high marginal abatement costs is more likely to be non-compliant. Thus, to minimize the monitoring costs of achieving full compliance to emissions standards, a regulator will want to target more of its monitoring effort at firms with higher marginal abatement costs. Of course, to target monitoring perfectly, a regulator must have perfect knowledge of the marginal abatement costs of all regulated firms. In most cases, this information will be impossible to obtain.[14]

The result that effective enforcement of a transferable permit system does not require targeted monitoring depends on the result that all firms face the same price for an emissions permit. However, if there are significant transaction costs associated with trading permits, firms may face different effective prices. A transactions cost that varies with the number of permits transferred between a buyer and a seller drives a wedge between the price a buyer pays for an emissions permit and the price a seller receives (Stavins 1995). Consequently, buyers of permits have a greater incentive to be noncompliant than sellers. Thus, effective enforcement in the presence of transaction costs would likely involve monitoring buyers of permits more closely than sellers.

Another imperfection that might cause a regulator to seek a targeted monitoring strategy is the case in which a firm has market power in a transferable permit system. In a model of a dominant firm and a competitive fringe that is based upon Hahn's (1984) work, van Egteren and Weber (1996) show that the initial allocation of permits to the dominant firm can affect the compliance decisions of all firms. The authors obtained their results under the assumption of a fixed enforcement strategy that is insufficient to generate complete emissions compliance. However, their analysis suggests that effective enforcement in the presence of market power will likely involve targeted monitoring according to whether or not a firm has market power, as well as the initial allocation of permits.

4.3. Setting Penalties in Transferable Emissions Permit Systems

A particularly attractive feature of competitive transferable permit systems is that they are expected to adjust more easily to a variety of changes than other emissions-control policies. Changes in firms' marginal control costs, technological advance, industry growth and decline, and inflationary pressures are accommodated automatically by a transferable permit system through changes in the equilibrium permit price. In contrast, emissions taxes and standards that are designed to meet an aggregate emissions target must be adjusted constantly in response to these changes. (Hanley, Shogren and White 1997, pp. 94–95; Baumol and Oates 1988, p. 178). However, since effective enforcement of a competitive transferable permit system requires $p = \pi(0)[g'(0) + f'(0)]$, if the penalties are fixed, $\pi(0)$ must be tied directly to the equilibrium permit price, and hence, must keep pace with its fluctuations. This may be a difficult task for a regulator.

It may be more sensible to tie marginal penalties directly to the equilibrium permit price so that the monitoring requirement can be stabilized. For example, suppose that the marginal penalty for a reporting violation is chosen to be $g'(e - r) = \gamma p$, where $\gamma > 0$, and the marginal penalty for an emissions violation is $f'(e - l) = \phi p$, where $\phi \geq 1$ to satisfy the

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14 This difference between enforcing emissions standards and transferable permit systems also holds in a different policy context. Garvie and Keeler (1994) show that a budget-constrained regulator that wants to maximize compliance to emissions standards should direct more monitoring effort at firms with high marginal abatement costs. Stranlund and Dhanda (1999) apply the model of Garvie and Keeler to the enforcement of a transferable permit system and find that enforcement targeting based on marginal abatement costs is not productive.

requirement that $p \leq f'(0)$. From the requirement that $p \leq \pi(0)[g'(0) + f'(0)]$, a constant audit probability $\pi = 1/(\gamma + \phi)$ will guarantee accurate emissions reports and complete emissions compliance, and is independent of fluctuations of the equilibrium permit price. This particular suggestion may be somewhat simplistic because, if the compliance period is long enough, say one year as in the SO_2 Allowance Trading and RECLAIM programs, permit prices will fluctuate to some degree during the year but marginal penalties need to be tied to a single price. In practice, penalties could be tied to some average price during the year; for example, the regulation may include a provision that the penalties in a given year will be some constant multiple of the highest of the average monthly prices during the year. Choosing the highest average monthly price will provide a stronger deterrent against noncompliance than, say, the simple average price during the year.

Our recommendation to tie marginal penalties to the equilibrium permit price corresponds well with suggestions that penalties for violations of environmental regulations be based on the economic gain of the violation to the offender (Wasserman 1992; for a discussion see Cohen 1999, section 3.5). Since the equilibrium permit price is the marginal cost for a firm to achieve full emissions compliance, it also represents the marginal gain from being non-compliant. Gain-based penalties are usually considered to enforce emissions standards, but there is a major difference between applying the gain-based criterion to enforce standards and to enforce transferable permits. A gain-based penalty for violations of emissions standards requires that the enforcement authority estimate the violators' marginal control costs on a case-by-case basis. For transferable permits the enforcement authority need only observe the equilibrium permit price. In most cases, the latter information will be much easier to obtain.

Of course, tying marginal penalties to the permit price depends on the existence of a relatively efficient permit market; a market in which a large number of trades take place at roughly the same price. In thin markets in which trades may take place at widely divergent prices, our suggestion has less appeal because it may be difficult to identify a single price upon which to set penalties. The suggestion may also be problematic in markets in which some set of firms can exercise some influence on the market price. If penalties are tied to the permit price, then firms with market power will be able to exert influence on the resulting penalties as well. It is not clear how our suggestion may fare in the presence of market power, but we think it is an important issue to explore in the future.

5. Conclusion

We have developed a number of new results that should be helpful in the design of enforcement strategies for market-based environmental policies. We have shown that a self-reporting requirement can conserve monitoring costs, not because it allows for targeted monitoring as in the context of enforcing emissions standards, but because it allows the application of a penalty for a reporting violation that serves as an additional deterrent to non-compliance. We have also noted that there appears to be no justification for targeted monitoring as long as the permit market is truly competitive. Additional analysis is necessary to identify the appropriate place for targeted monitoring in the presence of significant transaction costs and market power. Lastly, we have suggested that policymakers consider tying penalties in transferable permit systems to the current equilibrium price of permits. Doing so would allow enforcement authorities to choose a monitoring strategy that is effective, yet independent of permit market fluctuations.

Of course, our analysis can and should be extended in a number of directions. We have mentioned a number of these throughout the paper that we feel are the most important. Pursuing these and other extensions will provide policymakers with a more complete conceptual foundation for designing enforcement strategies for market-based policies that achieve acceptable levels of compliance in a cost-effective manner.

Appendix

Proof of Proposition 5: *In the absence of a self-reporting requirement a firm chooses its emissions and permits to*

$$\begin{aligned}&\min\ c(e) + p(l - l_0) + \pi(l)f(e - l),\\ &s.t.\ e \geq l > 0.\end{aligned}$$

The Lagrange equation is $\theta = c(e) + p(l - l_0) + \pi(l)f(e - l) - \eta(e - l)$*. Assuming* $l > 0$*, the Kuhn-Tucker conditions are*:

$$\theta_e = c'(e) + \pi(l)f'(e - l)] - \eta = 0; \quad (A.1)$$

$$\theta_l = p + \pi'(l)f(e - l) - \pi(l)f'(e - l) + \eta = 0; \quad (A.2)$$

$$\theta_\eta = l - e \leq 0, \eta \geq 0, \eta \times (l - e) = 0. \quad (A.3)$$

If a firm is compliant, (A.2) becomes $\theta_l = p - \pi(l)f'(0) + \eta = 0$*. Since* $\eta \geq 0$*, a firm is compliant only if* $p - \pi(l)f'(0) \leq 0$*. Furthermore, suppose that* $e > l$ *while* $p - \pi(l)f'(0) \leq 0$*. Since* $e > l, \eta = 0$*. Furthermore,* $e > l$ *and* $p - \pi(l)f'(0) \leq 0$ *imply* $p - \pi(l)f'(e - l) < 0$*. Therefore, since* $\pi'(l) \leq 0, \theta_l = p + \pi'(l)f(e - l) - \pi(l)f'(e - l) < 0$*, indicating that non-compliance is a sub-optimal choice when* $p - \pi(l)f'(0) \leq 0$*. Thus, given* $\pi'(l) \leq 0$*, a firm is compliant if and only if* $p - \pi(l)f'(0) \leq 0$*. Q.E.D.*

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