Environmental and Resource Economics **25:** 65–78, 2003.

Enforcing Transferable Permit Systems in the Presence of Market Power

CARLOS A. CHAVEZ[1] and JOHN K. STRANLUND[2,*]
[1] *Department of Economics, Universidad de Concepcion, Chile;* [2] *Department of Resource Economics, Stockbridge Hall, University of Massachusetts, 80 Campus Center Way, Amherst MA 01003-9246, USA (*Corresponding author: E-mail: stranlund@resecon.umass.edu.)*

Accepted 29 October 2002

Abstract. We derive an enforcement strategy for a transferable permit system in the presence of market power that achieves complete compliance in a cost-effective manner. We show that the presence of a firm with market influence makes designing an enforcement strategy more difficult than enforcing a perfectly competitive system. We also re-consider Hahn's (1984) suggestion that a firm with market influence should be allocated permits so that it chooses to not participate in the permit market. When enforcement and its costs are taken into account, Hahn's suggestion does not hold except in a very special case.

Key words: compliance, emissions trading, enforcement, environmental policy, market power, transferable permits

JEL classification: L51, Q28

1. Introduction

The presence of market power will limit the extent to which transferable emissions permit systems can fulfill their theoretical promises. Hahn (1984) was the first to show that permit trading in the presence of market power cannot be expected to result in a distribution of emissions that minimizes aggregate abatement costs. Furthermore, the distribution of emissions will never be completely independent of the initial allocation of permits. Modeling a transferable permit system in which one firm has market power while the rest are perfect competitors (a dominant firm/competitive fringe model), Hahn demonstrated that aggregate abatement costs are minimized only when the dominant firm is allocated exactly the number of permits it will choose to hold in equilibrium. Simply, aggregate abatement costs are minimized only when a firm that can manipulate the permit price does not because it chooses to not trade permits.

Like most of the theoretical literature on transferable permit systems, Hahn ignored the fact that compliance in a permit system must be enforced. Recognizing this important omission, van Egteren and Weber (1996) extended Hahn's work to examine compliance choices in the same context, and found that the exercise of market power is likely to affect the compliance decisions of all firms.[1] Furthermore, since a powerful firm's initial allocation of permits determines in large measure its ability to manipulate a permit market, the initial allocation of permits will also impact compliance behavior throughout a transferable permit system.

In this paper we examine compliance and enforcement in an emissions trading program with market power in a way that complements the work of van Egteren and Weber. While they chose to treat enforcement as exogenous and concentrate on how the exercise of market power affects compliance choices, we treat enforcement as endogenous to examine how enforcing a permit system with market power is different from enforcing a competitive permit system. Furthermore, to re-consider Hahn's suggestion that a firm with market influence should be allocated permits so that it chooses to not participate in the permit market, we examine how endogenous enforcement effort and costs affect the regulatory choice of the initial allocation of permits. While van Egteren and Weber's analysis makes it clear that the initial distribution of permits in the presence of market power will have a significant impact on the compliance decisions of all firms in a permit system, they do not address directly whether Hahn's prescription continues to hold when enforcement and its costs are taken into account. We find that, except in a very special case, aggregate abatement costs and enforcement costs can be balanced in an efficient manner if the dominant firm participates in the permit market.

2. Enforcing a Transferable Permit System in the Presence of Market Power

In this section we derive an enforcement strategy for a dominant firm/competitive fringe model that is a straightforward extension of our work on enforcing competitive transferable permit systems (Stranlund and Chavez 2000). We derive an enforcement strategy, including a self-reporting requirement, that achieves complete compliance in the cheapest manner possible.[2] Our primary purpose here is to show how enforcing a transferable permit system in the presence of market power differs from enforcing a perfectly competitive system.

Throughout we consider a fixed set of n risk-neutral firms operating under a transferable emissions permit system. Firm 1 can influence the market for emissions permits, while firms $i = 2, \dots, n$ are price takers in this market. Let $c_j(e_j)$ be firm j's abatement cost function and assume that it is strictly decreasing and convex in the firm's actual emissions e_j; that is, $c_j'(e_j) < 0$ and $c_j''(e_j) > 0$. (Throughout we will index the set of all firms by j and reserve i to index firms in the competitive fringe). An enforcer cannot observe a firm's actual emissions e_j without an audit. However, each firm j is required to provide a costless report r_j of its emissions to the enforcer.

Each firm is also required to hold an emissions permit for each unit of emissions it releases. Let l_j^0 be the number of permits that are initially allocated to firm j, and let l_j be the number of permits that it chooses to hold after trade. Throughout, we assume that the total number of permits L is fixed, and that an enforcer can readily observe l_j^0 and l_j for each j.

In a permit market equilibrium, all trades take place at a single price p. However, the dominant firm 'sets' this price by its choice of how many permits it makes available to the competitive fringe. That is, permits trade at price $p = p(L - l_1)$. Later we will show that $p' < 0$.

There are two ways in which a firm can be non-compliant. First, an emissions violation occurs whenever a firm's emissions exceed the number of permits it holds ($e_j > l_j$). Second, a reporting violation occurs whenever a firm's actual emissions exceed its reported emissions ($e_j > r_j$). If a firm is fully compliant, it reports its emissions truthfully and holds enough permits to cover these emissions ($e_j = r_j = l_j$). A firm will never have an incentive to report that its emissions are greater than they actually are, or that its emissions are less than the number of permits it holds. At the outset, therefore, we restrict each firm j's choices to $e_j \geq r_j \geq l_j$. In addition, we assume that $l_j > 0$ for each j.

Enforcement consists of audits to determine a firm's actual emissions, as well as penalties for emissions and reporting violations. We assume that an audit of a firm reveals its true level of emissions. Let the probability that firm j is audited be π_j, which the enforcer may choose to vary by firm. In contrast, penalties are applied uniformly. Following Harford (1987), a penalty $f(r_j - l_j)$ is automatically imposed on firm j if it reports an emissions violation ($r_j - l_j > 0$). If an audit of the firm reveals that it has under-reported its emissions, a penalty $g(e_j - r_j)$ is imposed for the reporting violation ($e_j - r_j > 0$), as well as an incremental penalty of $f(e_j - l_j) - f(r_j - l_j)$ for that part of its emissions violation that the firm did not report. Penalties are zero for zero emissions and reporting violations [$f(0) = g(0) = 0$], but marginal penalties for zero emissions and reporting violations are greater than zero [$f'(0) > 0$ and $g'(0) > 0$]. Penalties for both emissions and reporting violations are increasing at an increasing rate in the size of the violation.

We are now ready to examine how firms choose their emissions, emissions reports, and permit holdings. We will focus on the dominant firm's compliance choices and refer the analysis of the choices of the competitive firms to our previous work (Stranlund and Chavez 2000). Assuming that the enforcer commits itself to a strategy and communicates this strategy to each firm, the dominant firm chooses its emissions, its emissions report, and its permit holdings to minimize its expected compliance costs, taking the enforcement strategy as given:

$$\begin{aligned} &\mathit{min}\ c_1(e_1) + p(L - l_1) \times (l_1 - l_1^0) + f(r_1 - l_1) \\ &+\pi_1 \times [g(e_1 - r_1) + f(e_1 - l_1) - f(r_1 - l_1)] \\ &s.t.\ e_1 \geq r_1 \geq l_1 > 0. \end{aligned} \tag{1}$$

The Lagrange equation for (1) is $\mathcal{L} = c_1(e_1) + p(L - l_1) \times (l_1 - l_1^0) + f(r_1 - l_1) + \pi_1 \times [g(e_1 - r_1) + f(e_1 - l_1) - f(r_1 - l_1)] - \beta_1(e_1 - r_1) - \mu_1(r_1 - l_1)$, and the Kuhn-Tucker conditions are:

$$\mathcal{L}_e = c_1'(e_1) + \pi_1 \times [g'(e_1 - r_1) + f'(e_1 - l_1)] - \beta_1 = 0; \tag{2a}$$

$$\begin{aligned}\mathcal{L}_l &= -p'(L-l_1)\times(l_1-l_1^0)+p(L-l_1)-f'(r_1-l_1)\\ &\quad +\pi_1\times[f'(r_1-l_1)-f'(e_1-l_1)]+\mu_1=0; \qquad (2b)\\ \mathcal{L}_r &= f'(r_1-l_1)-\pi_1\times[g'(e_1-r_1)+f'(r_1-l_1)]+\beta_1-\mu_1=0; \qquad (2c)\\ \mathcal{L}_\beta &= r_1-e_1\leq 0,\ \beta_1\geq 0,\ \beta_1\times(r_1-e_1)=0; \qquad (2d)\\ \mathcal{L}_\mu &= l_1-r_1\leq 0,\ \mu_1\geq 0,\ \mu_1\times(l_1-r_1)=0. \qquad (2e)\end{aligned}$$

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

To derive an enforcement strategy that guarantees complete compliance in the cheapest possible manner, we must determine the necessary and sufficient conditions for each firm to choose full compliance. That part of the following proposition that focuses on the dominant firm is proved in the Appendix. Stranlund and Chavez (2000) provide the analogous proof for the firms in the competitive fringe.

PROPOSITION 1: *The following is a sufficient condition for the dominant firm to provide a truthful report of its emissions, whether it holds enough permits to cover its emissions or not:*

$$p(L-l_1)-p'(L-l_1)\times(l_1-l_1^0)\leq\pi_1\times[g'(0)+f'(0)]. \qquad (3)$$

Furthermore, (3) *is a necessary condition for the firm to hold enough permits to cover its emissions. Given* (3), *and hence the dominant firm submits a truthful emissions report, it chooses to hold enough permits to cover its emissions if and only if*

$$p(L-l_1)-p'(L-l_1)\times(l_1-l_1^0)\leq f'(0). \qquad (4)$$

Similarly, a firm i in the competitive fringe will provide a truthful emissions report if

$$p(L-l_1)\leq\pi_i\times[g'(0)+f'(0)], \qquad (5)$$

and will choose complete emissions compliance only if (5) *is satisfied. Given* (5), *it chooses complete emissions compliance if and only if*

$$p(L-l_1)\leq f'(0). \qquad (6)$$

The enforcement strategy that generates complete emissions compliance in the cheapest manner possible is given by the following equations:

$$\pi_1^{min} = \frac{p(L-l_1)-p'(L-l_1)\times(l_1-l_1^0)}{g'(0)+f'(0)}; \qquad (7)$$

$$\pi_i^{min} = \frac{p(L-l_1)}{g'(0)+f'(0)},\quad i=2,\ldots,n; \qquad (8)$$

$$f'(0)\geq max[p(L-l_1),\ p(L-l_1)-p'(L-l_1)\times(l_1-l_1^0)]. \qquad (9)$$

Equations (7) and (8) are taken from equations (3) and (5) of Proposition 1, respectively. They specify minimal amounts of monitoring that guarantee that each firm provides truthful emissions reports. Equation (9) combines (4) and (6), and guarantees complete emissions compliance by every firm, provided that they have the proper incentives to reveal their true levels of emissions.

Let us assume that equation (9) is satisfied and focus on the implications of the monitoring strategy specified by (7) and (8). In a perfectly competitive setting, equation (8) would fully characterize an effective monitoring strategy. Note that since the penalty schedules apply uniformly to all firms and competitive firms face the same permit price, there is nothing specific about individual firms that is necessary to determine the appropriate monitoring strategy. This has two implications. First, given the trivial requirement that the enforcer knows the penalty functions, the enforcer need only observe the prevailing permit price – information about firms' abatement costs is not useful. Second, provided that penalties are applied uniformly, competitive firms in a transferable permit system should be monitored with the same probability.

These desirable characteristics largely disappear when we add a firm with market influence to the mix. First, the information requirements for monitoring in a dominant firm/competitive fringe environment are more demanding than in a perfectly competitive environment. Equation (7) reveals that the enforcer must determine $p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0)$ to set $\pi_1^{\min}$. The prevailing permit price, the dominant firm's permit holdings, and its initial allocation of permits will be readily available, but determining the dominant firm's marginal impact on the permit price will be problematic. Explicitly,

$$p'(L - l_1) = -\left(\sum_{i=2}^{n}(1/c_i'')\right)^{-1} < 0.^3 \tag{10}$$

Calculating $p'(L - l_1)$ requires knowledge of the abatement costs of the firms in the competitive fringe, which, in many cases, will be hidden from an enforcer.[4]

In contrast to the finding that there is no reason to target enforcement in perfectly competitive settings, a comparison of (7) and (8) makes it clear that when market power is present the dominant firm should be monitored differently than the competitive firms. In fact, if the firm is a net buyer of permits so that $l_1 > l_1^0$, then $p(L - l_1) < p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0)$. This suggests that when the dominant firm is a net buyer of permits it has a stronger incentive to be non-compliant than the competitive firms. Therefore, it should be monitored more closely. When the dominant firm is a net seller of permits it has a lower incentive to be non-compliant than the competitive firms, and therefore does not need to be monitored as closely.

These results have practical importance because they suggest to enforcers that firms that can influence permit market outcomes should be treated differently. This may be more critical with firms that can exercise power in the permit market and do so by buying permits. A uniformly applied enforcement strategy that induces compliance from competitive firms may not provide the proper compliance incentives to influential buyers of permits. On the other hand, firms that manipulate permit prices by selling permits will be deterred by any strategy that is effective in inducing compliance by perfectly competitive firms. In this situation, there may be an opportunity to conserve enforcement resources by spending less on ensuring the compliance of an influential seller of permits. The extent to which the enforcer is able to do so and still provide adequate incentives for compliance depends upon whether it can obtain the information necessary to calculate the influence of the dominant firm's permit transactions on prevailing permit prices.[5]

3. Aggregate Program Costs and the Initial Allocation of Permits

Having specified an effective enforcement strategy for a transferable permit system in the presence of market power, we now turn our attention to the initial allocation of permits. Our primary motivation in this section is to consider whether Hahn's prescription to allocate permits to the dominant firm so that it chooses to not trade permits continues to hold when enforcement and its costs are taken into account. Throughout we assume that the enforcer is able to commit itself to the enforcement strategy given by (7), (8), and (9). This means that the enforcer is able to overcome the information difficulties of monitoring the dominant firm. In fact, like Hahn and van Egteren and Weber, we assume that a regulator has complete information about all firms' abatement costs. Furthermore, since the enforcement strategy generates complete compliance, no penalties are collected, and the only costs of enforcing the program are the monitoring costs. To simplify the analysis we assume quadratic abatement costs for each firm.

We first consider monitoring costs. The effect of the initial allocation of permits to the dominant firm on monitoring will work through the firm's demand for permits and the resulting impact on the permit price. By combining the Kuhn-Tucker conditions (2a), (2b), and (2c) it is straightforward to show that the dominant firm chooses its emissions so that $p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0) + c_1'(e_1) = 0$. Referring to equation (10), the assumption of quadratic abatement costs implies that the demand function of the competitive fringe has a constant slope, which we will denote simply as p'. Furthermore, because the enforcement strategy induces the dominant firm to be fully compliant, $e_1 = l_1$. Therefore,

$$p(L - l_1) - p' \times (l_1 - l_1^0) + c_1'(l_1) = 0 \tag{11}$$

implicitly defines $l_1(l_1^0)$, the dominant firm's demand for permits as a function of its initial allocation. From (11) we can obtain

$$l_1'(l_1^0) = \frac{-p'}{c_1'' - 2p'} \in (0, 1/2). \tag{12}$$

This indicates that if the dominant firm receives more permits initially, it will choose to hold more permits, but only less than half of the additional allocation. Note that $l_1'(l_1^0)$ is a constant.

The impact of l_1^0 on the equilibrium permit price is determined from $p(L - l_1(l_1^0))$:

$$\partial p/\partial l_1^0 = -p' \times l_1'(l_1^0) > 0. \tag{13}$$

If the dominant firm receives a larger allocation of permits from a fixed stock, it will choose to hold a greater number of permits. Since fewer permits would then be available to the competitive fringe, the equilibrium permit price increases.

The monitoring strategy given by equations (7) and (8) can be written as functions of the initial allocation of permits to the dominant firm; that is and $\pi_1^{min}(l_1^0)$, and $\pi_i^{min}(l_1^0)$, $i = 2, \ldots, n$. The marginal impact of the firm's initial allocation on the required monitoring strategy is:

$$\begin{aligned}\frac{\partial \pi_1^{min}}{\partial l_1^0} &= \frac{-p' \times l_1'(l_1^0) - p' \times (l_1'(l_1^0) - 1)}{g'(0) + f'(0)} \\ &= \frac{-p' \times [2l_1'(l_1^0) - 1]}{g'(0) + f'(0)} < 0;\end{aligned} \tag{14}$$

$$\frac{\partial \pi_i^{min}}{\partial l_1^0} = \frac{\partial p/\partial l_1^0}{g'(0) + f'(0)} = \frac{-p' \times l_1'(l_1^0)}{g'(0) + f'(0)} > 0 \quad i = 2, \ldots, n. \tag{15}$$

The sign of (14) follows from $p' < 0$ and (12), while the sign of (15) follows from (13). These marginal effects yield the following proposition:

PROPOSITION 2: *An increase* (*decrease*) *in the dominant firm's initial allocation of permits implies that the firm should be monitored less* (*more*) *closely, while the firms in the competitive fringe should be monitored more* (*less*) *closely.*

Since allocating more permits from a fixed stock to the dominant firm increases the permit price for firms in the competitive fringe, the amount of monitoring necessary to keep them fully compliant must also increase. On the other hand, $p(L - l_1(l_1^0)) - p' \times (l_1(l_1^0) - l_1^0)$ is decreasing in l_1^0, implying that the dominant firms needs to be monitored less closely when it is allocated a greater number of permits from a fixed stock. van Egteren and Weber (1996) found a similar result treating enforcement as exogenous. Paraphrasing their Propositions 1 and 2 (pp. 168–169): Given a fixed enforcement strategy, the dominant firm will tend toward lower violations if it receives a larger initial allocation of permits from a fixed stock, while the rest of the firms will tend toward greater levels of non-compliance. Our Proposition 2 is complementary in that we have characterized how the monitoring strategy necessary to keep all firms compliant must change as the initial allocation of permits to the dominant firm changes.

We are now ready to determine how the initial allocation of permits to the dominant firm affects aggregate monitoring costs.[6] Assuming that the cost of an audit is a constant w, aggregate monitoring costs as a function of the initial allocation of permits to the dominant firm are $M(l_1^0) = w[\pi_1^{min}(l_1^0) + (n - 1)\pi_i^{min}(l_1^0)]$.

Differentiating with respect to l_1^0, substituting (14) and (15), and collecting terms yields

$$M'(l_1^0) = \frac{-wp'}{g'(0) + f'(0)}[(n+2)l_1'(l_1^0) - 1]. \tag{16}$$

First note that $M'(l_1^0)$ is a constant. Furthermore, since the first term of (16) is positive, the sign of $M'(l_1^0)$ is the same as the sign of $(n+2)l_1'(l_1^0) - 1$. Using equation (12), it can be shown that the sign of $(n+2)l_1'(l_1^0) - 1$ is the same as the sign of $-(p'n + c_1'')$. Therefore, whether monitoring costs are increasing or decreasing in the initial allocation of permits to the dominant firm depends in straightforward way on the extent of the firm's influence on permit prices (p'), the slope of the firm's marginal abatement costs (c_1''), and the number of firms in the system (n).

We now turn our attention to aggregate abatement costs. Recall from equation (11) that the dominant firm's demand for permits, $l_1(l_1^0)$, is implicitly defined by $p(L - l_1) - p' \times (l_1 - l_1^0) + c_1'(l_1) = 0$. In the same fashion, the demand by a firm in the competitive fringe when it is fully compliant is $l_i(l_1^0) = l_i(p(L - l_1(l_1^0)))$, which is implicitly determined by $p(L - l_1(l_1^0)) + c_i'(l_i) = 0$. Aggregate abatement costs are therefore $A(l_1^0) = c_1(l_1(l_1^0)) + \sum_{i=2}^{n} c_i(l_i(l_1^0))$. Differentiate this with respect to l_1^0 and substitute $c_1'(l_1(l_1^0)) = -[p(L - l_1(l_1^0)) - p' \times (l_1(l_1^0) - l_1^0)]$ and $c_1'(l_i(l_1^0)) = -p(L - l_1(l_1^0))$ to obtain

$$\begin{aligned} A'(l_1^0) &= p' \times (l_1(l_1^0) - l_1^0) \times l_1'(l_1^0) - p(L - l_1(l_1^0)) \times \sum_{j=1}^{n} l_j'(l_1^0) \\ &= p' \times l_1'(l_1^0) \times (l_1(l_1^0) - l_1^0). \end{aligned} \tag{17}$$

Note that $\sum_{j=1}^{n} l_j'(l_1^0) = 0$ because the aggregate stock of permits is fixed. Furthermore, recalling that p' is a negative constant and that $l_1'(l_1^0)$ is a constant between zero and one-half (equation (12)), $A''(l_1^0) = p' \times l_1'(l_1^0) \times ((l_1^0) - 1) > 0$. Hence, aggregate abatement costs are strictly convex in l_1^0. Hahn's (1984) result that aggregate abatement costs are minimized only when the dominant firm does not trade permits is easily confirmed by (17), where $A'(l_1^0) = 0$ if and only if $l_1(l_1^0) = l_1^0$.

However, allocating permits to the dominant firm so that it does not trade will not minimize the sum of abatement costs and monitoring costs, $A(l_1^0) + M(l_1^0)$. Since aggregate abatement costs are strictly convex in l_1^0 and monitoring costs are weakly convex (since $M'(l_1^0$ is a constant), total program costs are strictly convex. Therefore, the allocation of permits to the dominant firm that minimizes total program costs is determined uniquely by the marginal condition $A'(l_1^0) = -M'(l_1^0)$. Our last proposition follows from this condition.

PROPOSITION 3: *The initial allocation of permits to the dominant firm should be such that the firm is a net buyer* (*seller*) *of permits if and only if* $M'(l_1^0) > 0$ (< 0).

The allocation of permits to the dominant firm should be such that it chooses to not trade permits if and only if $M'(l_1^0) = 0$.

Proof: Using equation (17), $A'(l_1^0) = -M'(l_1^0)$ can be rewritten as $l_1(l_1^0) - l_1^0 = -M'(l_1^0)/p' \times l_1'(l_1^0)$. Since $p' \times l_1'(l_1^0)$ is negative, the sign of $l_1(l_1^0) - l_1^0$ is the same as the sign of $M'(l_1^0)$. The proposition follows from this relationship. QED

Proposition 3 implies that Hahn's suggestion – the dominant firm should be allocated permits so that it chooses to not participate in the market – holds only when its initial allocation has no effect on monitoring costs. In all other cases its market influence can be exploited to reduce total program costs. Whether the firm should be a buyer or seller of permits depends directly on whether monitoring costs are increasing or decreasing in the firm's initial allocation. If monitoring costs are increasing in l_1^0, Proposition 3 calls for allocating a smaller share of permits to the dominant firm so that it chooses to purchase permits. When monitoring costs are decreasing in the dominant firm's permit allocation, it should be allocated a larger share of permits so that it is motivated to sell part of its initial allocation.[7]

In general, therefore, the exercise of market power is not entirely undesirable. Thus, the motivation to use the initial distribution of permits to minimize aggregate abatement costs by making sure that powerful firms do not trade permits should be balanced against our finding that market power can be exploited to reduce enforcement costs.

Since the efficient initial distribution of permits is likely to result in permit trading by the dominant firm, the final allocation of permits will not equalize marginal abatement costs – the marginal abatement costs of all the price-taking firms will be equal, but the marginal abatement costs of the dominant firm will be higher or lower depending on whether the firm is a net buyer or seller of permits. This has implications for empirical analyses of the inefficiency due to market power, which typically compare an after-trade equilibrium distribution of permits to the distribution that equates marginal abatement costs.[8] Our results suggest that when enforcement costs are taken into account, efficiency is not a simple matter of equating marginal abatement costs. Analyses that use this outcome as a benchmark ignore an important component of the costs of transferable permit systems that, if included, could significantly alter results about the inefficiency of market power.

Although we have focused on using the initial allocation of permits to minimize total program costs, we need to recognize that doing so will not be a trivial undertaking. On the issue of implementation, Hahn's prescription and ours are identical. Both prescriptions have the same demanding information requirements. A regulator must know which firm (or firms) can exert influence in the permit market. Furthermore, to determine the exact nature of this influence and how it affects enforcement and aggregate abatement costs, the regulator must know every firm's marginal abatement cost function.[9] Both prescriptions would also have to overcome the tendency to allocate permits by some sort of grandfathering rule. Since neither Hahn's prescription nor ours have anything to do with historic rates of emissions, they would likely be opposed by firms that might argue that grandfathering is a fair way to allocate permits while ignoring the efficiency consequences of doing so.

Because of these implementation difficulties, policymakers may be more inclined to pursue options to limit the exercise of market power rather than fine-tuning the initial allocation of permits.[10] For example, Lyon (1982 and 1986) has suggested that emission permits can be allocated with incentive-compatible auctions that eliminate the incentive for powerful firms to manipulate permit prices. However, it is not known whether auctioned permits are likely to be more or less costly to enforce than freely allocated, transferable permits. An analysis of the enforcement requirements for auctioned permits in the spirit of this paper could provide a more complete accounting of the viability of confronting market power problems in this way.

4. Conclusion

Building on Hahn's (1984) analysis of permit systems in the presence of market power and van Egteren and Weber's (1996) extension to allow for non-compliant behavior, we have two new results about enforcing transferable permit systems in the presence of market power. First, our development of an endogenous enforcement strategy that generates complete compliance in a cost-effective manner suggests that, relative to enforcing a perfectly competitive permit system, adding a firm with market influence to the mix makes choosing the appropriate enforcement strategy more difficult. An enforcer must monitor a firm with market influence differently from other firms, depending on whether the firm is a buyer or seller of emissions permits. Furthermore, effective enforcement of a competitive permit system does not require any firm-specific information, while the presence of market power makes information about the competitive firms' marginal abatement costs relevant to an enforcer.

Second, our determination of the initial allocation of permits to the market power firm to minimize enforcement and aggregate abatement costs suggests that it may be desirable for a powerful firm to participate in the permit market. Whether it should do so as a buyer or seller of permits depends on how its endowment of permits affects aggregate monitoring costs. This result stands in direct contrast to Hahn's (1984) prescription to eliminate the inefficiency of imperfect permit trading by making sure that firms with market influence do not trade permits. Our analysis suggests that market influence can be exploited to balance the abatement costs of reaching an aggregate emissions target against the costs of enforcement to make sure that goal is met.

In general, it is clear that the theoretical promises of transferable emissions permit systems must be given careful re-consideration when the potential for non-compliance must be dealt with and the standard assumptions of perfect competition do not hold. Extending the theoretical foundations of designing and managing permit systems to deal with these and other issues will continue to be an important part of the search for efficient environmental policies.

Acknowledgements

We are grateful to Barry Field for his comments in the early stages of this research, and to the referees of this journal for their helpful comments. Partial support for this research was provided by the Cooperative State Research, Extension, and Education Service, U.S. Department of Agriculture, Massachusetts Agricultural Experiment Station, under Project No. MAS00799. Manuscript No. 3323.

Notes

1. Their work was motivated by research on compliance in perfectly competitive permit systems that appeared in the early 1990s (Malik 1990, 1992; Keeler 1991).
2. In Phase I of the SO_2 Allowance Trading Program all firms were perfectly compliant (U.S. EPA 1999, 2000), and nearly so in the RECLAIM program of Southern California (South Coast Air Quality Management District 1998, 2000). Furthermore, self-reporting of emissions is a key component of the enforcement strategies of these programs.
3. It is straightforward to derive $p'(L - l_1)$. Stranlund and Chavez (2000) show that a competitive firm i that faces the enforcement mechanism employed here will choose its emissions so that $p + c_i'(e_i) = 0$. Given effective enforcement so that each firm's emissions are exactly equal to the number of permits it holds, this equation implicitly defines i's demand for permits, $l_i(p)$, with - $l_i'(p) = -1/c_i''$. Aggregate demand for permits by the competitive fringe is $\sum_{i=2}^{n} l_i(p) = L - l_1$, which implicitly defines the equilibrium permit price $p(L - l_1)$. Equation [10] is obtained by differentiating $\sum_{i=2}^{n} l_i(p(L - l_1)) \equiv L - l_1$ with respect to l_1, substituting $l_i'(p) = -1/c_i''$, and rearranging the result. The sign of $p'(L - l_1)$ follows from $c_i'' > 0$ for each i.
4. At least conceptually, it would be possible to design an incentive scheme that simultaneously elicits truthful revelation of emissions and abatement costs. Doing so is beyond the scope of this paper, but would be an interesting topic for further investigation.
5. Our concern about market power is with a firm that seeks to manipulate an emissions permit market. Another related concern has been with the possibility that firms may manipulate permit markets to gain a strategic advantage in output markets (Misiolek and Elder 1989; Innes, Kling and Rubin 1991; Sartzetakis 1997). Our general results are likely to apply in these contexts as well. Firms that use permit markets to influence output competition will have different compliance incentives than perfectly competitive firms, and fine-tuning an enforcement strategy to respond to these incentives will require more information than in competitive settings. Of course, the form of an effective enforcement strategy for this other context will be different. Deriving such a strategy may be an interesting extension of our approach.
6. Although our assumption of quadratic abatement costs is not necessary to prove Proposition 2 – it can be proved by imposing the appropriate second-order condition on the choices of the dominant firm – making this assumption allows us to derive clear results about how the initial allocation affects monitoring costs, and therefore greatly simplifies the following analysis.
7. Although van Egteren and Weber (1996) do not address whether the dominant firm should be allowed to participate in the permit market, in their section 4 they do offer some limited results about how the initial distribution of permits should be chosen. However, they take a very different approach that we believe is also less natural. They assume that the initial distribution of permits to the dominant firm is chosen to minimize net social costs, which consist of aggregate abatement costs, emissions damages, and enforcement costs. To simplify their analysis they

assume that the aggregate stock of permits is chosen to minimize aggregate abatement costs and emissions damages. Furthermore, they assume a fixed enforcement strategy that is not sufficient to generate complete compliance by firms in the competitive fringe. This approach, which is substantially more complicated that ours, does not allow them to fully characterize the optimal initial allocation of permits to the dominant firm as we do.

8. See Tietenberg (1985) for some early examples of this approach, and Westkog (1999) for a more recent analysis.
9. As we suggested in the context of designing an effective enforcement strategy, extending our approach to include an incentive scheme to elicit information about firms' abatement costs may yield useful results about allocating permits in the presence of market power.
10. Certain provisions of the Sulfur Dioxide Trading Program were added because of fears of non-competitive market behavior. These included the EPA's annual allowance auction, and the so-called "Direct Sales Reserve," through which the EPA offered a small number of allowances for sale at a fixed price (Joskow, Schmalensee and Bailey 1998).

References

Hahn, R. (1984), 'Market Power and Transferable Property Rights', *Quarterly Journal of Economics* **99**(4), 753–765.

Harford, J. (1987), 'Self-Reporting of Pollution and the Firm's Behavior under Imperfectly Enforceable Regulations', *Journal of Environmental Economics and Management* **14**(3), 293–303.

Innes, R., C. Kling and J. Rubin (1991), 'Emission Permits Under Monopoly', *Natural Resource Modeling* **5**(3), 321–343.

Joskow, P., R. Schmalensee and E. M. Bailey (1998), 'The Market for Sulfur Dioxide Emissions', *American Economics Review* **88**(4), 669–685.

Keeler, A. (1991), 'Noncompliant Firms in Transferable Discharge Permit Markets: Some Extensions', *Journal of Environmental Economics and Management* **21**(2), 180–189.

Lyon, R. M. (1982), 'Auctions and Alternative Procedures for Allocating Pollution Rights', *Land Economics* **58**(1), 16–32.

Lyon, R. M. (1986), 'Equilibrium Properties of Auctions and Alternative Procedures for Allocating Transferable Permits', *Journal of Environmental Economics and Management* **13**(2), 129–152.

Malik, A. (1990), 'Markets for Pollution Control when Firms are Noncompliant', *Journal of Environmental Economics and Management* **18**(2), 97–106.

Malik, A. (1992), 'Enforcement Costs and the Choice of Policy Instruments for Pollution Control', *Economic Inquiry* **30**(4), 714–721.

Misiolek, W. S. and H. W. Elder (1989), 'Exclusionary Manipulation of Markets for Pollution Rights', *Journal of Environmental Economics and Management* **16**(2), 156–166.

Sartzetakis, E. S. (1997), 'Raising Rivals' Costs Strategies via Emission Permit Markets', *Review of Industrial Organization* **12**(5–6), 751–765.

South Coast Air Quality Management District (1998), *RECLAIM Program Three-Year Audit and Progress Report*. Diamond Bar, CA: South Coast Air Quality Management District.

South Coast Air Quality Management District (2000), *Annual RECLAIM Audit Report for the 1998 Compliance Year*. Diamond Bar, CA: South Coast Air Quality Management District.

Stranlund, J. K. and C. A. Chavez (2000), 'Effective Enforcement of a Transferable Emission Permit System', *Journal of Regulatory Economics* **18**(2), 113–131.

Tietenberg, T. H. (1985), *Emissions Trading: An Exercise in Reforming Pollution Policy*. Washington DC: Resources for the Future.

U.S. Environmental Protection Agency (1999), *Acid Rain Program 1998 Compliance Report*. Washington DC: U.S. EPA Acid Rain Program.

U.S. Environmental Protection Agency (2000), *Acid Rain Program 1999 Compliance Report*. Washington DC: U.S. EPA Acid Rain Program.

van Egteren, H. and M. Weber (1996), 'Marketable Permits, Market Power, and Cheating', *Journal of Environmental Economics and Management* **30**(2), 161–173.

Westskog, H. (1996), 'Market Power in a System of Tradeable CO_2 Quotas', *The Energy Journal* **17**(3), 85–103.

Appendix

Proof of Proposition 1 for the dominant firm: The proof proceeds in three steps. First, we show that (3) is a sufficient condition for the firm to give a truthful report of its emissions ($e_1 = r_1$). Second, we show that (3) is also a necessary condition for the firm to choose full emissions compliance ($e_1 = l_1$). Third, we show that, given (3) and hence truthful emissions reports, (4) is a necessary and sufficient condition for the firm to choose full emissions compliance.

To show that (3) guarantees that the dominant firm will submit truthful emissions reports, first note that if $e_1 = l_1$, $r_1 = e_1$. That is, if the firm chooses full emissions compliance there is no reason for it to submit a false emissions report. Therefore, we need only show that (3) guarantees truthful emissions reporting whenever $e_1 > l_1$. Toward a contradiction, suppose that (3) holds but that $e_1 > l_1$ and $e_1 > r_1$. Noting from (2d) that $e_1 > r_1$ implies $\beta_1 = 0$, substitute (2b) into (2c) to obtain

$$\begin{aligned}\mathcal{L}_r &= p(L-l_1) - p'(L-l_1)\times(l_1-l_1^0) - \pi_1\times[g'(e_1-r_1)+f'(e_1-l_1)] \\ &= 0. \end{aligned} \tag{A1}$$

However, note that the strict convexity of $g'(e_1 - r_1)$ and $f'(e_1 - l_1)$ implies

$$\pi_1\times[g'(e_1-r_1)+f'(e_1-l_1)] > \pi_1\times[g'(0)+f'(0)]. \tag{A2}$$

Therefore, (3) and (A.2) imply $\mathcal{L}_r < 0$. This last inequality contradicts (A.1) and establishes the sufficiency of (3) to induce truthful emissions reports.

Toward a contradiction of the claim that (3) is necessary to induce complete emissions compliance, suppose that

$$p(L-l_1) - p'(L-l_1)\times(l_1-l_1^0) > \pi_1\times[g'(0)+f'(0)] \tag{A3}$$

but $e_1 = l_1$. Again, if $e_1 = l_1$, the firm will submit a truthful emissions report ($e_1 = r_1$). Using (2b) and (2c), if $e_1 = r_1 = l_1$ is optimal,

$$\mathcal{L}_l = p(L-l_1) - p'(L-l_1)\times(l_1-l_1^0) - f'(0) + \mu_1 = 0 \tag{A4}$$

and

$$\mathcal{L}_r = f'(0) - \pi_1\times[g'(0)+f'(0)] + \beta_1 - \mu_1 = 0. \tag{A5}$$

Substitute (A.5) into (A.4) to obtain

$$\mathcal{L}_l = p(L-l_1) - p'(L-l_1)\times(l_1-l_1^0) - \pi_1\times[g'(0)+f'(0)] + \beta_1 = 0. \tag{A6}$$

However, (A.3) and $\beta_1 \geq 0$ imply $\mathcal{L}_l > 0$, which contradicts (A.6), and hence, establishes the necessity of (3) to induce full emissions compliance.

Finally, we show that given (3), and hence the firm reports its emissions truthfully, (4) is necessary and sufficient to induce the firm to choose complete emissions compliance. To establish necessity evaluate (2b) at $e_1 = r_1 = l_1$:

$$\mathcal{L}_l = p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0) - f'(0) + \mu_1 = 0. \tag{A7}$$

Since $r_1 = l_1$, $\mu_1 \geq 0$. Therefore, (A.7) requires that $p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0) \leq f'(0)$, which is (4). To establish the sufficiency of (4) to induce full emissions compliance given the proper incentive are in place to guarantee truthful reporting, suppose toward a contradiction that (4) holds, but $e_1 = r_1 > l_1$. From (2e), since $r_1 > l_1$, $\mu_1 = 0$, and therefore, if $e_1 = r_1 > l_1$ is optimal, (2b) is

$$\mathcal{L}_l = p(L - l_1) - p'(L - l_1) \times (l_1 - l_1^0) - f'(r_1 - l_1) = 0. \tag{A8}$$

However, (4) and the fact that $f'(r_1 - l_1) > f'(0)$ for $r_1 > l_1$ imply that $\mathcal{L}_l < 0$ when $e_1 = r_1 > l_1$. This contradicts (A.8) and establishes the sufficiency of (4) to induce full emissions compliance provided that (3) is satisfied. QED.