Public technological aid to support compliance to environmental standards

Public Technological Aid to Support Compliance to Environmental Standards[1]

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Public aid to encourage the adoption of superior emissions-control technologies is com-bined with monitoring to achieve a predetermined level of compliance to firm-specific abatement standards. Technological aid serves as an indirect enforcement tool in the sense that its provision reduces the direct enforcement effort necessary to reach the compliance goal. Furthermore, when direct enforcement effort and technological aid are combined to minimize the costs of reaching the compliance goal, more aid should be provided when direct enforcement effort is expensive. As a consequence, regulated firms adopt better control technologies, which, in turn, may serve to promote further innovative activity.

1. INTRODUCTION

It is widely accepted that the development and diffusion of advanced pollution-control technologies is an important determinant of progress toward achieving environmental quality goals. In fact, a number of policies have been designed, at least in part, to promote the adoption of advanced control technologies. Typically such policies offer various forms of public aid that reduce the costs of adopting more effective technologies. For example, the U.S. Environmental Protection Agency's 33/50 Program seeks to reduce the emissions of toxic pollutants of participating firms by gathering and disseminating information about advanced control technologies and by providing technical assistance [18]. Similarly, the EPA's Green Lights Program is designed to help firms adopt more efficient lighting systems by providing information about advanced lighting systems, technical support, and information about financing the purchase of new lighting systems [19].[2]

One reason that policymakers may want to pursue such policies is that the widespread adoption of more effective control technologies decreases aggregate emissions-control costs, thereby making environmental regulation more palatable. Furthermore, the pace of technological advance in pollution control is likely to be

[1] Thanks are due Joe Moffitt, Cleve Willis, three anonymous referees, and an Associate Editor of this *Journal* for their insightful comments and suggestions.

[2] Participation in these programs is voluntary; consequently, analyses of the programs have focused on the determination of the characteristics of firms that influence voluntary participation. For examples, see DeCanio [4] and Arora and Cason [2].

positively related to the quality of control technologies in actual use. Because of learning-by-doing and learning-by-using, the adoption and operation of new technologies invariably generates new knowledge and new skills, which, in turn, tend to support further innovative activity (for a thorough discussion of these issues and others related to technological advance, see Dosi [5]). This paper explores a third benefit of technological aid that has been overlooked: namely, we shall consider whether public efforts to promote the adoption of advanced control technologies may also serve to support efforts to maintain compliance to environmental controls.

To explore the notion of technological aid as an indirect enforcement mechanism, we shall consider a regulatory environment in which heterogeneous firms face firm-specific abatement standards, a penalty schedule for noncompliance, and firm-specific audit probabilities. In this setting, each firm chooses a pollution control technology and the degree to which it is compliant. As is most common in the literature, we shall assume that the penalty schedule is beyond the regulator's influence, so its enforcement effort is limited to choosing the probability with which a firm is to be audited. Before the firms make their choices, the regulator, taking the abatement standards as given, commits to a monitoring program and a level of technological aid to achieve a predetermined level of compliance by each firm in a cost-effective manner.

Like the actual policies described above, technological aid in this paper is modeled as a cost-reducing, public input into the production of environmental quality (emissions control). More specifically, it is a nonexcludable public investment that is meant to promote the adoption of advanced control technologies by reducing the firms' costs of adopting these technologies. Such investments may include public research and development of new technologies, collecting and disseminating information about new technologies, and providing direct technical support to help firms choose, install, and maintain new control technologies.

The primary results of the analysis reveal that these sorts of aid instruments are substitutes for direct enforcement activities. We shall see that the amount of enforcement effort required to bring a firm to a certain level of compliance decreases with the provision of aid; thus, technological aid may be used to support a compliance goal by reducing the burden on direct enforcement efforts. Furthermore, when the provision of aid is a worthwhile investment (an issue that we shall address), the optimal choice of aid is increasing with the cost of conducting an audit of a firm's emissions. Thus when monitoring is difficult because the sources of pollution are widely dispersed or because emissions are not measured easily as in nonpoint pollution problems, regulators should be motivated to consider substituting technological aid for direct enforcement. Furthermore, there is a potentially important by-product of this relationship. The greater reliance on technological aid that is called for when enforcement is expensive induces firms to adopt more effective control technologies. If it is true that there is a positive relationship between the quality of technologies in use and the pace of technological change in pollution control, then those situations in which enforcement is difficult may ultimately result in quicker innovations than when enforcement is relatively easy.

This paper draws from and contributes to the theoretical literature concerning the enforcement of environmental policies (for examples, see Keeler [10], Malik

[13], and Garvie and Keeler [6]).[3] In fact, the treatment of regulated firms in this paper is typical of what one finds in this literature, except that their choices of control technologies are modeled explicitly. The most important extension, however, is that we shall endow an environmental authority with the ability to use technological aid to manipulate these technology choices to help maintain compliance to an emissions-control policy. Perhaps the most closely related work is Stranlund's [17] welfare comparison of a regime of mandatory compliance to an environmental standard that is supported by penalties for noncompliance to a regime of voluntary compliance supported by unspecified public efforts to reduce the costs of compliance. Because the two regimes were analyzed in isolation and then compared, the substitution possibilities between direct enforcement and compliance cost-reducing public efforts were not examined. In the current paper, direct enforcement and a specific public investment (i.e., technological aid) are combined into a coherent policy to focus on the substitution possibilities between the two activities.

This paper also contributes to the literature on technological advance in pollution control. Much of this literature focuses on the incentives firms have to adopt a new control technology under the usual control options: emissions standards, fees, and transferable permits.[4] (See Milliman and Prince [14] and Jung, Krutilla, and Boyd [9] for good examples of this literature, and Kemp [11] for a comprehensive literature review). None, however, allows the possibility that firms may be noncompliant, and it is not common in this literature to consider public efforts to promote the adoption of cleaner technologies. An exemption is Carraro and Soubeyran [3], who ask whether it is better to tax emissions or to subsidize the adoption of a cleaner production technology. As is common practice, they assumed perfect compliance under the emissions tax policy. It is also important to note the different instruments that are used to promote the adoption of more effective technologies. We will not consider a subsidy, but instead will focus on the public provision of nonexcludable goods that reduce the firms' costs of adopting more effective control technologies.

The remainder of the paper is organized as follows: The first part of Section 2 examines a firm's choices of technology and compliance when it is provided a certain amount of technological aid. Although the regulator's goal is to combine technological aid and monitoring to achieve a predetermined compliance goal in a cost-effective manner, it is convenient and informative to break this problem into parts. Consequently, the second half of Section 2 specifies the monitoring necessary for the regulator to reach its compliance goal given some arbitrary level of aid. Armed with the firms' optimal choices and the specification of the required

[3] For excellent discussions of the problems of monitoring and enforcement of U.S. environmental policy, see Russell et al. [16] and Russell [15]. Recent empirical analyses include Gray and Deily [7] and Laplante and Rilstone [12].

[4] In this paper we shall restrict the analysis of technological aid and enforcement to the case of emissions standards and leave the extension to emissions taxes and transferable permits for the future.

monitoring strategy, in Section 3 we shall examine the provision of aid that minimizes the aggregate costs of achieving the compliance goal. Section 4 concludes.

2. COMPLIANCE, MONITORING, AND TECHNOLOGICAL AID

2.1. *Technological Aid and Firm Choices*

Consider a set $N = (1, \ldots, n)$ of heterogeneous, risk-neutral firms, each of which chooses a level of abatement a^i and a pollution control technology z^i to minimize its costs under a regulatory regime consisting of abatement standards and an enforcement mechanism. Let a firm i's abatement cost function be $v^i(a^i, z^i)$, which is increasing in a^i ($v^i_a > 0$; throughout, subscripts denote derivatives in the usual fashion). Define e^i_0 to be i's emissions in an unregulated setting. Then, a^i is an element of the closed interval $[0, e^i_0]$. The value of z^i is taken from a positive index of pollution control technologies that is assumed to be continuous for analytic convenience. The index orders the technologies according to their effectiveness in reducing the firm's abatement cost so that $v^i(a^i, z^i)$ is decreasing in z^i $[v^i_z < 0]$. Technologies that take on higher values of z^i are said to be superior to those that take on lower values of z^i. Assume that marginal abatement cost is also decreasing in superior control technologies $[v^i_{az} < 0]$. In addition, $v^i(a^i, z^i)$ is strictly convex $[v^i_{aa} > 0,\ v^i_{zz} > 0$, and $(v^i_{aa})(v^i_{zz}) - (v^i_{az})^2 > 0]$, and, to simplify the analysis, suppose that all the third derivatives of $v^i(a^i, z^i)$ are zero.

The cost of adopting a control technology is $w^i(z^i, q)$, which is increasing in superior technologies $[w^i_z > 0]$. A regulator seeks to promote the adoption of superior control technologies by providing technological aid q that reduces the firm's total and marginal costs of adopting superior technologies $[w^i_q < 0$ and $w^i_{zq} < 0]$. Assume that $w^i(z^i, q)$ is strictly convex $[w^i_{zz} > 0,\ w^i_{qq} > 0$, and $(w^i_{zz})(w^i_{qq}) - (w^i_{zq})^2 > 0]$, and that its third derivatives are also zero.

The firm faces an abatement standard s^i, which is contained in the open interval $(0, e^i_0)$. As is commonly assumed in the literature on enforcement of environmental policies, the firm operates under an enforcement regime that consists of a probability of an audit p^i and a penalty schedule $f(s^i - a^i)$. The penalty schedule assigns a fine if and only if the firm is found to be noncompliant $(a^i < s^i)$, and the penalty increases at an increasing rate with the level of the violation. Thus, $f(s^i - a^i) = 0$ if and only if $s^i \leq a^i$, and $f'(s^i - a^i) > 0$ and $f''(s^i - a^i) > 0$ for $s^i \geq a^i$. Once again, assume that the third derivative of the penalty schedule is zero. It is also common to assume that the penalty schedule is determined by a government body other than the environmental regulator (for example, a judiciary or a legislature), so that the regulator's enforcement policy is limited to choosing the probability with which a firm is to be audited. We shall take the same approach in this paper.[5]

The firm reacts to the standard, the enforcement policy, and the provision of aid by choosing a control technology and a level of abatement to minimize its expected

[5] For an extension of this approach, see Garvie and Keeler [6], who distinguish between the probability that a firm is audited (monitoring) and efforts to punish a violation once it has been detected (enforcement).

compliance cost; that is, it chooses z^i and $a^i \leq s^i$ to minimize

$$C^i(a^i, z^i) = v^i(a^i, z^i) + w^i(z^i, q) + p^i f(s^i - a^i). \tag{2.1}$$

Given our earlier assumptions, it is easy to verify that $C^i(a^i, z^i)$ is strictly convex in the choice variables.[6] Assuming interior choices, the following first-order conditions are necessary and sufficient to determine them uniquely:

$$v_z^i(a^i, z^i) + w_z^i(z^i, q) = 0; \tag{2.2}$$

$$v_a^i(a^i, z^i) - p^i f'(s^i - a^i) \leq 0, \quad \text{if} < 0, a^i = s^i. \tag{2.3}$$

The regulator in this model is going to combine monitoring and technological aid to hold each firm to a certain level of compliance; hence, firm i will ultimately be induced to choose a certain level of abatement. It is therefore convenient to consider the firm's abatement-constrained technology choice $z^i(a^i, q)$, which is implicitly defined by (2.2). Note that

$$z_a^i = -v_{az}^i / \left[v_{zz}^i + w_{zz}^i \right] > 0; \qquad z_q^i = -w_{zq}^i / \left[v_{zz}^i + w_{zz}^i \right] > 0. \tag{2.4}$$

As one should expect, the firm chooses a better technology when its abatement is greater and, holding its abatement fixed, when more aid is provided. Because $v^i(a^i, z^i)$ and $w^i(z^i, q)$ have zero third derivatives, z_a^i and z_q^i are positive constants.

Now rewrite the Kuhn–Tucker condition (2.3) taking $z^i(a^i, q)$ into account:

$$v_a^i\left(a^i, z^i(a^i, q)\right) - p^i f'(s^i - a^i) \leq 0, \quad \text{if} < 0, a^i = s^i. \tag{2.5}$$

Let $a^i(q, s^i, p^i)$ be the solution to (2.5) when it holds with equality and note that $a^i(q, s^i, p^i) \leq s^i$. Hence, $a^i(q, s^i, p^i)$ is i's optimal abatement choice when it is noncompliant or when it is just compliant. From (2.5), obtain the following comparative statics:

$$a_q^i(q, s^i, p^i) = -v_{az}^i z_q^i / S > 0; \tag{2.6}$$

$$a_s^i(q, s^i, p^i) = p^i f'' / S \in (0, 1); \tag{2.7}$$

$$a_p^i(q, s^i, p^i) = f' / S > 0. \tag{2.8}$$

In these relations, $S = v_{aa}^i + v_{az}^i z_a^i + p^i f''$, which can be shown to be positive by using (2.4) and the strict convexity of $v^i(a^i, z^i)$. These comparative statics are what one should expect: technological aid makes abatement cheaper, so a firm will increase its abatement with more aid; a higher abatement standard induces it to increase its abatement, but by less than the decrease in the emissions standard; and the firm increases its abatement with a higher audit probability.

[6] A few notes are appropriate here: First, this formulation of the firm's expected compliance costs is nearly identical to that of Amacher and Malik [1], but it is used for a different purpose. Second, since the firms' choices are analyzed in a static framework, we assume a time period that is long enough for them to make adjustments to their control technologies, but we ignore dynamic considerations such as the decision about when to adopt a particular technology. Jaffe and Stavins [8] constructed a dynamic empirical model of technology adoption and compliance. Considering the provision of technological aid in a dynamic context may be a fruitful exercise for future research.

2.2. *Technological Aid and Monitoring*

The goal of the environmental authority is to combine technological aid and enforcement effort to achieve a predetermined level of compliance by each firm in a cost-effective manner. Rather than treat this as a simultaneous-choice problem, we break it into parts. Let us first treat technological aid as exogenous and examine the monitoring effort that is required to reach the regulator's compliance goal.

From the regulator's point of view the abatement standards $(s^1, s^2, \ldots, s^n)$ are fixed, but it wants to hold each firm to a level of violation that is no more than α; that is, the regulator's compliance goal is $s^i - a^i(q, s^i, p^i) \leq \alpha$ for each i.[7] (In Malik [13] and Amacher and Malik [1], $\alpha = 0$). Recall from (2.8) that $a^i(q, s^i, p^i)$ is increasing in p^i. Thus, given a fixed level of nonexcludable aid, the regulator's compliance goal is met with minimum monitoring effort by $p^i(q, \alpha, s^i)$ $i \in N$, where for each i,

$$s^i - a^i\big(q, s^i, p^i(q, \alpha, s^i)\big) \equiv \alpha. \tag{2.9}$$

Differentiate (2.9) with respect to q and rearrange the result to obtain

$$p^i_q(q, \alpha, s^i) = -a^i_q/a^i_p < 0. \tag{2.10}$$

Thus, the burden on direct enforcement activities of maintaining a compliance goal is lessened with the provision of technological aid. This is precisely the sense in which technological aid may serve to support direct enforcement efforts in the maintenance of compliance to environmental standards. This does not imply that aid should be used for this purpose—we take this issue up in the next section—it only implies that the opportunity exists.

The underlying reasons for the result that technological aid may substitute for direct enforcement are quite intuitive. Recall from (2.6) that the provision of aid induces more abatement from a firm $[a^i_q > 0]$. This is due to the fact that it motivates a firm to adopt a better control technology, which reduces its marginal abatement costs. The firm's abatement also responds positively to the probability that it will be audited $[a^i_p > 0$; see (2.8)$]$. Since aid induces greater abatement from a firm, to hold its violation to α, the regulator may reduce its monitoring of the firm as it increases its provision of aid. Clearly, if technological aid is nonexcludable as we assume, its provision allows the regulator to reduce its monitoring of all firms.[8]

[7] Of course, other regulatory objectives may be considered. For example, we might have assumed that monitoring is chosen optimally along with technological aid. However, the simultaneous choice of enforcement and aid does not provide much insight because it turns out that few definitive conclusions can be drawn about the structure of aggregate compliance costs. Besides, the approach taken here may be of greater immediate service to policymakers who might be more interested in applying technological aid to existing regulatory standards and existing enforcement goals rather than the much more difficult task of optimally and simultaneously determining each aspect of environmental policy.

[8] From (2.9) we may also obtain $p^i_\alpha(q, \alpha, s^i) = -1/a^i_p < 0$ and $p^i_s(q, \alpha, s^i) = (1 - a^i_s)/a^i_p > 0$, the signs of which follow from (2.7) and (2.8). These indicate that the required monitoring of firm i increases with a higher compliance goal (i.e., lower α) and with an increase in the abatement standard.

3. TECHNOLOGICAL AID TO MINIMIZE AGGREGATE COMPLIANCE COSTS

3.1. *Aggregate Compliance Costs and the Optimal Provision of Aid*

In this section we shall consider the problem of choosing the level of aid that minimizes the aggregate costs of maintaining the regulator's enforcement goal. The aggregate compliance costs include the firms' emissions-control costs, aggregate monitoring costs, and the cost of technological aid. The firms' expected penalties are not included because we have assumed that there are no costs associated with collecting penalty payments from the firms and, therefore, we may treat them as simple transfer payments that have no real effects. Let us consider each component of aggregate compliance costs in turn.

A firm's emissions-control costs include its abatement costs and technology-adoption costs, which are given by $c^i(a^i, z^i) = v^i(a^i, z^i) + w^i(z^i, q)$. Recall that the firm's choice of technology is $z^i(a^i, q)$ (from Section 2.1) and that the regulator's enforcement policy induces it to choose its abatement so that $a^i(q, s^i, p^i) = s^i - \alpha$. Thus, given that the firm makes optimal choices of abatement and technology, its emissions-control costs are

$$c^i\big(s^i - \alpha, q\big) = v^i\big(s^i - \alpha, z^i\big(s^i - \alpha, q\big)\big) + w^i\big(z^i\big(s^i - \alpha, q\big), q\big). \tag{3.1}$$

Using (2.2), the first-order condition that determines $z^i(a^i, q)$, the effect on a firm's emissions-control costs of a marginal change in technological aid is

$$c^i_q\big(s^i - \alpha, q\big) = w^i_q\big(z^i\big(s^i - \alpha, q\big), q\big) < 0. \tag{3.2}$$

Thus, the effect on a firm's emissions-control costs of applying technological aid is simply the reduction of the firm's technology-adoption costs.

It is also straightforward to show that the firm's emissions-control costs plus its expected penalty payment are decreasing in technological aid. Though not surprising, this result is important because it indicates that technological aid can make pollution control more acceptable to regulated firms.

Although the provision of technological aid reduces each firm's emissions-control costs, it does so at a diminishing rate. To see this, note from (3.2) that $c^i_{qq}(s^i - \alpha, q) = w^i_{zq} z^i_q + w^i_{qq}$. Upon substitution for z^i_q from (2.4), obtain

$$c^i_{qq}\big(s^i - \alpha, q\big) = \Big[w^i_{qq} w^i_{zz} - \big(w^i_{qz}\big)^2 + w^i_{qq} v^i_{zz}\Big] \big/ \big[v^i_{zz} + w^i_{zz}\big] > 0. \tag{3.3}$$

The sign of (3.3) follows from the strict convexity of $v^i(a^i, z^i)$ and $w^i(z^i, q)$.

Assuming that the cost of an audit is a constant r, aggregate monitoring costs are

$$r \sum_{i \in N} p^i\big(q, \alpha, s^i\big). \tag{3.4}$$

From (2.10), aggregate monitoring costs are decreasing in the amount of aid provided. Interestingly, the marginal effectiveness of technological aid as a substitute for monitoring is enhanced as more aid is provided; that is,

$$p^i_{qq}\big(q, \alpha, s^i\big) < 0. \tag{3.5}$$

(This result is derived in the Appendix.) As a consequence, aggregate monitoring costs are strictly *concave* in technological aid.

Finally, let us consider the cost of providing nonexcludable aid. Suppose for simplicity that the marginal cost of providing aid to only one firm is constant at 1. However, the total cost of providing the same type and level of aid to all firms depends on the inherent rivalry of the aid instrument. The creation and dissemination of information concerning advanced control techniques may be considered to be close to perfectly nonrival since the cost of providing the same type and level of information to another firm is close to zero. On the other hand, direct technical assistance is a perfectly rival aid instrument since the cost of providing the amount q to one more firm is simply q. To allow for intermediate degrees of rivalry, let the total cost of technological aid be $Q = (1 + \phi(n-1))q$, where $\phi \in [0,1]$. This specification of the total cost of technological aid indicates that it is a nonexcludable investment with degree of rivalry given by ϕ. Note that since the marginal cost of providing the same level of nonrival aid to another firm is zero, $\phi = 0$ and the total cost is $Q = q$. For an aid instrument that is perfectly rival, $\phi = 1$ and the total cost is $Q = nq$. Intermediate cases are captured by $\phi \in (0,1)$, where lower values of ϕ indicate less rival aid instruments. Note that $(1 + \phi(n-1))$ can be interpreted as the unit price of nonexcludable aid and that less rival instruments have lower unit prices.

Bringing all the cost components together, the regulator's choice of aid is $q \geq 0$ that minimizes the objective

$$\sum_{i \in N} c^i(s^i - \alpha, q) + r \sum_{i \in N} p^i(q, \alpha, s^i) + (1 + \phi(n-1))q. \tag{3.6}$$

There are at least two potential difficulties with the determination of the optimal provision of technological aid. Since aggregate emissions-control costs are strictly convex in q while aggregate monitoring costs are strictly concave, (3.6) may be a rather complicated objective with multiple local optima and boundary solutions. The second difficulty is a common one: clearly, the information needed to estimate aggregate compliance costs is extensive and will, at best, be difficult to obtain.

From here on let us assume that (3.6) is strictly convex so that its minimizer is unique. Denote this level of aid as $\bar{q}$, and note that it is the solution to the following Kuhn–Tucker condition:

$$\sum_{i \in N} c_q^i(s^i - \alpha, \bar{q}) + r \sum_{i \in N} p_q^i(\bar{q}, \alpha, s^i) + (1 + \phi(n-1)) \geq 0, \quad \text{if} > 0, \bar{q} = 0. \tag{3.7}$$

The effect on a firm's emissions-control costs of applying technological aid is simply the reduction of its technology-adoption costs [$c_q^i = w_q^i$; see (3.2)]. Thus, the first term of (3.7) captures the marginal reduction in the firms' costs of adopting control technologies, while the second captures the marginal reduction in aggregate monitoring costs. These two terms represent the marginal benefits of technological aid. The last term is the unit price of nonexcludable aid.

Condition (3.7) provides a few immediate conclusions about when technological aid should be provided to support compliance. Clearly, technological aid is a profitable public investment if and only if the reduction in aggregate technology-

adoption costs plus the reduction in monitoring costs achieved by the first unit of aid is greater than the unit price of nonexcludable aid. [This is true whether or not (3.6) is convex.] In addition, this is more likely to occur when the cost of conducting an emissions audit is high and when the unit price of aid is low. Thus, the situations in which direct enforcement is difficult are those in which the provision of technological aid is more likely to be a beneficial investment. Furthermore, since less rival aid instruments have lower unit prices, everything else equal, these are more likely to be profitable investments than rival instruments. Consequently, the development and dissemination of information about advanced control techniques is more likely to be a worthwhile investment than direct technical assistance because the former is less rivalrous.

3.2. *Another Sense in Which Technological Aid and Enforcement are Substitutes*

Assume that the optimal provision of aid is nonzero. Then (3.7) holds with equality and it implicitly defines the optimal choice of aid $\bar{q}(r, \phi, \alpha, \mathbf{s})$, where $\mathbf{s} = (s^1, s^2, \ldots, s^n)$. Of course, a unique interior choice of aid requires the following convexity condition:

$$R = \sum_{i \in N} c^i_{qq} + w \sum_{i \in N} p^i_{qq} > 0.$$

Associated with the optimal choice of aid is the set of audit probabilities,

$$\bar{p}^i(r, \phi, \alpha, \mathbf{s}) = p^i\big(\bar{q}(r, \phi, \mathbf{s}), \alpha, s^i\big), \qquad i \in N, \tag{3.8}$$

and associated with the choice of aid and the enforcement policy are the firms' choices of control technologies,

$$\bar{z}^i(r, \phi, \alpha, \mathbf{s}) = z^i\big(s^i - \alpha, \bar{q}(\phi, r, \mathbf{s})\big), \qquad i \in N. \tag{3.9}$$

From (3.7), obtain $\bar{q}_r = -\sum_{i \in N} p^i_q / R > 0$, and from (3.8), obtain $\bar{p}^i_r = p^i_q \bar{q}_r < 0$. These indicate another sense in which technological aid is a substitute for direct enforcement efforts: when the usual enforcement methods are expensive, an enforcement authority should rely more heavily on technological aid and less on direct enforcement. There are two interesting by-products of this relationship. From (3.9) obtain $\bar{z}^i_r = z^i_q \bar{q}_r > 0$. [Recall from (2.4) that $z^i_q > 0$]. This indicates that the combination of expensive enforcement and the optimal provision of technological aid leads to the adoption of more effective control technologies. If the pace of technological advance in pollution control is positively related to the quality of control technologies in use, the optimal provision of aid when direct enforcement methods are expensive may serve to promote greater innovation in pollution control than when enforcement is relatively cheap. In addition, the regulated firms are better off when enforcement is expensive. This is not because the reduction in monitoring allows them to cheat more—their violations are held constant by the regulator's enforcement policy. Rather, their emissions-control costs are lower because they receive more aid, and their expected penalty payments are lower as well because they are audited less frequently.

We should expect the same sorts of comparative statics with respect to a change in the price of providing nonexcludable aid. Recall that the unit price of nonex-

cludable aid is $(1 + \phi(n - 1))$ and that it increases with more rival aid instruments (higher ϕ). From (3.7) and (3.8) obtain $\bar{q}_\phi = -(n - 1)/R < 0$ and $\bar{p}^i_\phi = \bar{p}^i_q \bar{q}_\phi > 0$. Since a less rival aid instrument has a lower unit cost, the use of such an instrument calls for greater reliance on technological aid and less on monitoring. Now, from (3.9) obtain $\bar{z}^i_\phi = z^i_q \bar{q}_\phi < 0$: since more aid is provided when a less rival instrument is employed, the firms adopt more effective control technologies.

3.3. *Further Comparative Static Results*

The other comparative static results of this model are concerned with changes in the compliance goal and the abatement standards. Both types of changes yield similar results because both have the effect of changing the firms' abatement choices.[9] It turns out that the regulator's choice of technological aid is increasing with a higher compliance target (i.e., lower α) and with a uniform increase in the abatement standards that the firms face. However, the effects of these parametric changes on monitoring is ambiguous because they induce countervailing incentives for the regulator. Holding the provision of technological aid constant, an increase in the compliance target and the abatement standards both require more intense monitoring. On the other hand, however, the increased provision of aid that is called for in these situations motivates the regulator to reduce its monitoring effort. The overall effects of a stricter compliance goal and higher abatement standards on monitoring depend in both cases on the relative magnitudes of these effects. Finally, there is no ambiguity about the effects of these changes on the firms' technology choices. A stricter compliance goal and higher abatement standards motivate the firms to choose more effective control technologies whether the regulator responds to these changes with more aid or not. The increased provision of aid that is called for in these situations provides an additional incentive to the firms to adopt better technologies.

4. CONCLUDING REMARKS

We have examined the potential of combining technological aid that reduces regulated firms' costs of adopting superior technologies with direct enforcement to maintain compliance to environmental standards. We have focused on the substitution possibilities between technological aid and enforcement, and found that the provision of aid can reduce the burden placed on enforcement efforts to maintain a compliance goal. Furthermore, the provision of aid is more attractive when monitoring is difficult, and less rival investments like the development and dissemination of information about advanced control techniques are more attractive than rival investments like direct technical assistance. We have also noted that the provision of aid reduces the compliance costs of regulated firms and may serve to quicken the pace of technological advance in pollution control because its application motivates firms to adopt better control technologies.

There are, of course, many ways in which the analysis of this paper can and should be extended. Future research should examine the same questions posed in this paper in the context of compliance to incentive-based polices like effluent fees

[9] Derivations of these comparative statics are available from the author on request.

and marketable permit systems. Future research should also incorporate some features of the actual problems of monitoring and enforcement that were not considered in this paper. Monitoring in the United States often relies heavily on self-reporting by regulated firms. Considering the consequences of providing technological aid when monitoring relies on the firms' accounts of their own emissions is likely to be a fruitful exercise.

Models of the sort employed in this paper ignore a feature of monitoring and enforcement in the United States that has not received adequate attention. A common form of noncompliance is that, although firms have the necessary equipment installed to meet their emissions standards, the equipment is not maintained or operated properly. This form of noncompliance results because authorities often audit firms to check if they have sufficient control equipment installed (this is called monitoring for initial compliance), but are not very diligent about monitoring actual emissions (monitoring for continuous compliance). (This feature of monitoring and enforcement in the United States is discussed in Russell [15]). Typical models in the literature consider only monitoring of emissions: they do not include an initial audit by an authority to check if the technology a firm has installed is sufficient to meet its abatement standard. Hence, firms in these models have no incentive to install a piece of control equipment and then fail to operate it properly. The combination of monitoring for initial compliance and monitoring for continuous compliance appears not to have received much attention. Considering the application of technological aid in these contexts would help fill this gap in the existing literature as well as further the examination of the potential of publicly provided technological aid.

APPENDIX

To derive $p^i_{qq}(q, \alpha, s^i) < 0$, first recall from (2.10) that $p^i_q(q, \alpha, s^i) = -a^i_q(q, s^i, p^i)/a^i_p(q, s^i, p^i)$. Then,

$$p^i_{qq}(q, \alpha, s^i) = -[A - B]/\left(a^i_p\right)^2, \tag{A.1}$$

where

$$A = \left(a^i_{qq} + a^i_{qp}p^i_q\right)a^i_p \tag{A.2}$$

and

$$B = \left(a^i_{pq} + a^i_{pp}p^i_q\right)a^i_q. \tag{A.3}$$

Recall from (2.6) that $a^i_q(q, s^i, p^i) = -v^i_{az}z^i_q/S$, where $S = v^i_{aa} + v^i_{az}z^i_a + p^i f'' > 0$. Also recall that $v^i(a^i, z^i)$ has zero third derivatives and that z^i_a and z^i_q are positive constants. Therefore,

$$a^i_{qq}(q, s^i, p^i) = v^i_{az}z^i_q\left(p^i_q f''\right)/S^2 = -a^i_q p^i_q f''/S\,, \tag{A.4}$$

$$a^i_{qp}(q, s^i, p^i) = v^i_{az}z^i_q(f'')/S^2 = -a^i_q f''/S\,. \tag{A.5}$$

Upon substitution for a^i_{qq} and a^i_{qp} in (A.2), we have $A = -2f''p^i_q a^i_q a^i_p/S$. Since $p^i_q = -a^i_q/a^i_p$,

$$A = 2f''\left(a^i_q\right)^2/S. \tag{A.6}$$

Now, from (2.8), $a_p^i(q, s^i, p^i) = f'(s^i - a^i(q, s^i, p^i))/S$. Then,

$$a_{pp}^i(q, s^i, p^i) = \left(-f'' a_p^i S - f'' f'\right)/S^2 = -2f'' a_p^i/S. \tag{A.7}$$

Upon substitution for a_{qp}^i and a_{pp}^i in (A.3) and applying $p_q^i = -a_q^i/a_p^i$,

$$B = f''\left(a_q^i\right)^2/S. \tag{A.8}$$

Substituting (A.8) and (A.6) into (A.1) yields $p_{qq}^i(q, \alpha, s^i) = -f''(a_q^i)^2/(a_p^i)^2 S$, which is negative because both f'' and S are positive.

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