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Controlling Pollution with Relaxed Regulations*

CARMEN ARGUEDAS
Universidad Europea de Madrid
Departamento de Economía, C/Tajo, s/n. 28670 Villaviciosa de Odón, Madrid, Spain
E-mail: mcarmen.arguedas@fae.eco.uem.es

HAMID HAMOUDI
Universidad Europea de Madrid
Departamento de Economía, C/Tajo, s/n. 28670 Villaviciosa de Odón, Madrid, Spain
E-mail: hamid.hamoudi@fae.eco.uem.es

Abstract
We investigate the features of optimal environmental policies composed of pollution standards and costly inspection processes, where fines for exceeding the standards depend both on the degree of transgression and the environmental technology that the firm uses to reduce the social impact of its polluting activity. We show that the main characteristics of these policies depend crucially on when the firm selects that technology with respect to the timing of the policy announcement. In fact, the firm has incentives to over-invest in green technologies when the policy is announced afterwards; and to under-invest in them if the environmental authority plays first. Surprisingly, we find that both the firm and the regulator prefer that the firm invests in technology before the policy is announced, even when this implies that expected penalties for noncompliance might be zero.

Key words: environmental standard—setting, costly inspections, reduced fines, clean technologies

JEL Classification: L51, K32, K42

1. Introduction

The purpose of environmental regulations is to protect individuals against pollution. These regulations are diverse and currently used by governments worldwide. For instance,

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authorities require polluting firms to comply with prescribed pollution limits or standards, and persuade them to use clean, though expensive, production processes. Normally, regulators cannot implement these policies easily, since they do not observe without cost the performance of firms with respect to the policies. Therefore, they design inspection programs that consist of monitoring frequencies and sanctions in case firms are found violating the policies.

In recent Spanish legislation on hazardous waste,[1] sanctions depend on several factors, such as the degree of noncompliance (the difference between the observed pollution levels and the standards) and the efforts of firms to minimize the social pollution effects of their infractions.

For instance, water consumption in the production process is considered a key parameter to determine both the likelihood of an inspection and the eventual sanction in case of noncompliance. This is so, not only because water is a scarce resource and its excessive consumption creates a social problem, but also because it is the means by which liquid waste is released. By law, firms which show an investment plan in clean production techniques that provides a responsible water consumption are rarely inspected. Moreover, they are rarely punished in case they are inspected and found to be non-complying with the regulations.[2]

There is no doubt in the literature that fines should depend on the degree of noncompliance with the standards.[3] However, the optimality issues about the dependence of penalties on the investment of firms in clean technologies, such as the one described, have not been studied before.

In this paper, we explore the conditions under which sanctions should depend on the environmental technology of the firm together with the degree of noncompliance. For that purpose, we present a principal-agent model in which the regulator chooses standards and probabilities of inspection considering that fines depend on the two factors mentioned above, and where a larger expenditure in technology is associated with a smaller fine.

We demonstrate that the answer to our question depends crucially on the timing at which its respective decision is made, in particular the technology investment. In some instances, the firm may anticipate its investment to be prepared for future environmental policies. In other cases, the firm may invest in technology just to adapt to the latest requirements.

When the firm anticipates its investment, we find that it has incentives to over-invest in technology if the fines for noncompliance are contingent on that investment, since the additional expenditure is compensated by the savings in the expected fines. On one

1 Law 5/03 of Residuals and Law 10/93 of Liquid Industrial Waste of Comunidad de Madrid.

2 Casbega S.A., a company that belongs to the Coca Cola Group, has recently developed an environmental technology which saves a considerably amount of water in the production process and it also reduces the amount of water pollutants. The environmental efforts of this company consist not only on the emissions reduction but also in making the released residuals less dangerous: for given water emissions, the availability of a larger amount of clean water results in a smaller percentage of pollutants per, say, liter of water, making emissions less harmful.

3 In fact, sanctions should be progressive in the degree of transgression to conform with both moral and efficiency considerations. See Shavell (1992) for a discussion on this issue.

hand, the cleaner the technology, the smaller the penalty itself. On the other hand, the over-investment is a good signal for the regulator, that might decide not to inspect the firm at all. In this case, the firm prefers that fines are contingent on the investment in technology, while the regulator prefers that fines depend on the degree of noncompliance only.

However, the firm under-invests in technology when it makes the expenditure after the policy announcement. Environmental policies are more rigid here since the firm cannot affect the policy by means of that investment. The firm prefers that fines depend on the technology investment. Contrary to the previous case, the regulator may prefer that fines are contingent on the technology also, to give enough incentives to the firm to avoid large environmental damages.

Finally, we find that it is beneficial for both the firm and the regulator that the firm invests in technology before the policy is announced. The result is surprising from the point of view of the regulator, since the induced regulation in this case is more lenient, that is, expected fines are smaller. However, the firm induces that leniency with the over-investment, which results in smaller environmental damages and larger social welfare.

The closest paper to ours is Stranlund (1997). There, firms choose pollution abatement levels and emissions-control technologies, in response to a monitoring process to achieve a specified level of compliance combined with a public aid program which provides incentives for the adoption of superior technologies. The basic result is that public aid results in less enforcement effort to achieve a given compliance level. In a sense, the spirit of our results is similar, since providing those incentives (in our case, reducing sanctions for noncompliance), pollution is controlled with less monitoring efforts. However, there are three crucial differences between Stranlund (1997) and ours. First, cleaner technologies reduce firms' pollution control costs in Stranlund (1997), as opposed to societal environmental costs in ours. This difference justifies why fines for noncompliance should be dependant on the investment effort, and allows us to study welfare implications. Second, the positive effects of the technology investment in Stranlund (1997) rely on the reduction of the firm's pollution control costs and the subsidy obtained; here, they are those of having smaller penalties and inspection frequencies if firms anticipate their investment. Finally, compliance levels are given exogenously in Stranlund (1997), while they are endogenously obtained here.

We provide an alternative explanation for the leniency of the regulations, in the sense of infrequent inspections or small sanctions.[4] In environmental regulation, the enforcement aspect has been widely studied (see Heyes 2000 for a complete review), where contested enforcement (Kambhu 1989; Malik 1990), self-reporting (Malik 1993; Livernios and

4 Becker (1968) was the first who proved the optimality of imposing maximal fines, given costly enforcement. Subsequently, several authors have explained the reasons why fines need not be maximal: Polinsky and Shavell (1979), in the case of risk aversion; Bebchuk and Kaplow (1991) and Kaplow (1990), under agents' imperfect information about the regulation; Polinsky and Shavell (1990), under agents' differences in wealth; Shavell (1992), in the context of marginal deterrence; Kambhu (1989), in the case of agents' penalty evasion; Arguedas (1999), in a bargaining context; among others. In the environmental context, see also Harrington (1988), Heyes and Rickman (1999) and Raymond (1999).

Mackenna 1999 and, more generally, the literature on tax evasion[5]) and multi-period enforcement (Harrington 1988; Harford and Harrington 1992) have received special attention.

The remainder of the paper is organized as follows. In the next section, we present the model. In section 3, we study the case in which the firm anticipates the technology investment in advance of the policy announcement. In section 4, we analyze the case where the firm waits until the policy is announced. In section 5, we compare the results of the two previous Sections in terms of the firm's expected payoff and the social welfare. We conclude in section 6.

2. The Model

We consider a firm that emits pollution $e > 0$ as a result of its production process. The social effects of pollution are related to the environmental technology that the firm uses, $\beta \in (0, \overline{\beta}]$, where, for convenience, we take $\beta > 1$. We associate a larger β with a dirtier technology and vice versa.[6] The firm obtains private profits which depend on the pollution level and the investment in technology, represented by the function

$$b(e, \beta) = ke - \frac{e^2}{\beta}, \tag{1}$$

where $k > 0$ represents the degree of profitability of the firm. Given β, profits are strictly concave in the pollution level with an interior maximum at $e = k\beta/2$. Also, profits are strictly increasing in β, that is, dirtier technologies are cheaper and, therefore, private profits associated with these technologies are larger.

Pollution generates external damages whose monetary value depends on the pollution level and the dirtiness of the technology, as follows:

$$d(e, \beta) = \beta e^2. \tag{2}$$

Given a technology β, damages are increasing and convex in the pollution level. Also, given a pollution level, the associated damages are increasing in β.[7]

In the absence of a regulation, the firm does not internalize the presence of external damages and it selects the technology and the pollution level that maximize (1), that is, $\beta = \overline{\beta}$ and $e = k\overline{\beta}/2$, obtaining private profits of $k^2\overline{\beta}/4$. By contrast, if damages are fully internalized (i.e., if (1) and (2) are maximized), we obtain the efficient levels $\beta^* = 1$ and $e^* = k/4$, which lead to private profits of $3k^2/16$, smaller than in the previous case.

We assume that there exists an environmental authority that is concerned about the above external damages and regulates the polluting activity. To do so, the regulator sets a standard $s \geq 0$, that is, a maximum level of permitted pollution. We consider that the regulator observes the technology that the firm uses but cannot know the emitted pollution level unless it monitors the firm, which costs $c > 0$. This means that the regulator needs to inspect the firm to verify its performance with respect to the standard. Since monitoring is costly, though perfectly accurate, it is not necessarily optimal to monitor the firm always, but occasionally. Therefore, the regulator sets the probability of inspection, $p \in [0, 1]$.

If, once monitored, the firm is discovered to be exceeding the standard, then it is forced to pay a sanction that depends both on the degree of violation, $e - s$, and the technology that the firm uses, β. We assume that the sanction is not decided by the regulator, but given exogenously by another government entity, for example, the legislature. The penalty function takes the following structure:

$$f(\beta, e - s) = \begin{cases} \phi(\beta)(e - s)^2, & e - s > 0; \\ 0, & \text{otherwise}, \end{cases} \tag{3}$$

where $\phi(\beta) \geq \beta$ and $\phi'(\beta) \geq 0$. Given β, the fine is increasing and convex in the degree of violation, that is, the penalty is contingent on the magnitude of the crime. Also, given a degree of transgression $e - s$, the worse the technology, the more severe the penalty.[8] Throughout the paper, we study the effects of considering two alternatives for the dependency of the fines on β: $\phi(\beta) = \beta$ and $\phi(\beta) = t$, where t is a positive constant. In particular, we analyze what structure is better from both the regulator's and the firm's view points under alternative assumptions.[9]

We consider a principal-agent framework in which the regulator chooses the policy instruments (the standard s and the probability of inspection p) considering that sanctions for noncompliance are given and anticipating the firm's optimal response to the policy. The firm selects the pollution level and the technology to maximize its expected payoff, which includes not only its private profits but also the expected fine in the case that it decides to violate the standard. Formally, the firm's expected payoff function is the following:

5 Some examples include Pestieu et al. (1997), who assume that fines are independent of the degree of violation; and Greenberg (1984), in the context of multi-period enforcement.

6 For instance, going back to the Casbega S.A. example cited in section 1, β can be interpreted as the total amount of water used in the production process. The more water used, the worse the environmental consequences of water pollution.

7 Again, in the case of our example, damages depend positively on the quantity of released pollutants and negatively on the availability of clean water.

8 We consider $\phi(\beta) \geq \beta$ to ensure that $p \leq 1$ later on in Lemma 3.2 and Proposition 3.3.

9 One may think that, since society is concerned about the resulting damages and not at all on emissions, it would be more natural to apply standards directly to damages and not on emissions *per se*. In our setting, the results would be qualitatively identical to the ones presented here. However, we keep the present structure because in more general settings with incomplete information and valuation problems, it can be more difficult to implement a standard based on the resulting damages. In fact, current legislation applies standards to emissions and then it positively considers the efforts of firms to minimize the social impact of the infractions. The dependence of penalties on β accounts for the latter fact.

$$\Pi(e,\beta,s,p) = ke - \frac{e^2}{\beta} - pf(\beta, e-s). \tag{4}$$

To derive the optimal policy, we assume that the regulator maximizes an expected social welfare function that considers the firm's expected payoff, the external damages, the expected collection of the fines and the expected monitoring costs. Considering that imposing fines is socially costless, the expected social welfare function can be written as follows:

$$R(e,\beta,s,p) = ke - \frac{e^2}{\beta} - \beta e^2 - pc. \tag{5}$$

As described in the Introduction, we consider two possibilities depending on the timing of the technology investment decision with respect to the policy announcement. In the following section, we analyze the characteristics of the optimal policy when the firm anticipates its investment.

3. Results of the Three-Stage Game

In this problem, the firm first chooses the technology β; then, the regulator selects the policy (s,p); and, finally, the firm decides the pollution level e. We solve the problem by backward induction to find the subgame perfect equilibrium. That is, in the first stage we obtain the firm's optimal pollution level, given the policy and the pollution technology. In the second stage, we find the optimal policy, given the technology and considering the optimal pollution level obtained in stage one. Finally, in the third stage we obtain the optimal technology considering both the optimal pollution level and the optimal policy obtained in the two previous stages.

3.1. Stage 1

Given $\beta \in [0, \bar{\beta}]$ and the policy $s \geq 0, p \in [0,1]$, the firm solves the problem:

$$\max_{e} \quad \left\{ ke - \frac{e^2}{\beta} - p\phi(\beta)(e-s)^2 \right\},$$
$$\text{s.a.} \quad s - e \leq 0;\ e - \frac{k\beta}{2} \leq 0. \tag{6}$$

The first restriction guarantees that the firm chooses a pollution level that is at least as large as the prescribed standard (else, it has no sense to consider the fine in the objective function). The second restriction ensures that the pollution level is at most the one the firm would choose in the absence of the regulation. These two restrictions combined guarantee that the firm chooses the pollution level on the basis of a meaningful regulation.

The Lagrangian of problem (6) is the following:

$$L(e,\lambda_1,\lambda_2) = ke - \frac{e^2}{\beta} - p\phi(\beta)(e-s)^2 - \lambda_1(s-e) - \lambda_2\left(e - \frac{k\beta}{2}\right),$$

where (λ_1, λ_2) are the corresponding Lagrange multipliers.

Lemma 3.1: *The solution to problem* (6) *is*

$$e = \frac{\beta(k + 2ps\phi(\beta))}{2(1 + p\beta\phi(\beta))};\quad \lambda_1 = \lambda_2 = 0;\quad \textit{where } s \leq \frac{\beta k}{2}. \tag{7}$$

As expected, the pollution level is positively related to the standard and negatively related to the probability of inspection. As far as the effect of the technology is concerned, only when either there is no regulation $(p = 0)$ or if the fines do not depend on the technology $(\phi' = 0)$, we obtain that the dirtier the technology, the larger the associated pollution level, and vice versa. This dependence plays a crucial effect on the results, as we will see later on.

3.2. Stage 2

We now present the regulator's problem considering the optimal response of the firm, given in (7).

$$\max_{s,p} \quad \left\{ ke - \frac{e^2}{\beta} - \beta e^2 - pc \right\},$$
$$\text{s.a.} \quad s - \frac{\beta k}{2} \leq 0;\quad -s \leq 0;\quad -p \leq 0;\quad p - 1 \leq 0. \tag{8}$$

Lemma 3.2: *The solution to problem* (8) *is given by the following conditions:*[10]

i. If $0 \leq c \leq \beta^4\phi(\beta)k^2/2$, *then*

$$s = 0;$$
$$g(\beta,p) = \beta^3 k^2 \phi(\beta)(\beta - p\phi(\beta)) - 2c(1 + p\beta\phi(\beta))^3 = 0;$$
$$\beta - p\phi(\beta) \geq 0;\quad \mu_1 = \mu_3 = \mu_4 = 0,\quad \mu_2 = \frac{2cp(1 + p\beta\phi(\beta))}{k\beta} \geq 0.$$

ii. If $c \geq \beta^4\phi(\beta)k^2/2$, *then*

$$s = 0;\quad p = 0;\quad \mu_1 = \mu_2 = \mu_4 = 0;\quad \mu_3 = c - \frac{\beta^4\phi(\beta)k^2}{2} \geq 0.$$

10 $(\mu_1, \mu_2, \mu_3, \mu_4)$ are the corresponding Lagrange multipliers.

Given an inspection cost $c > 0$, it is more likely that the regulator inspects the firm when either the technology is dirty enough (i.e., when β is large) or when the firm's degree of profitability (k) is large enough.

If monitoring is not expensive (case i), then the optimal policy is such that the standard is zero and the probability of inspection is given implicitly by the expression $g(\beta,p) = 0$. If the regulator considered an infinitesimal increase in the standard, social welfare would decrease by μ_2, the Lagrange multiplier. This is due to the fact that the regulator would have to increase the inspection probability as well to induce the firm to pollute the same amount, which would increase monitoring costs.[11] Also, as expected, the optimal probability of inspection decreases when monitoring costs increase and when the degree of firm's profitability decrease. Considering (7), the optimal pollution level reduces to:

$$e(\beta,p) = \frac{\beta k}{2(1+p\beta\phi(\beta))}. \tag{9}$$

If monitoring is expensive enough (case ii), the best is to leave the firm unregulated (again, $\mu_3 \geq 0$ shows that an infinitesimal increase in the probability of inspection would reduce social welfare) and then the level of the standard loses importance (reflected in $\mu_2 = 0$). In this case, considering (7), the firm chooses $e = \beta k/2$.

3.3. Stage 3

Finally, we find the technology that maximizes the firm's expected payoff considering the solution to the two previous lemmas. First, considering (9), the firm's expected payoff reduces to the following expression:

$$\Pi(\beta) = ke - \frac{e^2}{\beta} - p\phi(\beta)(e-s)^2 = \frac{ek}{2}. \tag{10}$$

That is, the firm's expected payoff is an increasing linear function of the pollution level. We now present the problem the firm faces in this stage:[12]

11 The result $s = 0$ depends on the assumptions of strict convexity of the fines with respect to the degree of noncompliance and the complete information about k, the degree of profitability of the firm. The case of linear fines is studied in Arguedas and Hamoudi (2003), where we obtain a range of optimal standards (including zero always), each one of them associated to a different pair pollution level—technology investment, with the corresponding welfare implications. The case of incomplete information is studied in Arguedas (1999) in a simpler model in which firms choose pollution levels only, and an incentive compatible regulatory policy is obtained with different combinations of standards—probabilities associated with different values of k.

12 To be precise, in this stage the firm decides the level of the technology only, but it induces the probability of inspection through the expression $g(\beta,p) = 0$ obtained in stage two, due to the backward induction process that we are considering. Therefore, the problem in which the firm decides the level of the technology only is mathematically equivalent to the problem in which the firm decides both the technology and the probability of inspection. Here, we analyze the latter for purposes of clarity in presenting the results, and also to stress the fact that in this case the firm can manipulate the regulatory policy in its own benefit.

$$\begin{aligned} &\max_{\beta,p} \quad \frac{ek}{2}, \\ &\text{s.a.} \quad \beta - \overline{\beta} \leq 0, \\ &\qquad g(\beta,p) = k^2\beta^3\phi(\beta - p\phi) - 2c[1+p\beta\phi]^3 = 0, \\ &\qquad -\beta + p\phi(\beta) \leq 0; \quad -p \leq 0. \end{aligned} \tag{11}$$

The first restriction stands for the admissible range of choices of the technology β. The remaining restrictions come from stage 2 above, and link the technology and the probability of inspection for given parameters k and c. These restrictions come specifically from part (*i*) of Lemma 3.2, where $0 \leq c \leq \beta^4\phi(\beta)k^2/2$, and where the probability of inspection is positive. Remember that part (*ii*) of Lemma 3.2 summarizes the case of no regulation, and the solution to stage three in that case is obvious, that is, $\beta = \overline{\beta}$.

The following proposition summarizes the solution of problem (11), where $(\gamma_1, \ldots, \gamma_4)$ are the corresponding Lagrange multipliers. We have included the case of no regulation as case (*iii*).

Proposition 3.3: *Given $c \geq 0$ and $k > 0$, if the firm chooses the technology before the policy announcement and fines for noncompliance depend monotonically on β $(\phi'(\beta) \geq 0)$, then the solution is the following:*

i. If $0 \leq c \leq \beta^4\phi(\beta)k^2/2$, then

$$\begin{aligned} &\gamma_1 = \gamma_3 = \gamma_4 = 0; \quad \gamma_2 = \frac{k^2\beta}{4(1+p\beta\phi)^2[k^2\beta^2\phi + 6c(1+p\beta\phi)^2]} > 0, \\ &\beta^2\phi'(p\phi - \beta) + \phi(1-\beta^2) = 0, \\ &k^2\beta^4\phi^2\phi'(1-\beta^2) - 2c[\beta\phi'(1+\beta^2) - \phi(1-\beta^2)]^3 = 0, \\ &\beta \in (0,1]; \quad p \geq 0. \end{aligned}$$

ii. If $\beta^4\phi(\beta)k^2/2 \leq c \leq \overline{\beta}^4\phi(\overline{\beta})k^2/2$, then

$$\begin{aligned} &\gamma_1 = \gamma_3 = 0; \quad \gamma_2 = \frac{1}{4\beta^3[4\phi + \beta\phi']} > 0, \\ &\gamma_4 = \frac{k^2\phi[\phi(\beta^2-1) + \beta^3\phi']}{4(4\phi + \beta\phi')} \geq 0, \\ &k^2\beta^4\phi - 2c = 0; \quad p = 0. \end{aligned}$$

iii. If $c \geq \overline{\beta}^4\phi(\overline{\beta})k^2/2$, then

$$p = 0; \quad s \geq 0; \quad e = \frac{\overline{\beta}k}{2}; \quad \beta = \overline{\beta}.$$

Observe that this is the general solution of the three stage game for any $\phi(\beta) \geq \beta$. Concentrating on case (*i*) of the proposition, since $p\phi - \beta \leq 0$, we obtain that the optimal technology investment is at most one. Remember that the efficient technology level is $\beta^* = 1$ (see section 2, above). This means that the firm over-invests in a clean technology with respect to the efficient level as a means of having a more favorable policy with a smaller expected penalty for noncompliance. In this case, the optimal probability of inspection is positive, and it decreases as the monitoring costs increase. In case (*ii*) of the proposition, the optimal probability of inspection is zero. In this case, the firm induces the non-regulation with a sufficiently large effort in technology investment. This result is different from case (*iii*), in which the inspection probability is zero because monitoring costs are large enough.

In order to explain the overall solution of the problem, we now simplify the penalty structure considering two alternatives for the dependence of the fine on β : $\phi(\beta) = \beta$ and $\phi(\beta) = t$, where t is a positive parameter. The results of the two cases are presented in the Appendix as Models A and B, respectively. Also, we have computed the firm's expected payoff and social welfare (using (4) and (5), respectively), leaving the discussion for section 5.

In figure 1, we represent the solution when $\phi(\beta) = \beta$, specifically the relationships between the optimal technology β and the monitoring cost c, and the optimal pollution

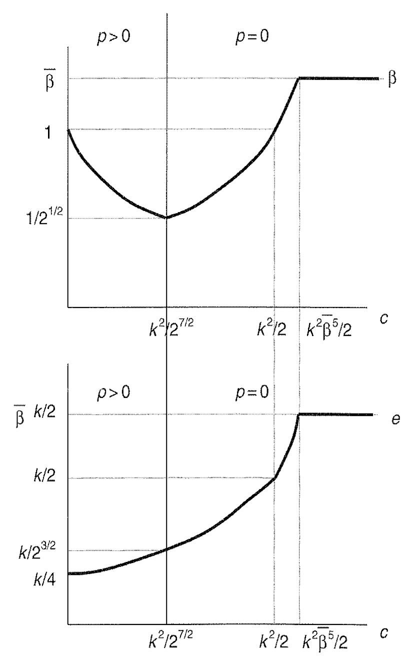

Figure 1. The optimal choice of the firm in the three-stage game when $\phi(\beta) = \beta$.

level e and the monitoring cost. In the horizontal axis of both graphs, we measure the monitoring cost. In the vertical axis of each graph, we measure the technology and the pollution level, respectively.

When monitoring is cheap enough (case i), it is optimal for the regulator to monitor the firm ($p > 0$), and the smaller the cost, the larger the probability of inspection. Observe that $p^* = 1, \beta^* = 1$ and $e^* = k/4$ when $c = 0$. That is, the regulator can induce the efficient solution when monitoring has zero cost only. Also, there exists a negative relationship between the technology level and the monitoring cost, and a positive relationship between the pollution level and the monitoring cost. Therefore, the firm over-invests in technology with respect to the efficient level.

When monitoring is expensive enough (cases *ii* and *iii*), it is optimal to leave the firm unregulated ($p = 0$). However, there is a range of values of the monitoring cost (case *ii*) where the firm induces $p = 0$ through the appropriate selection of the technology and the pollution level. The larger the monitoring cost, the larger both the technology and the pollution level necessary to induce a zero inspection probability. Finally, there exists a threshold value of the monitoring cost ($c = k^2\bar{\beta}^5/2$) beyond which we obtain $\beta = \bar{\beta}$ and $e = \bar{\beta}k/2$, respectively, the technology and pollution level chosen by the firm in the absence of regulation.

In figure 2, we represent the solution when $\phi(\beta) = t$. Here, when monitoring is cheap

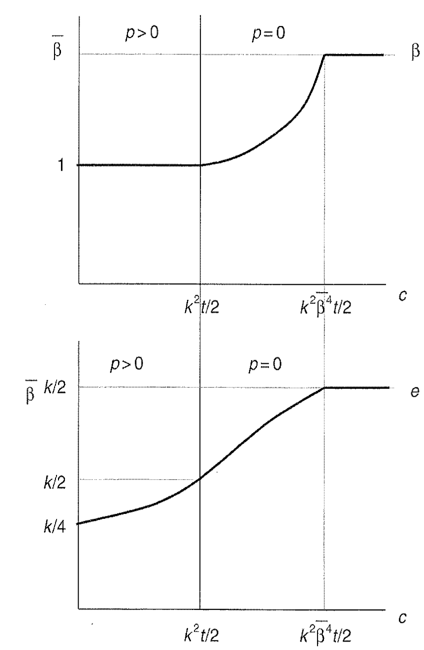

Figure 2. The optimal choice of the firm in the three-stage game when $\phi(\beta) = t$.

enough (case *i*), the firm is monitored, but the fine for noncompliance does not depend on the technology β. In this case, the optimal technology level on that range is equal to 1, the efficient level. Now, when $c = 0$, we have that $p^* = 1/t$, $\beta^* = 1$ and $e^* = k/4$. Therefore, the regulator can induce the efficient solution when monitoring has zero cost only, as in the previous case. The difference is that here the regulator needs to inspect the firm with a smaller frequency than before and, therefore, with smaller associated monitoring costs. This is the reason why the regulator in general prefers that fines are independent of β in the three stage game, as we will see in section 5. When monitoring is expensive enough (cases *ii* and *iii*), the firm is left unregulated. In case (*ii*), the firm induces that non-regulation through the appropriate selection of β.

4. Results of the Two-Stage Game

Now, the regulator first announces the policy (s, p). The firm then selects both the pollution level e and the technology β. As in the previous section, we solve the problem backwards to find the subgame perfect equilibrium. Therefore, in the first stage we find the optimal firm's response to any announced regulatory policy. Then, in the second stage we find the policy that maximizes social welfare considering the firm's response.

In order to establish a comparison with the results of the previous section, we analyze the two cases, $\phi(\beta) = \beta$ and $\phi(\beta) = t$. Here, we consider the resolution of each case separately from the first stage, since the specific form of $\phi(\beta)$ affects the firm's decision on β and e.

4.1. Stage 1

Given the policy (s, p), the firm solves the following problem:

$$\max_{e,\beta} \left\{ ke - \frac{e^2}{\beta} - p\phi(\beta)(e-s)^2 \right\},$$
$$\text{s.a.} \quad s - e \le 0; \quad e - \frac{k\beta}{2} \le 0; \quad \beta - \overline{\beta} \le 0. \tag{12}$$

Lemma 4.1: *The solution to problem* (12) *when* $\phi(\beta) = \beta$ *is the following*:

i. If $(k + 2p^{1/2}s) - \overline{\beta}p^{1/2}(k - 2p^{1/2}s) \le 0$, *then*

$$e = \frac{k + 2p^{1/2}s}{4p^{1/2}}; \quad \beta = \frac{k + 2p^{1/2}s}{kp^{1/2} - 2ps},$$
$$\lambda_1 = \lambda_2 = 0; \quad k > 2p^{1/2}s.$$

ii. Else

$$e = \frac{\overline{\beta}(k + 2p\overline{\beta}s)}{2(1 + p\overline{\beta}^2)}; \quad \beta = \overline{\beta},$$
$$\lambda_1 = \lambda_2 = 0; \quad \lambda_3 = \frac{e^2}{\beta^2} - p(e-s)^2 \ge 0.$$

In case (*i*), as expected, the pollution level is positively related to the standard and negatively related to the probability of inspection. Also, the technology level is positively related to the standard, and negatively related to the probability of inspection only when $s = 0$. In case (*ii*), the sense of the relationships of the pollution level and both the standard and the probability of inspection are the same as those of case (*i*). Here, we obtain exactly the same solution as the one presented in Lemma 3.1, when $\phi(\beta) = \beta$ and $\beta = \overline{\beta}$.

Lemma 4.2: *The solution to problem* (12) *when* $\phi(\beta) = t$ *is*

$$e = \frac{\overline{\beta}(k + 2pts)}{2(1 + pt\overline{\beta})}; \quad \beta = \overline{\beta},$$
$$\lambda_1 = \lambda_2 = 0; \quad \lambda_3 = \left(\frac{k + 2pts}{2(1 + \overline{\beta}pt)} \right)^2 > 0.$$

Here, since the firm plays after the regulator and fines do not depend on the selected technology, the firm chooses the cheapest technology. Therefore, the solution to problem (12) when $\phi(\beta) = t$ is equivalent to that of Lemma 3.1, when $\phi(\beta) = t$ and $\beta = \overline{\beta}$.

4.2. Stage 2

The summary of the overall solution of the cases $\phi(\beta) = \beta$ and $\phi(\beta) = t$ is in the Appendix, Models C and D, respectively. In Model C, case (*i*) corresponds to case (*i*) of Lemma 4.1; cases (*ii*) and (*iii*) correspond to case (*ii*) of Lemma 4.1, and they are equivalent to cases (*i*) and (*ii*) of Lemma 3.2 when $\beta = \overline{\beta}$. By contrast, the solution to Model D is identical to that of Lemma 3.2, where $\beta = \overline{\beta}$ and $\phi(\beta) = t$.

In Model C, the firm decides to optimally under-invest in technology, that is, $\beta \ge 1$. We only have $\beta = 1$ when monitoring is costless, where the optimal probability of inspection is $p = 1$. Here, we also have that the pollution level is positively linked to the monitoring costs. But, contrary to the results of the three-stage game presented in the previous section, the technology investment is positively related to the monitoring costs also. This is so because in this case the firm cannot induce a lenient regulation with the selection of a more expensive technology and, therefore, the extra investment cost cannot be compensated with smaller expected fines. Cases (*ii*) and (*iii*) of Model C are exactly the same as those of Lemma 3.2, when $\beta = \overline{\beta}$ and $\phi(\beta) = \beta$. Here, only when monitoring is expensive enough (case *iii*), the authority optimally decides to leave the firm unregulated, which results in $\beta = \overline{\beta}$ and $e = k\overline{\beta}/2$. These results are different from those of the three-stage game, in which the firm decides, in advance, a sufficiently expensive technology to induce a zero expected fine for noncompliance. By contrast, in Model D, the regulator cannot persuade the firm to invest in a cleaner technology since it does not provide the necessary incentives.

5. Discussion

In this section, we compare the results of the solutions obtained in sections 3 and 4 in terms of the firm's expected payoff and social welfare, whose general expressions are in the Appendix.

Due to the difficulty of comparing the results, we have concentrated on the following example. Observe that the firm's degree of profitability (k) positively affects both the firm's expected payoff and the social welfare in the four problems. Therefore, from now on, and without loss of generality, we consider $k = 1$. As for the other parameters of the problem (t and $\overline{\beta}$), we take the case in which $t = \overline{\beta} = 2$. We consider both parameters equal in order to make the four problems equivalent from a sufficiently large level of the monitoring cost, as we will see later on.

Considering the mentioned levels of the parameters, we have computed the corresponding values of the firm's expected payoff and the social welfare for alternative levels of the monitoring costs and the results are depicted in figures 3 and 4, respectively.

Regarding figure 3, the firm's expected payoff is positively related to the monitoring costs. This is so because, when the monitoring costs increase, the announced probability of inspection is smaller and, therefore, this is beneficial for the firm's own interest. We also see that the three-stage game is superior to the two stage game from the firm's viewpoint, independently of the selected structure of the fines ($\pi_A \geq \pi_C$ and $\pi_B \geq \pi_D$, for all $c \geq 0$). This can be explained arguing that, in the three-stage game, the firm can affect the regulatory policy, anticipating the investment in technology. In section 3, we obtained that this anticipation results in an over-investment in technology with respect to the efficient

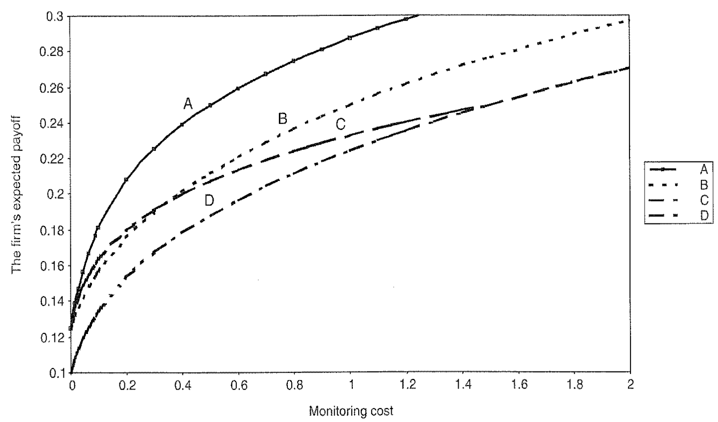

Figure 3. The firm's expected payoff as a function of the monitoring cost.

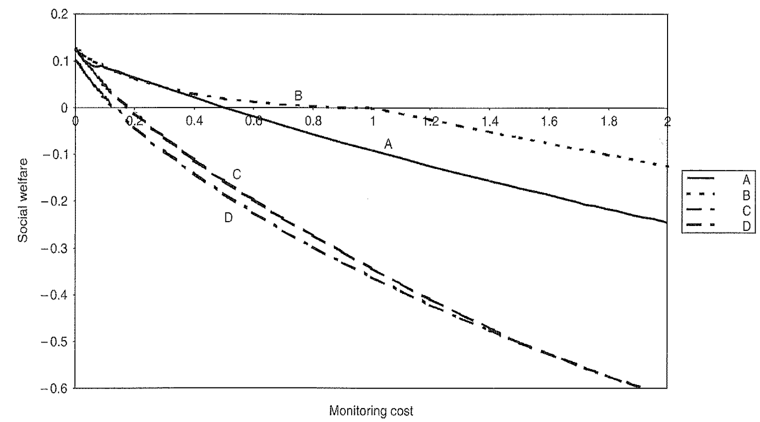

Figure 4. The social welfare as a function of the monitoring cost.

level, but this is more than compensated with a lenient regulation that allows for a saving in expected penalties. For example, in Model A, the optimal probability of inspection is zero if $c \geq \sqrt{2}/16$, and if $c \geq 1$ in Model B. However, at those levels of the monitoring costs, the respective optimal probabilities of inspection in Models C and D are $p_C = 0.60213$ and $p_D = 0.6984$ if $c = \sqrt{2}/16$, and $p_C = 0.28797$ and $p_D = 0.30737$ if $c = 1$. Also, the firm weakly prefers that fines depend on the investment in technology, since the firm has more flexibility in this case to affect penalties (we obtain $\pi_A > \pi_B$, when $c < 16$ and $\pi_C > \pi_D$, when $c < 1$). Finally, the results of the four problems are equivalent when $c \geq 16$, where the firm is unregulated and decides $e^* = 1$, $\overline{\beta}^* = 2$, resulting in $\pi^* = 0.5$ and $R^* = -1.5$.[13]

Considering figure 4, social welfare is negatively related to the monitoring costs. Surprisingly, the three-stage game is also superior to the two-stage game from the regulator's viewpoint (here, we have $R_A \geq R_C$ and $R_B \geq R_D$, for all $c \geq 0$). The explanation is that, in the former case, the regulator creates the firm's necessary inducement to invest in technology with the promise of a lenient regulation and the corresponding savings in monitoring costs and environmental damages. For instance, in problem A, the optimal probability of inspection is zero when $c = \sqrt{2}/16$, resulting in $\beta_A = 1/\sqrt{2}$, $e_A = \sqrt{2}/4$ and $R_A = 0.088$. However, at that same monitoring cost, we have $p_C = 0.60213$, $\beta_C = 1.2887$, $e_C = 0.322175$ and $R_C = 0.04564$. Also, at $c = 1$, we obtain $p_B = 0$, $\beta_B = 1$, $e_B = 1/2$ and $R_B = 0$, while $p_D = 0.30737$, $\beta_D = 2$, $e_D = 0.4485$ and $R_D = -0.3618$. Regarding the structure of the fines preferred by the regulator, we see that

13 All these results are true in general with some precisions. For instance, in the three-stage game, the firm prefers a fine contingent on β to a fixed fine at least when the regulator imposes a positive probability of inspection. However, when monitoring costs are large enough, we might have the opposite result if $\overline{\beta} > t$, since the firm may achieve maximum profits $k^2\overline{\beta}/4$ earlier when fines do not depend on β.

it depends on the game we consider. In the three-stage game, in general, the regulator prefers Model B to A. In both cases, the firm has incentives to invest in clean technology, but in the second case, the firm has more flexibility to avoid the penalty, with the appropriate over-investment in the technology. However, in the two-stage game, the regulator prefers Model C to D, since with the latter structure, the firm has no incentive to invest in clean technology at all, resulting in large environmental damages.[14]

Summarizing, both the firm and the regulator would agree that the three-stage game is beneficial for both, that is, the fact that the firm may invest in technology in advance of the policy announcement. Therefore, this would result in inspections being very occasional and, therefore, expected penalties being very small. In fact, expected penalties are zero in problem A when $c \geq \sqrt{2}/16$, and in problem B when $c \geq 1$, while expected penalties are zero in problems C and D when $c \geq 16$. While it seems logical that the firm would prefer to anticipate its investment to the policy announcement, however, it is quite surprising that the regulator would also prefer that anticipation, since the subsequent penalties for noncompliance would be very small. The explanation for this result relies on the fact that the regulator induces the firm to over-invest in technology if it waits to announce the policy, obtaining small environmental damages with small expected monitoring costs. Finally, while the firm always prefers that fines depend on the investment in technology, the regulator would only prefer that possibility in the two-stage game, that is, when the firm postpones its investment decision.

6. Conclusions

In this paper, we have presented a principal-agent model in which the regulator chooses the terms of the policy and the firm selects the pollution level and the investment in environmental technology. By considering fines contingent on that investment together with the degree of noncompliance, we have shown that the firm over-invests in clean technology when that investment is prior to the policy announcement; while it under-invests in clean technology when that decision is taken after knowing the terms of the policy.

We have shown that the firm prefers that fines are contingent on the technology investment, independently of the timing of that decision with respect to the policy announcement. However, that timing is relevant for deciding the best structure of the fines from the regulator's viewpoint, since it prefers fixed fines when the firm decides the investment first, and contingent fines when the investment decision is made afterwards.

Finally, we have found that both the firm and the regulator prefer that the firm anticipates its investment decision. On one hand, the firm obtains a lenient regulation

14 Again, these results can be extended at least for the values of the monitoring costs for which the regulator imposes a positive probability of inspection. However, if monitoring costs are large enough and $\overline{\beta} > t$, social welfare achieves its minimum earlier under $\phi(\beta) = t$ than under $\phi(\beta) = \beta$, which means that, for those values, the regulator might prefer the scheme $\phi(\beta) = \beta$.

overinvesting in pollution technology; on the other hand, society saves monitoring costs and environmental damages.

In light of these results, environmental authorities would promote technology investment with a very simple mechanism: the regulator would announce that a regulatory policy with the characteristics studied would be implemented in a near future, and that investment in technology would be considered in the monitoring/sanctioning process. Given that announcement, the firm would realize that it is better to anticipate its investment, since it can induce a lenient regulation. Therefore, the regulator would only need to give enough time for firms to invest in technology and, contingent on that, announce the terms of the policy.

Since we have considered a complete information model, one may ask why not then using a command-and-control regulation that forces the firm to choose the efficient levels of pollution and technology investment. First, we are allowing for firm's sovereignty, which is particularly important in the three-stage-game, where the firm decides to over-invest in technology to influence in the regulatory policy. And second, the results of this paper can be used as a benchmark for more general settings under incomplete information.

For instance, some extensions may include the possibility to have violations to positive standards, an aspect normally observed in practise that cannot be explained here. Our results suggest that probabilistic taxes (i.e., standards equal to zero, with a positive chance of being discovered) are always better than positive standards from an optimal point of view, at least when fines are strictly convex in the degree of violation and when there is complete information about the characteristics of the firms. We believe that some kind of asymmetry with respect to those characteristics may result in violations to positive standards. Also, we could consider that technology investments are effort variables that cannot be observed by regulators and, therefore, sanctions have to be contingent on the resulting damages. All these issues are left for further research.

Appendix

Model A. *The optimal policy in the three-stage game when* $\phi = \beta$

i. If $0 \leq c \leq k^2\sqrt{2}/16$, *then*

$$p = 2 - \frac{1}{\beta^2}; \quad s = 0; \quad e = \frac{k}{4\beta}; \quad k^2(1-\beta^2) - 16c\beta^3 = 0; \quad \pi = \frac{k^2}{8\beta};$$
$$R = \frac{k^2[\beta^4 + (2\beta^2 - 1)^2]}{16\beta^3}.$$

ii. If $k^2\sqrt{2}/16 \leq c \leq k^2\overline{\beta}^5/2$, *then*

$$p = 0; \quad s \geq 0; \quad e = \left(\frac{k^3 c}{16}\right)^{1/5}; \quad \beta = \left(\frac{2c}{k^2}\right)^{1/5}$$

$$\pi = \frac{k^2\beta}{4}; \quad R = \frac{k^2\beta(1-\beta^2)}{4}.$$

iii. If $c \geq k^2\overline{\beta}^5/2$, *then*

$$p = 0; \quad s = 0; \quad e = \frac{\overline{\beta}k}{2}; \quad \beta = \overline{\beta}; \quad \pi = \frac{k^2\overline{\beta}}{4}; \quad R = \frac{k^2\overline{\beta}(1-\overline{\beta}^2)}{4}.$$

Model B. *The optimal policy in the three-stage game when* $\phi = t$

i. If $0 \leq c \leq k^2t/2$, *then*

$$k^2t(1-pt) - 2c(1+pt)^3 = 0; \quad s = 0; \quad e = \frac{k}{2(1+pt)};$$

$$\beta = 1; \quad \pi = \frac{k^2}{4(1+pt)}; \quad R = \frac{p^2k^2t^2}{(1+pt)^3}.$$

ii. If $k^2t/2 \leq c \leq k^2\overline{\beta}^4t/2$, *then*

$$p = 0; \quad s \geq 0; \quad e = \left(\frac{ck^2}{8t}\right)^{1/4}; \quad \beta = \left(\frac{2c}{k^2t}\right)^{1/4};$$

$$\pi = \frac{k^2\beta}{4}; \quad R = \frac{k^2\beta(1-\beta^2)}{4}.$$

iii. If $c \geq k^2\overline{\beta}^4t/2$, *then*

$$p = 0; \quad s = 0; \quad e = \frac{\overline{\beta}k}{2}; \quad \beta = \overline{\beta}; \quad \pi = \frac{k^2\overline{\beta}}{4}; \quad R = \frac{k^2\overline{\beta}(1-\overline{\beta}^2)}{4}.$$

Model C. *The optimal policy in the two-stage game when* $\phi = \beta$

i. If $0 \leq c \leq 3k^2\overline{\beta}^3(\overline{\beta}^2 - 1)/32$, *then*

$$3k^2(1-p) - 32p^{5/2}c = 0; \quad s = 0; \quad e = \frac{k}{4p^{1/2}};$$

$$\beta = \frac{1}{p^{1/2}}; \quad \pi = \frac{k^2\beta}{8}; \quad R = \frac{k^2\beta(2-\beta^2)}{8}.$$

ii. If $3k^2\overline{\beta}^3(\overline{\beta}^2 - 1)/32 \leq c \leq k^2\overline{\beta}^5/2$, *then*

$$\overline{\beta}^5k^2(1-p) - 2c(1+p\overline{\beta}^2)^3 = 0; \quad s = 0;$$

$$e = \frac{k\overline{\beta}}{2(1+p\overline{\beta}^2)}; \quad \beta = \overline{\beta}; \quad \pi = \frac{k^2\overline{\beta}}{4(1+p\overline{\beta}^2)};$$

$$R = \frac{k^2\overline{\beta}[(1-\overline{\beta}^2)(1+3p\overline{\beta}^2) + 4p^2\overline{\beta}^4]}{4(1+p\overline{\beta}^2)}.$$

iii. If $c \geq k^2\overline{\beta}^5/2$, *then*

$$p = 0; \quad s = 0; \quad e = \frac{\overline{\beta}k}{2}; \quad \beta = \overline{\beta}; \quad \pi = \frac{k^2\overline{\beta}}{4}; \quad R = \frac{k^2\overline{\beta}(1-\overline{\beta}^2)}{4}.$$

Model D. *The optimal policy in the two-stage game when* $\phi = t$

i. If $0 \leq c \leq k^2\overline{\beta}^4t/2$, *then*

$$\overline{\beta}^3k^2t(\overline{\beta} - pt) - 2c(1+p\overline{\beta}t)^3 = 0; \quad s = 0; \quad e = \frac{\overline{\beta}k}{2(1+p\overline{\beta}t)}; \quad \beta = \overline{\beta};$$

$$\pi = \frac{k^2\overline{\beta}}{4(1+p\overline{\beta}t)}; \quad R = \frac{k^2\overline{\beta}[(1-\overline{\beta}^2)(1+3p\overline{\beta}t) + 4p^2\overline{\beta}^2t^2]}{4(1+p\overline{\beta}t)}.$$

ii. If $c \geq k^2\overline{\beta}^4t/2$, *then*

$$p = 0; \quad s = 0; \quad e = \frac{\overline{\beta}k}{2}; \quad \beta = \overline{\beta}; \quad \pi = \frac{k^2\overline{\beta}}{4}; \quad R = \frac{k^2\overline{\beta}(1-\overline{\beta}^2)}{4}.$$

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EDITOR'S REPORT

Submissions

In 2003, the *Journal of Regulatory Economics* (*JRE*) received and processed 91 papers. The Journal has averaged 103 papers a year for the last 4 years, with a record of 121 papers received in 2001. Prior to 2000 the record for submissions was 98 received in 1999. *JRE* has received a total of 1313 papers through December 2003, including 25 papers that were judged by the Editor to be outside the scope of the Journal. Overall, the average is 7.1 submissions per month. June is the month with the highest average for submissions, while the fewest submissions are received in December.

Refereeing

Since its inception, *JRE* has received a total of 2,236 referee reports for an average of 144 reports per year. Of 1,288 papers refereed, 30% of decisions were made with one referee report; 6% with three reports; and 64% with two referee reports each. However, in the case of papers which were declined, 38% were declined on the basis of only one referee report. Overall, 47 days was the mean response time to requests for referee reports. In the last 4 years we have consulted 100 referees in addition to those on our Editorial Board.

Decisions

JRE aims to provide prompt decisions to those submitting papers, where prompt is defined as being within two months. From 2000-2003 this goal was achieved 58% of the time, and 52% of the time since the inception of the Journal. The longest decision took 186 days (approximately six months). The mean decision time was 56 days in 2003 and 54 days in 2002. The mean was 60.4 days since the journal began. Overall, 86% of decisions were made within three months, and less than 3% of decisions took more than four months.

From 2000-2003, 2% of papers were accepted, 8% were accepted subject to revision, 30% were declined with the opportunity to revise and resubmit (with the revised paper going back to the original referees), and 60% were declined. Since the beginning, 2% of papers have been accepted; 10% revise; 39% declined with option to revise; and 49% declined.

Of the 123 papers submitted in four-year period that were declined with the option to revise, 71 (58%) have been revised. Of these, 50 (70%) have been accepted for publication, with another seven still under consideration.