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Environmental Enforcement with Endogenous Ambient Monitoring

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Summary

We consider an inspection game between "n" polluting firms and an environmental enforcement agency. If the cost of monitoring ambient pollution is low enough, the optimal inspection policy consists in imposing the maximal possible fine, and mixing between observing ambient pollution and not conducting any inspection at all. However, with stringent upper limits on the fine, the agency mixes between observing ambient pollution and inspecting all firms. The observation of ambient pollution is always followed by sequentially rational firm inspections. Comparisons with Franckx (2002a,2002b) show that commitment power has a very strong impact on the value of prior information.

Keywords: Environmental enforcement, ambient inspections, commitment

JEL: K42, Q20

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1 Introduction

Several authors have proposed to use ambient-based policies to regulate nonpoint source pollution - see for instance the survey in Xepapadeas (1999). The basic idea, first proposed by Segerson (1988), is that polluters would pay *full* marginal damages per unit deviation if ambient pollution concentration exceeds a given target, rather than their *contribution* to marginal damages. Thus, the tax basis is not individual emissions of the polluter, but observed ambient pollution. Others (see, for instance, Shortle and Abler (1997)) have however pointed out some problems with the feasibility of the proposed schemes.

A slightly different approach would be to compare a setting where the enforcement agency observes ambient pollution to guide its *enforcement* efforts with a setting where such ambient inspections do not take place. To the best of our knowledge, Franckx (2002a) and Franckx (2002b) are the first contributions using this approach.

A key question raised in these papers is how the only parameter that is determined by public authorities (the fine for noncompliance) affects the desirability of ambient monitoring. The answer is that the role of the fine depends crucially on the commitment power of the enforcement agency. In Franckx (2002b), it is assumed that the enforcement agency can commit both to the probability of firm-level inspections and to ambient monitoring. It is then shown that for high fines, the agency will prefer not to conduct ambient inspections. In Franckx (2002a), the agency can commit to ambient monitoring, but not to the probability of firm-level inspections. In this context, higher values of the fine *increase* the desirability of ambient inspections from the inspection agency's point of view.

In this paper, we drop the assumption that the agency can commit to ambient monitoring[1] and we endogenize the decision to hold ambient inspections. Therefore, we use the perfect Bayesian equilibrium solution concept (PBE): each player' strategy must be a best response to the others' equilibrium strategy (the strategies must thus constitute a Nash equilibrium (NE)). Moreover, if the agency conducts ambient inspections, it must update its *a priori* beliefs with respect to the firms' strategies according to Bayes' rule wherever possible. We show that this slight change in the institutional context again *completely* changes the role played by the fines for noncompliance.

Besides this change in the setting of the model, we also offer two technical generalizations: Franckx (2002a) and Franckx (2002b) use a very specific and controversial objective function for the inspection agency, and assume that the agency can put inspected noncompliant firms in compliance. We show that changing these assumptions does not affect the main results at all.

Finally, we extend the two-firm model considered in Franckx (2002a) to an arbitrary number of firms.

The technical and notational assumptions of this paper are the following.

We consider n polluting firms, who have no interaction, neither in the input, nor in the output market. They can choose between two levels of abatement expenditure, α and 0. If a firm spends α, it is in compliance. We assume a one-to-one relationship between emissions and the chosen abatement technology, so that the environmental damage due to the choice of a particular abatement technology only depends on that technology; we exclude any stochastic influences.

We assume that, for the agency, the cost of the compliant abatement technology is D_c; the cost of noncompliance will be represented as D_{nc}. Note that D_{nc} and D_c can be given a wide range of interpretations. For instance, if the agency maximizes social welfare, D_{nc} and D_c are the monetary value of environmental damages net of private compliance costs. Or, alternatively, for an agency that narrowly focuses on environmental effects, D_{nc} and D_c are just the monetary value of environmental damages. We assume that $D_{nc} > D_c$: otherwise, the agency would have no reason to pursue compliance.

Ambient environmental inspections costs a per time period. Inspecting the firm costs b. If a firm is inspected and is found in noncompliance it will have to pay a fine $\Psi > 0$ with certainty. Except in Section 3.2.5, we assume that this fine is set by a higher authority in government, say the legislator, and is thus exogenous in this model.

We also assume that the agency derives *some* benefit $\triangle$ from inspecting a noncompliant firm. For instance, the career perspectives of the agency's staff may depend on the number of detected noncompliant firms, or the staff may derive some moral satisfaction from fining noncompliant firms. Alternatively, the agency might have the authority to put a noncompliant in compliance during an inspection; $\triangle$ then represents the environmental benefit (net of private compliance costs) of inspecting a noncompliant firm. In order to allow for this latter interpretation, we shall from now on assume that a firm that is found in noncompliance has to incur a fraction γ of the costs of purchasing the new abatement technology, where $\gamma \in \{0, 1\}$. However, we shall assume no redistribution of fines to the agency, so that $\triangle$ is completely independent from Ψ.

Finally, we shall assume that $\triangle < D_{nc} - D_c$. This condition means that, even with zero inspection costs, the agency derives larger benefits from spontaneous compliance than from putting noncompliant firms in compliance. This assumption is not obvious, but will only turn out to be crucial in the proof of Lemma 15.

We only consider equilibria where the firms all play the same strategy. In the specific case of two polluting firms, Franckx (2002a) has shown the existence of equilibria where the firms play different strategies. The assumption of symmetry in the firms' strategies is thus only introduced to keep the analysis tractable, but excludes possibly interesting asymmetric behavior.

All parameters of the model are common knowledge.

The structure of the paper is as follows. In Section 2, we determine the agency's best response for any given probability of compliance. Next, we determine the firms' best response to the agency's and the other firms' strategies (Section 3). We show then that for all possible relative parameter values, we have a unique PBE. In Section 4, we show that the conclusions obtained in Franckx (2002a) and Franckx (2002b) do not depend, nor on the agency's objective function, neither on the assumption that the agency can put noncompliant firms in compliance. Thus, the agency's commitment power is the only critical factor in the outgome of the game. Section 5 summarizes the main findings.

2 The agency's best response

Suppose that the firms comply with probability p_α.

What is then the agency's optimal reaction?

First note that the inspection agency will certainly not undertake any type of inspections if $b > \triangle$: if the cost of inspecting one firm is higher than the benefit of bringing one non-compliant firm into compliance, it is optimal for the agency never to inspect. Therefore, we shall not consider $b > \triangle$ again.

Proposition 1 *If $b > \triangle$, the agency does not undertake any inspections (neither ambient inspections nor firm inspections). The firms never comply.*

In what follows, we shall also ignore the limiting case $b = \triangle$. The probability that these two technical parameters are equal to each other is zero, and the relevance of this case can thus be doubted. Moreover, allowing this to happen would lead to indeterminacies.

As the specific case of two polluting firms has been treated in detail in Franckx (2002a), we also assume from now on that $n > 2$.

In Section 2.1, we derive the agency's cost function with ambient inspections, assuming that it conducts sequentially rational strategies. In Section 2.2, we determine the agency's cost function without ambient inspections. In Section 2.3, we determine the agency's best response for a given probability of compliance. The mathematical details of the arguments used in Section 2.3 are given in Appendix A.

2.1 With ambient inspections

If the agency conducts ambient inspections, the timing of the game is:

- The firms simultaneously choose their abatement technology, without knowing whether the agency observes ambient pollution or not
- The enforcement agency observes ambient levels
- The enforcement agency chooses the firms it will inspect

We assume that the agency perfectly observes ambient levels and can thus correctly infer how many firms comply: it faces two singleton (all firms comply, no firm complies) and $n - 1$ non-singleton information sets.

In a perfect Bayesian equilibrium (PBE), the agency's strategy at each information set must be sequentially rational.

Let $p(i|j)$ be the probability that the agency inspects firm i if ambient inspections show that j firms comply and the others do not comply.

Let $\mu(i|j)$ be the agency's belief that firm i does not comply given that this information set has been reached. If the firms play the same strategy, then consistency requires $\mu(i|j) = \frac{n-j}{n}$.

It is straightforward to see that expected costs for the agency when this information set has been reached are:

$$a + (n-j)D_{nc} + jD_c + \sum_{i=1}^{n} p(i|j)\{b - \frac{n-j}{n}\triangle\} \tag{1}$$

Indeed, if the agency does not inspect any firm when this information set has been reached, its expected costs are $a + (n-j)D_{nc} + jD_c$. If it inspects firm i, its costs increase by $b - \frac{n-j}{n}\triangle$.

Excluding the limiting case $b = \frac{n-j}{n}\triangle$,[2] we can immediately conclude that if ambient inspections show that j firms comply

- the agency will inspect all firms with certainty if $b < \frac{n-j}{n}\triangle$; the agency's expected costs if this information set has been reached are then $a + nb - (n-j)\triangle + (n-j)D_{nc} + jD_c$.
- it will never inspect any firm if $b > \frac{n-j}{n}\triangle$; the agency's expected costs if this information set has been reached are then $a + (n-j)D_{nc} + jD_c$.

Now note that $\forall i < j, b < \frac{n-j}{n}\triangle$ implies $b < \frac{n-i}{n}\triangle$. In words, if it is sequentially rational to inspect all firms if j firms comply, then it is certainly sequentially rational to inspect all firms if less than j firms comply.

Moreover, because $\triangle > b$, there exists a natural number k such that $\frac{n-k-1}{n}\triangle < b < \frac{n-k}{n}\triangle$. This number exists and is unique, because $\frac{n-k-1}{n}\triangle < b < \frac{n-k}{n}\triangle \Leftrightarrow \frac{n(\triangle-b)}{\triangle} > k > \frac{(n-1)\triangle-nb}{\triangle}$ and $\frac{n(\triangle-b)}{\triangle} - \frac{(n-1)\triangle-nb}{\triangle} = 1$.

This implies immediately:

Lemma 1 *For any number of polluting firms n, there exists one and only one critical number of complying firms $k(n)$ such that $\frac{n-k-1}{n}\triangle < b < \frac{n-k}{n}\triangle$, and thus that*

- *the agency will inspect all firms with certainty if ambient inspections show that k firms or less comply;*
- *the agency will not inspect any firm if ambient inspections show that $k+1$ firms or more comply*

In other words, sequential rationality requires that the agency uses a "threshold strategy". As long as ambient pollution does not exceed an endogenous threshold, the costs of inspecting the firms are higher than the expected environmental benefits of putting them in compliance. Ambient inspections thus allow to avoid inspection costs that are suboptimal *ex post*. Note that as long as the firms play the same strategy, the threshold is independent from the firms' behavior: it only depends on n, b and $\triangle$.

If all the firms comply with probability p_α, then the probability that a given number j out of the n firms comply follows the binomial distribution $\binom{n}{j}(1-p_\alpha)^{n-j}(p_\alpha)^j$ (where $\binom{n}{j}=\frac{n!}{j!(n-j)!}$).

To simplify notation, let $p^n_{p_\alpha,j}=\binom{n}{j}(1-p_\alpha)^{n-j}(p_\alpha)^j$.

If the agency and the firms play their equilibrium strategy, then the probability that the agency will inspect the firms is equal to $(1-p_\alpha)^n+\sum_{j=1}^{k}p^n_{p_\alpha,j}$.

With a slight abuse of notation, we shall from now on write:

- $\sum_{j=0}^{k}p^n_{p_\alpha,j}$ instead of $(1-p_\alpha)^n+\sum_{j=1}^{k}p^n_{p_\alpha,j}$, which is correct as long as $p_\alpha>0$. If $p_\alpha=0$, then $(1-p_\alpha)^n+\sum_{j=1}^{k}p^n_{p_\alpha,j}=1$.
- $\sum_{j=k+1}^{n}p^n_{p_\alpha,j}j$ instead of $\{\sum_{j=k+1}^{n-1}p^n_{p_\alpha,j}j\}+(p_\alpha)^n n$, which is correct as long as $p_\alpha<1$. If $p_\alpha=1$, then $\{\sum_{j=k+1}^{n-1}p^n_{p_\alpha,j}j\}+(p_\alpha)^n n=n$.

Thus, if the agency conducts ambient inspections followed by sequentially rational firm inspections, its expected costs ($C_a^{k,n}$) in equilibrium are :

$$\begin{aligned}C_a^{k,n} &= a+\{\sum_{j=0}^{k}p^n_{p_\alpha,j}[nb+(n-j)D_{nc}+jD_c-(n-j)\triangle]\}\\ &\quad +\{\sum_{j=k+1}^{n}p^n_{p_\alpha,j}[(n-j)D_{nc}+jD_c]\}\end{aligned} \quad (2)$$

Indeed, the probability that the agency will reach an information set where j firms comply is $p^n_{p_\alpha,j}$. If $j\leq k$, all firms are inspected and the agency's expected costs in the information set are $a+nb+(n-j)D_{nc}+jD_c-(n-j)\triangle$. If $j>k$, no firm is inspected and the agency's expected costs in the information set are $a+(n-j)D_{nc}+jD_c$.

$C_a^{k,n}$ can be simplified to:

$$\begin{aligned}&a+\sum_{j=0}^{k}p^n_{p_\alpha,j}n(b-\triangle)+nD_{nc}+[D_c-D_{nc}+\triangle]\{\sum_{j=0}^{k}p^n_{p_\alpha,j}j\}\\ &\qquad +[D_c-D_{nc}]\{\sum_{j=k+1}^{n}p^n_{p_\alpha,j}j\}\end{aligned} \quad (3)$$

2.2 Without ambient inspections

Now suppose that the agency does not conduct ambient inspections:

- If the agency does not inspect the firms, its expected costs are:

$$np_\alpha D_c+n(1-p_\alpha)D_{nc} \quad (4)$$

- If the agency inspects all firms individually, its expected costs are:

$$np_\alpha D_c + n(1-p_\alpha)D_{nc} + nb - n(1-p_\alpha)\triangle \tag{5}$$

Thus, if the agency does not conduct ambient inspections, it will inspect all firms iff $(1-p_\alpha)\triangle > b$. Note that this condition can be rewritten as $\frac{\triangle - b}{\triangle} > p_\alpha$.

2.3 The best response

Let $\nabla_1^{na,a}(p_\alpha)$ be the difference between the agency's expected costs without and with ambient inspections if $\frac{\triangle - b}{\triangle} \geq p_\alpha$. Equations 3 and 5 imply that:

$$\begin{aligned}\nabla_1^{na,a}(p_\alpha) &= \\ np_\alpha D_c + n(1-p_\alpha)D_{nc} + nb - n(1-p_\alpha)\,\triangle \\ -a - \sum_{j=0}^{k} p_{p_\alpha,j}^n n(b-\triangle) - nD_{nc} - [D_c - D_{nc} + \triangle]\{\sum_{j=0}^{k} p_{p_\alpha,j}^n j\} \\ -[D_c - D_{nc}]\{\sum_{j=k+1}^{n} p_{p_\alpha,j}^n j\}\end{aligned}$$

Clearly, if $\frac{\triangle - b}{\triangle} \geq p_\alpha$, then the agency will conduct ambient inspections if and only if $\nabla_1^{na,a}(p_\alpha) > 0$.

Let $\nabla_2^{na,a}(p_\alpha)$ be the difference between the agency's expected without and with ambient inspections if $p_\alpha \geq \frac{\triangle - b}{\triangle}$. Equations 3 and 4 imply that:

$$\begin{aligned}\nabla_2^{na,a}(p_\alpha) &= \\ np_\alpha D_c + n(1-p_\alpha)D_{nc} \\ -a - \sum_{j=0}^{k} p_{p_\alpha,j}^n n(b-\triangle) - nD_{nc} - [D_c - D_{nc} + \triangle]\{\sum_{j=0}^{k} p_{p_\alpha,j}^n j\} \\ -[D_c - D_{nc}]\{\sum_{j=k+1}^{n} p_{p_\alpha,j}^n j\}\end{aligned}$$

Clearly, if $p_\alpha \geq \frac{\triangle - b}{\triangle}$, then the agency will conduct ambient inspections if and only if $\nabla_2^{na,a}(p_\alpha) > 0$.

Also, $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) = \nabla_2^{na,a}(\frac{\triangle - b}{\triangle})$.

In Appendix A, we shall proof the following Lemma's:

- **Lemma 2** $\nabla_1^{na,a}(0) < 0$.

  In words, if the firms never comply, the agency's best response is not to conduct ambient inspections but to inspect all firms individually.

- **Lemma 3** $\nabla_1^{na,a}(p_\alpha)$ *is increasing in* p_α.

  In words, if $\frac{\triangle - b}{\triangle} \geq p_\alpha$, the higher p_α, the more likely that the agency will prefer to conduct ambient inspections.

- **Lemma 4** $\nabla_2^{na,a}(1) < 0$.

  In words, if the firms always comply, the agency's best response is not to conduct any inspections at all.

- **Lemma 5** $\nabla_2^{na,a}(p_\alpha)$ *is decreasing in* p_α.

  In words, if $p_\alpha \geq \frac{\triangle - b}{\triangle}$, the higher p_α, the more likely that the agency will prefer not to conduct ambient inspections.

From these Lemma's, we can immediately see the agency's best response to any given p_α.

Suppose now first that $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) < 0$. Lemma's 2, 3, 4 and 5 then imply that $\nabla_1^{na,a}(p_\alpha) < 0$ for all p_α and we obtain immediately:

Lemma 6 *If* $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) < 0$*, the agency will never conduct ambient inspections; it will inspect all firms if* $\frac{\triangle - b}{\triangle} > p_\alpha$*; it will not inspect any firm if* $\frac{\triangle - b}{\triangle} < p_\alpha$ *and it will be indifferent between inspecting the firms and not inspecting the firms if* $\frac{\triangle - b}{\triangle} = p_\alpha$.

Suppose next that $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) > 0$ (we shall not consider limiting cases like $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) = 0$).

- Lemma's 2 and 3 imply then that there exists one and only p_α^{1*} such that $\frac{\triangle - b}{\triangle} > p_\alpha^{1*}$ and such that $\nabla_1^{na,a}(p_\alpha^{1*}) = 0$.

  The agency's best response to $\frac{\triangle - b}{\triangle} > p_\alpha$ is thus :

  - not to conduct ambient inspections but to inspect all firms individually if $p_\alpha^{1*} > p_\alpha$
  - to conduct ambient inspections (followed by sequentially rational firm inspections) if $p_\alpha > p_\alpha^{1*}$

- Lemma's 4 and 5 imply that there exists at one and only one p_α^{2*} such that $p_\alpha^{2*} > \frac{\triangle - b}{\triangle}$ and such that $\nabla_2^{na,a}(p_\alpha^{2*}) = 0$.

  The agency's best response to $p_\alpha > \frac{\triangle - b}{\triangle}$ is thus:

  - not to conduct any inspections at all (neither ambient inspections nor firm inspections) if $p_\alpha > p_\alpha^{2*}$
  - to conduct ambient inspections (followed by sequentially rational firm inspections) if $p_\alpha^{2*} > p_\alpha$

We can conclude:

Lemma 7 *If* $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) > 0$*, the agency's best response is:*

- *If* $p_\alpha^{1*} > p_\alpha$*, then the agency does not conduct ambient inspections but inspects all firms individually.*
- *If* $p_\alpha^{1*} = p_\alpha$*, then the agency is indifferent between conducting and not conducting ambient inspections; if the agency conducts ambient inspections, they are followed by sequentially rational firm inspections; if the agency does not conduct ambient inspections, it inspects all firms individually.*
- *If* $p_\alpha^{2*} > p_\alpha > p_\alpha^{1*}$*, then the agency conducts ambient inspections (followed by sequentially rational firm inspections).*
- *If* $p_\alpha^{2*} = p_\alpha$*, then the agency is indifferent between conducting and not conducting ambient inspections; if the agency conducts ambient inspections, they are followed by sequentially rational firm inspections; if the agency does not conduct ambient inspections, it does not inspect the firms.*
- *If* $p_\alpha > p_\alpha^{2*}$*, the agency does not conduct any inspections at all (neither ambient inspections nor firm inspections).*

The intuition behind this result is straightforward. The advantage of ambient inspections is that they allow better informed firm inspections: the "threshold strategy" implies that firms will only be inspected if, given the information embodied in ambient pollution levels, it is worth the while. Indeed, with ambient inspections, the probability that the probability that the agency will inspect the firms is decreasing in the probability of compliance:

Lemma 8

$$\frac{d\sum_{j=0}^{k} p_{p_\alpha,j}^{n}}{dp_\alpha} = -np_{p_\alpha,k}^{n-1} < 0$$

Proof

Note first that for all j such that $j \leq n-1$:

$$\begin{aligned} \frac{dp_{p_\alpha,j}^{n}}{dp_\alpha} &= \\ -\binom{n}{j}(n-j)(1-p_\alpha)^{n-j-1}(p_\alpha)^j + \binom{n}{j}(1-p_\alpha)^{n-j}j(p_\alpha)^{j-1} &= \\ -n\binom{n-1}{j}(1-p_\alpha)^{n-j-1}(p_\alpha)^j + n\binom{n-1}{j-1}(1-p_\alpha)^{n-j}(p_\alpha)^{j-1} &= \\ n\{p_{p_\alpha,j-1}^{n-1} - p_{p_\alpha,j}^{n-1}\} & \qquad (6) \end{aligned}$$

Equation 6 implies immediately:

$$\frac{d\sum_{j=0}^{k} p^n_{p_\alpha,j}}{dp_\alpha} \quad = \quad -n(1-p_\alpha)^{n-1} + n\sum_{j=1}^{k}\{p^{n-1}_{p_\alpha,j-1} - p^{n-1}_{p_\alpha,j}\}$$

Now note that $-n(1-p_\alpha)^{n-1} + \binom{n}{1}(1-p_\alpha)^{n-1} = 0$. The rest of the proof is obvious. □ QED □

It is straightforward to verify that were ambient inspections costless ($a = 0$), the agency would always conduct ambient inspections. However, with very low probabilities of compliance ($p^{1*}_\alpha > p_\alpha$), the *ex ante* probability that the agency will decide to inspect all firms after having observed ambient pollution becomes so high that gathering this information is not worth the while if it costly. On the other hand, with very high probabilities of compliance ($p_\alpha > p^{2*}_\alpha$), the *ex ante* probability that the agency will decide *not* to inspect any firm after having observed ambient pollution, becomes so high that gathering this information is not worth the while either. Thus, *ambient inspections are only a best response to intermediate probabilities of compliance.*

3 The firms' best response

If a firm complies, its expected costs are always α. If a noncompliant firm is not inspected, its expected costs are zero. If a noncompliant firm is inspected, its expected costs are $\Psi + \gamma\alpha$.

If $(1-\gamma)\alpha > \Psi$, then the firm will never comply, even if it is inspected with certainty. Therefore, we shall from now on assume that $\Psi > (1-\gamma)\alpha$.

Before proceeding further with the analysis, we can immediately eliminate some possible equilibria.

First, if the agency does not conduct any inspections at all, then the firms' optimal response obviously is not to comply. However, if the firms never comply, the agency's best response is to inspect all firms individually (Lemma 2), so this can never be part of a NE.

Suppose next that the agency inspects all firms individually. The firms will always comply, but then the agency's best response is not to conduct any inspections at all (Lemma 4), so this can never be part of a NE either.

This argument shows:

Lemma 9 *There is no NE where the firms play pure strategies, where the agency inspects all firms with certainty or where the agency does never inspect a firm.*

In what follows, we shall now determine all the possible equilibria, first if $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) < 0$ (Section 3.1), and next if $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) > 0$ (Section 3.2).

3.1 $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) < 0$

From Lemma 6, the agency never conducts ambient inspections. This implies that the optimal strategy for firm i is always independent from the choices made by the other firms.

Let p_i be the probability that firm i is inspected. Firm i's expected costs when it does not comply are then: $p_i\,(\Psi + \gamma\alpha)$.

Let p_i^α be the probability that firm i complies in a mixed strategy. Firm i's expected cost is then:

$$p_i^\alpha\,\alpha + (1 - p_i^\alpha)[\,p_i\,(\Psi + \gamma\alpha) + (1 - p_i).0] = p_i\,(\Psi + \gamma\alpha) + p_i^\alpha(\alpha - p_i\,(\Psi + \gamma\alpha)) \quad (7)$$

Expected costs are linear in p_i^α, which implies that they are increasing in p_i^α iff $(\Psi + \gamma\alpha)p_i < \alpha$. If $\Psi > (1 - \gamma)\alpha$, then $1 > \frac{\alpha}{\Psi + \gamma\alpha} > 0$. Firm i then complies if $p_i > \frac{\alpha}{\Psi + \gamma\alpha}$, does not comply if $p_i < \frac{\alpha}{\Psi + \gamma\alpha}$ and is indifferent between complying and not complying if $p_i = \frac{\alpha}{\Psi + \gamma\alpha}$. If we combine this with Lemma 6, we obtain the firms' and the agency's reaction function (see figure 1), and we can conclude:

Proposition 2 *If $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) < 0$, the following strategy pair is the unique NE: the firms comply with probability $p_\alpha = \frac{\triangle - b}{\triangle}$, the agency does not conduct ambient inspections but inspects the firms with probability $p_i = \frac{\alpha}{\Psi + \gamma\alpha}$.*

Comments

1. This is exactly the equilibrium in the game without ambient inspections and with $\gamma = 1$ analyzed in Franckx (2002a).

2. If all players play their equilibrium strategy, the expected cost for the inspection agency is:

$$n\{\frac{b}{\triangle}D_{nc} + (1 - \frac{b}{\triangle})D_c\} \quad (8)$$

   In a mixed-strategy equilibrium, the firms are indifferent between complying and not complying. This means that their expected costs in equilibrium are simply the compliance cost α.

3. If $\triangle$ is independent from the fine, then the probability of compliance does *not* depend on the magnitude of the fine. Indeed, in a Nash equilibrium, firms choose the probability of compliance to make the agency indifferent between inspecting and not inspecting them. If the fine has no intrinsic utility for the agency, then it should not play a role in the equilibrium strategy for the firms.

   The only role the fine plays in this game is that when the size of the fine increases, the equilibrium probability of inspection can go down. However, total expected costs for the agency are independent of the fine, because the firms' strategies make the agency indifferent with respect to the probability of inspection (and all terms that include the probability of inspection disappear from the agency's expected costs).

4. Suppose that the agency can commit to an inspection probability that is infinitesimally larger than $\frac{\alpha}{\Psi+\gamma\alpha}$. The agency then obtains perfect compliance and its expected costs are approximately:

$$n[\frac{\alpha}{\Psi + \gamma\alpha} b + D_c]$$

Compare this with Equation 8: $\frac{D_{nc}-D_c}{\triangle} > 1 > \frac{\alpha}{\Psi+\gamma\alpha}$ and the agency's expected costs are higher under the no-commitment hypothesis.

The reason is that if the agency is not committed to its inspection policy, its best response if all firms comply is not to inspect any firm. If inspecting firms were costless ($b = 0$), this distinction between commitment and no-commitment would however disappear.

3.2 $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) > 0$

Lemma's 7 and 9 imply that if $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) > 0$, we have to consider the firm's best response to the following strategies:

- the agency mixes between conducting ambient inspections and not conducting ambient inspections, but always inspects the firms if it does not conduct ambient inspections (strategy I)
- the agency mixes between conducting ambient inspections and not conducting ambient inspections, and never inspects the firms if it does not conduct ambient inspections (strategy II)
- the agency always conducts ambient inspections, followed by sequentially rational firm inspections (strategy III)

After having verified for each strategy whether an equilibrium exists where this strategy is played, we shall show existence and uniqueness in Section 3.2.4. Finally, we determine the optimal level of the fine from the agency's point of view in Section 3.2.5.

3.2.1 strategy I

First suppose that the agency mixes between conducting ambient inspections and not conducting ambient inspections, but always inspects the firms if it does not conduct ambient inspections. Firm i's expected costs become (where p^a is the probability that the agency conducts ambient inspections):

$$(1-p^a)[p_i^\alpha \alpha + (1-p_i^\alpha)(\Psi + \gamma\alpha)]$$
$$+p^a[p_i^\alpha \alpha + (1-p_i^\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} (\Psi + \gamma\alpha)]$$

The first term are the firm's expected costs if the agency does not conduct ambient inspections, the second term are the firm's expected costs if the agency conducts ambient inspections.

Indeed, with ambient inspections, the conditions for sequential rationality imply that the probability that firm i will be inspected if it does not comply is the probability that at most k of the $n-1$ other firms comply, this is $\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}$.

Rearranging terms, we see that the firm's expected costs are also equal to:

$$\begin{aligned}(1-p^a)[\Psi + \gamma\alpha + p_i^\alpha\{(1-\gamma)\alpha - \Psi\}] \\ +p^a[(\Psi+\gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} + p_i^\alpha\{\alpha - (\Psi+\gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}\}] &= \\ (1-p^a)[\Psi+\gamma\alpha] + p^a[\Psi+\gamma\alpha] \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} \\ +p_i^\alpha[(1-p^a)\{(1-\gamma)\alpha - \Psi\} + p^a\{\alpha - (\Psi+\gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}\}]\end{aligned}$$

We know from Lemma 7 that the agency will only play strategy I if $p_\alpha = p_\alpha^{1*}$.

Firm i will play a mixed strategy if and only if it is indifferent with respect to its choice of p_i^α, thus iff:

$$(1-p^a)\{(1-\gamma)\alpha - \Psi\} + p^a\{\alpha - (\Psi+\gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}\} = 0$$

Thus, if and only if the agency plays a mixed strategy such that:

$$p^a = \frac{\Psi - (1-\gamma)\alpha}{(\Psi+\gamma\alpha)(1 - \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1})}$$

It is clear that $\frac{\Psi-(1-\gamma)\alpha}{(\Psi+\gamma\alpha)(1-\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1})} \geq 0$. However, this is only a probability if $\frac{\Psi-(1-\gamma)\alpha}{(\Psi+\gamma\alpha)(1-\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1})} \leq 1$, which is equivalent with $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} \leq \frac{\alpha}{\Psi+\gamma\alpha}$.

Combining this argument with Lemma 7 allows us to conclude:

Lemma 10 *If $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) > 0$ and if $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} \leq \frac{\alpha}{\Psi+\gamma\alpha}$, then the following strategy pair is a PBE:*

- *the firms comply with probability p_α^{1*}*
- *the agency conducts ambient inspections (followed by sequentially rational firm inspections) with probability $\frac{\Psi-(1-\gamma)\alpha}{(\Psi+\gamma\alpha)(1-\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1})}$ and inspects all firms if it does not conduct ambient inspections.*

If $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} > \frac{\alpha}{\Psi+\gamma\alpha}$, then $(1-p^a)\{(1-\gamma)\alpha-\Psi\}+p^a\{\alpha-(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}\} < 0$. Whatever the probability that the agency conducts ambient inspections and whatever the other firms' probability of compliance, firm i will then always comply, but this can never be part of a NE (see Lemma 5).

Thus:

Lemma 11 *If $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} > \frac{\alpha}{\Psi+\gamma\alpha}$, there is no NE where the firms comply with probability p_α^{1*}.*

3.2.2 strategy II

Next, suppose that the agency mixes between conducting ambient inspections and not conducting ambient inspections, but never inspects the firms if it does not conduct ambient inspections. Firm i's expected costs become:

$$(1-p^a)p_i^\alpha \alpha + p^a[(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} + p_i^\alpha\{\alpha-(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}\}]$$

The first term are the firm's expected costs if the agency does not conduct ambient inspections, the second term are the firm's expected costs if the agency conducts ambient inspections.

Rearranging terms, we see that this expression is equal to:

$$p^a(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} + p_i^\alpha[(1-p^a)\alpha + p^a\{\alpha-(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}\}]$$

We know that from Lemma 7 the agency will only play strategy II if $p_\alpha = p_\alpha^{2*}$.

Firm i will only play a mixed strategy if it is indifferent with respect to the choice of p_i^α, thus if:

$$(1-p^a)\alpha + p^a\{\alpha-(\Psi+\gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1}\} = 0$$

Thus, if and only if the agency plays a mixed strategy such that:

$$p^a = \frac{\alpha}{(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j}}$$

It is clear that $\frac{\alpha}{(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j}} > 0$. However, this is only a probability if $\frac{\alpha}{(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j}} \leq 1$, thus if $\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j} \geq \frac{\alpha}{\Psi+\gamma\alpha}$.

Combining this argument with Lemma 7 allows us to conclude:

Lemma 12 *If $\nabla_1^{na,a}(\frac{\triangle-b}{\triangle}) > 0$, and if $\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j} \geq \frac{\alpha}{\Psi+\gamma\alpha}$, then the following strategy pair is a PBE:*

- *the firms comply with probability p^{2*}_α*
- *the agency conducts ambient inspections (followed by sequentially rational firm inspections) with probability $\frac{\alpha}{(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j}}$ but never inspects the firms if it does not conduct ambient inspections.*

If $\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j} < \frac{\alpha}{\Psi+\gamma\alpha}$, then $(1-p^a)\alpha + p^a\{\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j}\} > 0$. Whatever the probability that the agency conducts ambient inspections and whatever the other firms' probability of compliance, the firm's optimal reaction consists in never complying, , but this can never be part of a NE (see Lemma 5).

Lemma 13 *If $\sum_{j=0}^{k} p^{n-1}_{p^{2*}_\alpha,j} < \frac{\alpha}{\Psi+\gamma\alpha}$, there is no NE where the firms comply with probability p^{2*}_α.*

3.2.3 strategy III

Finally, suppose that the agency always conducts ambient inspections. From the discussion above, we know that firm i's expected cost is then:

$$(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j} + p_i^\alpha\{\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j}\}$$

Any given firm i will play a mixed strategy iff it is indifferent with respect to its choice of p_i^α, thus iff $\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j} = 0$ when the other firms play their equilibrium strategy. We need thus to show that there exists a unique value of p_α such that this equality is true. One possible way to do this is to show that $\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j}$ is a strictly monotonous function of p_α and that its sign changes in the domain.

Lemma 8 implies directly that $\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j}$ is strictly increasing in p_α. If $p_\alpha = 0$, then $\alpha - (\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j} = (1-\gamma)\alpha - \Psi < 0$. If $p_\alpha = 1$, then $\alpha - (\Psi + \gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} = \alpha > 0$. There must thus indeed be a unique value $p_\alpha \in]0,1[$ such that $\alpha - (\Psi + \gamma\alpha) \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} = 0$.

Combining this argument with Lemma 7 allows us to conclude:

Lemma 14 *If* $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) > 0$*, and if there exists a* $p_\alpha^* \in]p_\alpha^{1*}, p_\alpha^{2*}[$ *such that* $\alpha - (\Psi + \gamma\alpha) \sum_{j=0}^{k} p_{c,j,p_\alpha^*}^{n-1} = 0$*, then the following strategy pair is a PBE:*

- *the firms comply with probability* p_α^*
- *the agency always conducts ambient inspections followed by sequentially rational firms inspections*

3.2.4 Existence and uniqueness

It remains now to be shown that we indeed have a unique PBE for all possible parameter values.

Note first that Lemma 8 implies $\frac{d \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}}{dp_\alpha} < 0$ and thus $\sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1} < \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}$. Therefore, it is impossible to have $\sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1} \geq \frac{\alpha}{\Psi+\gamma\alpha} \geq \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}$. In words, it is impossible to have the PBE from Lemma 10 and 12 simultaneously.

Suppose now that we have $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} > \frac{\alpha}{\Psi+\gamma\alpha} > \sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1}$, and thus that the PBE from Lemma 10 and 12 do not exist. Lemma 8 then implies that p_α^* does indeed exist and we conclude:

Proposition 3 *If* $\nabla_1^{na,a}(\frac{\triangle - b}{\triangle}) > 0$*, the following strategy pairs are the unique PBE:*

- *If* $\frac{\alpha}{\Psi+\gamma\alpha} \geq \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}$*: see Lemma 10*
- *If* $\sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1} > \frac{\alpha}{\Psi+\gamma\alpha} > \sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1}$*: see Lemma 14*
- *If* $\sum_{j=0}^{k} p_{p_\alpha^{2*},j}^{n-1} \geq \frac{\alpha}{\Psi+\gamma\alpha}$*: see Lemma 12*

3.2.5 The optimal fine

The intuition behind Proposition 3 is not straightforward to see. This changes however if we ask the following question: suppose that the agency could determine herself the fine that we have assumed to be exogenous in this model, what would be her choice?

To answer this question, we first introduce $\Gamma(p_\alpha)$ as short hand notation for $\alpha \frac{1-\gamma \sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}}{\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}}$.

The conditions in Proposition 3 can then be rewritten as follows:

- $\frac{\alpha}{\Psi+\gamma\alpha} \geq \sum_{j=0}^{k} p_{p_\alpha^{1*},j}^{n-1}$ is equivalent with $\Gamma(p_\alpha^{1*}) \geq \Psi$.

- $\sum_{j=0}^{k} p^{n-1}_{p^{1*}_{\alpha},j} > \frac{\alpha}{\Psi+\gamma\alpha} > \sum_{j=0}^{k} p^{n-1}_{p^{2*}_{\alpha},j}$ is equivalent with $\Gamma(p^{2*}_{\alpha}) > \Psi > \Gamma(p^{1*}_{\alpha})$.
- $\sum_{j=0}^{k} p^{n-1}_{p^{2*}_{\alpha},j} \geq \frac{\alpha}{\Psi+\gamma\alpha}$ is equivalent with $\Psi \geq \Gamma(p^{2*}_{\alpha})$

Next, note the following Lemma (for the proof, see Appendix B)

Lemma 15 *If $\Gamma(p^{2*}_{\alpha}) \geq \Psi \geq \Gamma(p^{1*}_{\alpha})$, then the agency's expected costs are decreasing in the fine.*

We shall now look at the optimal fines for all the possible relative values.

- If $\Gamma(p^{1*}_{\alpha}) \geq \Psi$, the agency is indifferent between conducting ambient inspections and inspecting all firms. Its expected costs are thus $C^{k,n}_{a}(p^{1*}_{\alpha})$. These costs are independent from the level of the fine (indeed, remember that $\nabla^{na,a}_{1}(p^{1*}_{\alpha}) = 0$).
- If $\Gamma(p^{2*}_{\alpha}) > \Psi > \Gamma(p^{1*}_{\alpha})$, the agency always conducts ambient inspections, the firms comply with probability p^{*}_{α} and the agency's expected costs are $C^{k,n}_{a}(p^{*}_{\alpha})$. Moreover, Lemma 15 implies that $C^{k,n}_{a}(p^{*}_{\alpha}) < C^{k,n}_{a}(p^{1*}_{\alpha})$, and thus that it can never be optimal to set a fine such that the firms comply with probability p^{1*}_{α}.
- Finally, if $\Psi \geq \Gamma(p^{2*}_{\alpha})$, the agency's expected costs are $C^{k,n}_{a}(p^{2*}_{\alpha})$. Lemma 15 implies $C^{k,n}_{a}(p^{2*}_{\alpha}) < C^{k,n}_{a}(p^{*}_{\alpha})$, and thus it can never be optimal to set a fine such that the firms comply with probability p^{*}_{α}.

We can conclude immediately:

Proposition 4 *Suppose that $\nabla^{na,a}_{1}(\frac{\triangle-b}{\triangle}) > 0$. The optimal fine is any Ψ such that $\Psi \geq \Gamma(p^{2*}_{\alpha})$. The agency then conducts ambient inspections (followed by sequentially rational firm inspections) with probability $\frac{\alpha}{(\Psi+\gamma\alpha)\sum_{j=0}^{k} p^{n-1}_{p^{2*}_{\alpha},j}}$ but never inspects the firms if it does not conduct ambient inspections; the firms comply with probability p^{2*}_{α}.*

Lemma 15 (the agency's expected costs with ambient inspections are decreasing in the fine) and Equation 8 (the agency's expected costs without ambient inspections are independent from the fine) tell us immediately why the agency wants the fine to be as high as possible.

Therefore, it is worthwhile to understand why Lemma 15 holds.

Before inspection, the agency's expected costs with ambient inspections are:

$$a + (n - \sum_{j=0}^{n} p^{n}_{p_{\alpha},j} j) D_{nc} + (\sum_{j=0}^{n} p^{n}_{p_{\alpha},j} j) D_{c}$$

An increase in the probability of compliance means that more firms comply spontaneously. Equations 10 and 11 (see Appendix A) imply that

$$\frac{dnD_{nc} + [D_c - D_{nc}]\{\sum_{j=0}^{n} p_{p_\alpha,j}^{n} j\}}{dp_\alpha} = n[D_c - D_{nc}] < 0$$

Thus, the direct effect is that expected costs of noncompliance decrease.

Expected firm inspection costs are: $\sum_{j=0}^{k} p_{p_\alpha,j}^{n} nb$. From Lemma 8, we know that $\frac{d\sum_{j=0}^{k} p_{p_\alpha,j}^{n}}{dp_\alpha} < 0$. This means that expected firm inspections costs decrease when the probability of compliance increases. Indeed, if the probability of compliance increases, then the probability that the inspection threshold will be reached (and thus the probability that *all* firms will be inspected) decreases.

On the other hand, if the probability that the inspection threshold will be reached decreases, then the probability that the noncompliant firms will be put in compliance also decreases. Equations 9 and 10 (see Appendix A) imply that

$$\frac{d\sum_{j=0}^{k} p_{p_\alpha,j}^{n}(j-n)\triangle}{dp_\alpha} = \{(\sum_{j=0}^{k-1} p_{p_\alpha,j}^{n-1}) + p_{p_\alpha,k}^{n-1}(n-k)\}\triangle > 0$$

Thus, the indirect effect runs in the direction opposite to the direct effect.

However, remember that we have assumed that, even with zero inspection costs, the agency prefers that the firms comply spontaneously rather than as the result of inspections ($D_{nc} - D_c > \triangle$). Moreover, the inspection threshold is determined in such a way that $nb > (n-k-1)\triangle$. The Proof in Appendix B shows that this implies that *the positive effects on expected firm inspection costs and on the benefits of spontaneous compliance dominate the negative effect on the benefits of putting noncompliant firms in compliance.*

This explains why the agency wants the probability of compliance to be as high as possible with ambient inspections.

The Proof in Appendix B also shows that the probability of compliance is increasing in the fine. The reason is that if the firms play mixed strategies, their equilibrium strategy must make the other firms indifferent between complying and not complying. As the firms' expected costs depend on the level of the fine, this means that their equilibrium probability of compliance must also depend on the fine.

Now, if the fine increases, the expected costs of a non-compliant firm increase. A firm will thus only remain indifferent between complying and not-complying if the probability that the other firms comply increases, because then the probability of reaching the information sets where they are not inspected increases.

Our explanation for imposing high penalties is thus completely different from the traditional justification given by Becker[3].

However, once the fines strictly exceed the threshold $\Gamma(p_\alpha^{2*})$, the probability of compliance with ambient inspections becomes so high that the agency prefers not to inspect any firm at all, but this can never be part of a NE. Therefore, the agency mixes between conducting ambient inspections and not conducting ambient inspections.

Of course, in reality, with upper constraints on the fine (such as the assets of the firm), it might be impossible to impose a fine $\Psi \geq \Gamma(p_\alpha^{2*})$. It might then be optimal to have ambient inspections with certainty. With very strict upper constraints on the fine (the maximal possible fine is smaller than $\Gamma(p_\alpha^{1*})$), it might even be optimal to randomize between conducting ambient inspections and inspecting all firms (independently from ambient pollution).

4 Does commitment matter?

Let us now briefly explore what happens if we revert to the institutional assumptions used in Franckx (2002a) and Franckx (2002b).

First, it is absolutely straightforward to verify that the two technical generalizations we have introduced here do not affect the analysis in Franckx (2002b).

The comparison with Franckx (2002a) is slightly more elaborated. Let us therefore assume that the agency can commit to conducting ambient pollution, even if it cannot commit to firm inspection probabilities. The only change compared to the analysis in the rest of the paper is that it is now common knowledge whether or not the agency observes ambient pollution.

Suppose first that the agency credibly commits to inspecting ambient pollution levels.

In that case, the timing of the game is:

- The firms simultaneously choose their abatement technology, knowing that the agency observes ambient pollution.
- The enforcement agency observes ambient levels
- The enforcement agency chooses the firms it will inspect

Because the agency cannot commit to firm inspection probabilities, we still require the agency's policy to be sequential rational. It can easily be verified that the conditions for sequential rationality obtained in Section 2.1 do not change in this new context.

From the analysis in Section 3.2.3, we know that if the agency always conducts ambient inspections, then there exists a unique equilibrium probability of compliance p_α^*. From Lemma 15, we know that the agency's expected costs with ambient inspections are decreasing in the fine.

Suppose next that the agency credibly commits not to inspect ambient pollution levels. The game then reduces to the game analyzed in Section 3.1.

The difference between expected costs for the agency with and without ambient inspections is then (this follows directly from Equation 3 and 8):

$$a + \sum_{j=0}^{k} p_\alpha^* \, n(b - \triangle) + nD_{nc} + [D_c - D_{nc} + \triangle]\{\sum_{j=0}^{k} p_\alpha^* \, j\}$$

$$+[D_c - D_{nc}]\{\sum_{j=k+1}^{n} p_\alpha^* \, j\} - n\{\frac{b}{\triangle} D_{nc} + (1 - \frac{b}{\triangle}) D_c\}$$

From Lemma 15, we can immediately conclude:

Proposition 5 *The difference between the agency's expected costs with ambient inspections and without ambient inspections are a decreasing function of the fine.*

This is due to the fact that the agency's expected costs without ambient inspections are independent from the fine. Thus, *the higher the fine set by the legislator, the more likely that the agency will commit to ambient inspections if it has this commitment power.* This is exactly the central result obtained in Franckx (2002a).

On the other hand, from the analysis in Section 3.2.5, we see that this result completely disappears if we drop the assumption that the agency can commit to ambient inspections. Commitment power (or the lack of it) has thus a crucial impact on the outcome of the game.

5 Conclusion

This paper extends previous work by Franckx (2002a,2002b) to a new setting.

We have shown that if the agency can commit to ambient inspections, then the central result obtained in Franckx (2002a) does not change when we relax three apparently strong assumptions (2 polluting firms, the agency's objective function that does not include private compliance costs, the agency's power to put noncompliant firms in compliance) as long as the agency prefers the firm to comply spontaneously rather than as the results of inspections. In this respect, the results in Franckx (2002a) are rather robust.

However, if the agency cannot commit to ambient inspections, then our main conclusions are the following. Consider the probability of compliance that makes the agency indifferent between inspecting and not inspecting the firms in a game without ambient inspections.

- Suppose that the agency's expected costs are lower without ambient inspections if the firms comply with this probability. The agency will then never conduct ambient inspections. If the benefits of inspecting noncompliant firms are independent from the fine, then the probability of compliance and the agency's expected costs are also independent from the fine.

- Suppose next that the agency's expected costs are lower with ambient inspections if the firms comply with this probability. The agency's strategy then depends on the fine for noncompliance. If this fine is very high, then the agency mixes between conducting ambient inspections and not conducting any inspections at all. For intermediate values of the fine, the agency conducts ambient inspections. For very low values of the fine, the agency mixes between conducting ambient inspections and inspecting all firms. If the agency conducts ambient inspections, it inspects all firms if and only if an endogenous threshold of pollution has been exceeded. If the agency prefers the firm to comply spontaneously rather than as the results of inspections, then expected costs for the agency are a decreasing function of the fine.

These results contradict strongly the key conclusions obtained in Franckx (2002a) and Franckx (2002b). We have thus shown that apparently *small changes in the institutional context* dramatically affect the outcome of the inspection game: commitment power (or the lack of it) really has a very strong impact on the value of prior information and on the role played by the fines for noncompliance.

A Proofs of the results used in Section 2.3

Proof of Lemma 2

If $p_\alpha = 0$, then $\sum_{j=0}^{k} p^n_{p_\alpha,j} = 1$ and $\sum_{j=0}^{k} p^n_{p_\alpha,j} j = \sum_{j=k+1}^{n} p^n_{p_\alpha,j} j = 0$. This implies immediately:

$$\begin{aligned}\nabla_1^{na,a}(p_\alpha = 0) &= nb - n \triangle - a - n[b - \triangle] \\ &< 0\end{aligned}$$

which confirms our first claim.

Proof of Lemma 3

To see this, first note that:

- First, from Lemma 8, we already know that

$$\frac{d \sum_{j=0}^{k} p^n_{p_\alpha,j}}{dp_\alpha} = -np^{n-1}_{p_\alpha,k} \tag{9}$$

- Equation 6 implies immediately:

$$\begin{aligned}\frac{d \sum_{j=0}^{k} p^n_{p_\alpha,j} j}{dp_\alpha} &= \sum_{j=0}^{k} n\{p^{n-1}_{p_\alpha,j-1} - p^{n-1}_{p_\alpha,j}\} j \\ &= n[-kp^{n-1}_{p_\alpha,k} + \sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j}] \end{aligned} \tag{10}$$

- Note first that

$$\frac{dp^n_{p_\alpha,n}}{dp_\alpha} = np_\alpha^{n-1} = np^{n-1}_{p_\alpha,n-1}$$

Combine this with Equation 6 to see:

$$\begin{aligned}\frac{d\sum_{j=k+1}^{n} p^n_{p_\alpha,j}j}{dp_\alpha} &= n\sum_{j=k+1}^{n-1}\{p^{n-1}_{p_\alpha,j-1} - p^{n-1}_{p_\alpha,j}\}j + n^2 p^{n-1}_{p_\alpha,n-1} \\ &= n[(k+1)p^{n-1}_{p_\alpha,k} + \sum_{j=k+1}^{n-1} p^{n-1}_{p_\alpha,j}] \qquad (11)\end{aligned}$$

Combine Equations 9, 10 and 11 to see:

$$\begin{aligned}n^{-1}\frac{d\nabla_1^{na,a}}{dp_\alpha} &= \\ D_c - D_{nc} + \triangle & \\ +[b-\triangle]np^{n-1}_{p_\alpha,k} & \\ -[D_c - D_{nc} + \triangle][\sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j} - kp^{n-1}_{p_\alpha,k}] & \\ -[D_c - D_{nc}][(k+1)p^{n-1}_{p_\alpha,k} + \sum_{j=k+1}^{n-1} p^{n-1}_{p_\alpha,j}] &\end{aligned}$$

Because $\sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j} + p^{n-1}_{p_\alpha,k} + \sum_{j=k+1}^{n-1} p^{n-1}_{p_\alpha,j} = 1$, we obtain:

$$\begin{aligned}n^{-1}\frac{d\nabla_1^{na,a}}{dp_\alpha} &= \\ \triangle - \{\sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j}\} \triangle + p^{n-1}_{p_\alpha,k}\{nb - (n-k)\triangle\} &\end{aligned}$$

The definition of k implies $nb > (n-k-1)\triangle$ and thus (using $\sum_{j=0}^{k} p^{n-1}_{p_\alpha,j} = \sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j} + p^{n-1}_{p_\alpha,k}$):

$$\begin{aligned}n^{-1}\frac{d\nabla_1^{na,a}}{dp_\alpha} &> \\ \triangle - \{\sum_{j=0}^{k-1} p^{n-1}_{p_\alpha,j}\} \triangle - p^{n-1}_{p_\alpha,k}\triangle &=\end{aligned}$$

$$(1-\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1})\triangle \quad > \quad 0$$

This confirms our second claim.

Proof of Lemma 4

If $p_\alpha = 1$, then: $\sum_{j=0}^{k} p_{p_\alpha,j}^{n} j = \sum_{j=0}^{k} p_{p_\alpha,j}^{n} = 0$ and $\sum_{j=k+1}^{n} p_{p_\alpha,j}^{n} j = n$. This implies immediately:

$$\nabla_2^{na,a}(p_\alpha = 1) \quad = \quad nD_c - a - nD_{nc} - [D_c - D_{nc}]n$$

which confirms our third claim.

Proof of Lemma 2

Following the same arguments as in the proof of Lemma 3, we can see:

$$\frac{d\nabla_2^{na,a}}{dp_\alpha} \quad = \quad -n\{\sum_{j=0}^{k-1} p_{p_\alpha,j}^{n-1}\triangle\} - np_{p_\alpha,k}^{n-1}\{-nb+(n-k)\triangle\}$$

The definition of k implies $nb < (n-k)\triangle$ and thus:

$$\frac{d\nabla_2^{na,a}}{dp_\alpha} \quad < \quad 0$$

B Proof of Lemma 15

First note that in this equilibrium, the probability of compliance is an increasing function of the fine.

Indeed, in equilibrium, the following equation is identically true:

$$\alpha - (\Psi + \gamma\alpha)\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} \quad = \quad 0$$

This implies that in equilibrium (differentiating for Ψ and using Lemma 8):

$$\begin{aligned} 0 \quad &= \quad -\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} - (\Psi+\gamma\alpha)\frac{d\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}}{dp_\alpha}\frac{dp_\alpha}{d\Psi} \\ &\Updownarrow \\ \frac{dp_\alpha}{d\Psi} \quad &= \quad \frac{\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}}{(\Psi+\gamma\alpha)(n-1)p_{p_\alpha,k}^{n-2}} \\ &> \quad 0 \end{aligned}$$

Thus, to proof this Lemma, we only need to show that $C_a^{k,n}(p_\alpha^*)$ is decreasing in p_α^*.

As in the proof of Lemma 3, combine Equations 9, 10 and 11 to see:

$$n^{-1}\frac{dC_a^{k,n}}{dp_\alpha} =$$

$$D_c - D_{nc} + \{\sum_{j=0}^{k-1} p_{p_\alpha,j}^{n-1}\} \triangle + p_{p_\alpha,k}^{n-1}\{-nb + (n-k)\triangle\}$$

The definition of k implies $nb > (n-k-1)\triangle$ and thus:

$$\begin{aligned}\frac{dC_a^{k,n}}{dp_\alpha} &< D_c - D_{nc} + \{\sum_{j=0}^{k-1} p_{p_\alpha,j}^{n-1}\} \triangle + p_{p_\alpha,k}^{n-1} \triangle \\ &= D_c - D_{nc} + \{\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1}\}\triangle\end{aligned}$$

$\triangle < D_{nc} - D_c$ and $\sum_{j=0}^{k} p_{p_\alpha,j}^{n-1} < 1$ imply then that $\frac{dC_a^{k,n}}{dp_\alpha} < 0$. The chain rule for derivatives completes the proof. □ QED □

Notes

[1]I would like to thank Frans Spinnewyn in particular for suggesting this approach.

[2]The probability that these two technical parameters are equal is zero.

[3]In Becker's model (1968), the only effect of higher penalties is that they allow to reduce the probabilities of detection that are necessary to obtain a given level of compliance. If fines are a pure transfer, then they should indeed be as high as possible in order to save enforcement costs.

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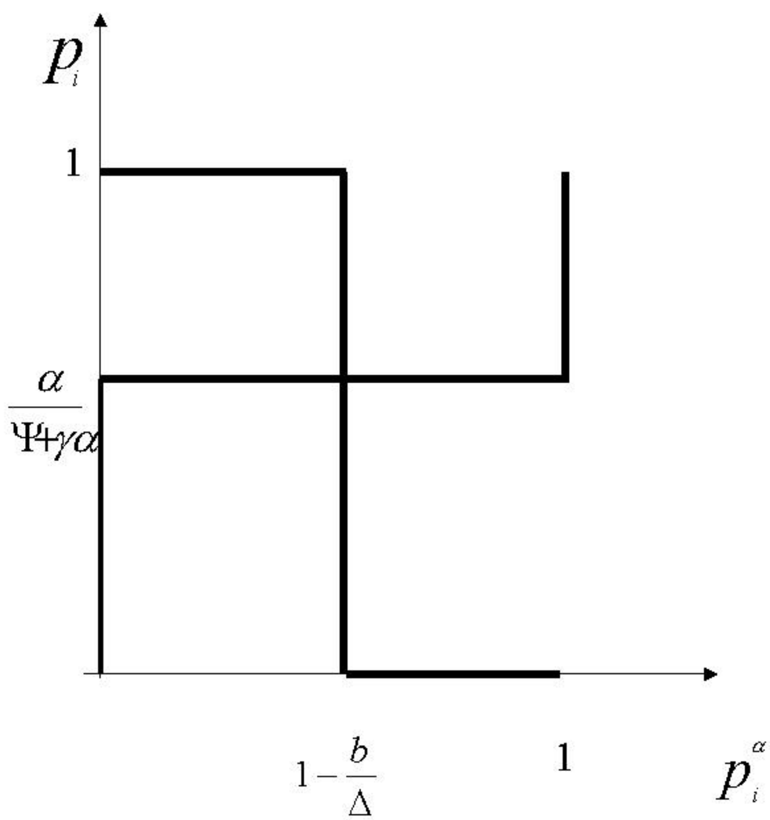

Figure 1: Reaction functions between firm i and the inspection agency without ambient inspections

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