FACULTY OF ECONOMICS AND
APPLIED ECONOMIC SCIENCES
CENTER FOR ECONOMIC STUDIES
ENERGY, TRANSPORT & ENVIRONMENT

KATHOLIEKE
UNIVERSITEIT
LEUVEN

WORKING PAPER SERIES
n°2005-08

The use of warnings when intended and measured emissions differ

S. Rousseau (ETE – CES, KULEUVEN)

December 2005

secretariat:
Isabelle Benoit
KULeuven-CES
Naamsestraat 69, B-3000 Leuven (Belgium)
tel: +32 (0) 16 32.66.33
fax: +32 (0) 16 32.69.10
e-mail: Isabelle.Benoit@econ.kuleuven.ac.be
http://www.kuleuven.be/ete

The use of warnings when intended and measured emissions differ

Sandra Rousseau[1]

Centre for Economic Studies, Catholic University of Leuven

Abstract

This article studies the effects of informal, non-monetary sanctions, such as warnings, which are often used as an enforcement instrument by environmental inspection agencies. In cases of uncertainty with respect to the measured emissions due to measurement errors or accidental violations, some firms are unjustly penalised. As warnings provide a buffer period in which the firm is informed about the violation without any monetary consequences, it will be theoretically shown that warnings can help to reduce the welfare cost of such type II-errors *and* reduce the overdeterrence of low-cost firms - albeit at the cost of underdeterring medium-cost firms.

Keywords: Enforcement; non-monetary sanctions; warnings; measurement errors

JEL codes: Q38 / K42

[1] Address: Centre of Economic Studies, K.U.Leuven, Naamsestraat 69, B-3000 Leuven, Belgium.
Tel: 00 32 16 32 66 36. Fax: 00 32 16 32 69 10. E-mail: Sandra.Rousseau@econ.kuleuven.be

1. Introduction

Firms that are subject to environmental regulations are induced by the regulator to comply through inspections and sanctions. These sanctions can be formal or informal, monetary or non-monetary. The economic literature[2] on the deterrence of crime, which started with Becker (1968), has focussed mainly on formal, monetary sanctions, and more specifically on fines. When non-monetary sanctions are studied in the literature, authors typically discuss prison sentences (e.g. Shavell, 1987 and Garoupa and Klerman, 2004). Informal, non-monetary sanctions, such as warnings and advices, are only rarely studied. Warnings are, nonetheless, often used as an enforcement instrument by the environmental inspection agency to instruct firms to end any situation of non-compliance and abide with all appropriate laws, decrees and permits. For example, Rousseau (2005) describes the enforcement actions taken after Flemish textile companies were found in violation during an inspection. In the majority of the cases (72 %) no action was taken. However, if an enforcement action was taken, a warning was given to the violator in 89 percent of the cases. This warning was either the only instrument used (19 %) or accompanied by a notice of violation (70 %).

A recent study focusing on warnings is Nyborg and Telle (2004), which investigates the potential of warnings to help regulators keep control. Using a game theoretic approach, Nyborg and Telle argue that *'warnings reduce substantially the probability of (...) accidental switches from the full-compliance to the no-compliance equilibrium'*. A more empirical approach is taken by Eckert (2004), who shows that warnings are used by the Canadian inspection agency to target firms for inspection, with past warnings increasing the probability of an inspection relative to a past finding of compliance.

[2] For an overview of this literature, see Cohen (2000).

This contribution focuses on an alternative explanation for the use of warnings as an enforcement instrument. If measurement errors are present or if emissions are stochastic, some compliant firms are unjustly sanctioned. In this instance warnings can provide a buffer and reduce the welfare cost of falsely accused firms. Bose (1995) has already shown that regulatory errors can cause the optimal penalty to be non-maximal. Looking at only one enforcement instrument, he has optimised the level of the fine, which is independent of the seriousness of violation. Similarly, Chu et al. (2000) argue that optimal sanctions are mild for first time offenders but severe for repeat offenders if erroneous conviction of innocent offenders is possible. Also Polinsky and Shavell (2000) state that '*introducing the possibility of mistakes may increase the desirability of lowering the fine because, due to type II errors*' (i.e. mistakenly punishing compliant individuals), *'individuals who do not violate the law are subject to the risk of having to pay a fine'.*

The model proposed here allows for a fine proportional to the size of the violation, but does not attempt to optimise the penalty. I show that informal, non-monetary sanctions should be considered as a complement to formal, monetary sanctions. In the presence of regulatory or managerial errors, the use of warnings can increase welfare.

2. Assumptions

The model considers two periods, in each of which firms face an emission standard $\overline{e}$. Firms are inspected with an exogenously given probability $\overline{p}_1$. If a firm was previously caught violating the emission standard, it will be more frequently inspected, $\overline{p}_2 > \overline{p}_1$. This exogenous increase in inspections after a firm was caught violating is consistent with the theoretical and empirical literature. Harrington (1988) shows theoretically that state-dependent enforcement, e.g. targeting firms on their compliance history, can greatly improve deterrence given a fixed regulatory budget. Studying actual inspection practices, for example, Gray and Deily (1996) found this effect for the US steel industry, Stafford (2002) for the US hazardous waste regulations, Laplante and Rilstone (1996) for the Canadian pulp and paper industry and Rousseau (2005) for the Flemish textile industry.

In this model, measured emissions during inspections equal:

$$\begin{aligned} e_i^m &= e_i && \textit{with probability} \left(1-q\right) \\ &= e_i\left(1+\gamma\right) && \textit{with probability}\, q \end{aligned}$$

This formulation implies that there is uncertainty with respect to the discharge level that is actually measured. This uncertainty is represented by the parameter $\gamma > 0$. This can imply that there are asymmetric, type II measurement errors[3] present. The measuring equipment used by the inspection agency or the analysis of samples is such that with probability $q \in \left[0; \frac{1}{2}\right[$ the measured result is higher than the actual emissions. Another explanation, following Nyborg and Telle (2004), is that sometimes violations occur by mistake. Even if the firm's manager decides to comply with the regulation, the firm can in reality be violating the standard. This disparity between intended and real emissions can be caused by principal-agent problems within the firm or by exogenous causes such as weather conditions or calamities. The asymmetry in measured emissions implies that the emission level on which the sanction is based is uncertain. The firm will respond to this uncertainty by adjusting its behaviour.

If a firm *i* is found in violation $\left(e_i^m > \overline{e}\right)$, then a fine $F_i\left(e_i^m\right)$ is levied with $F_i' > 0$ and $F_i'' > 0$.

[3] Errors of two types can occur in law enforcement. First, an individual who should be found liable might mistakenly not be found liable, i.e. a type I error. Second, an individual who should be found compliant might mistakenly be found violating, i.e. a type II error. I only consider the case where type II errors are present and type I errors are not. However, the results continue to hold as long as the disutility caused by type II errors is larger than that caused by type I errors.

Firms are assumed to be risk neutral and identical except for the cost parameter θ_i. Firms initially emit $e_o\left(>\overline{e}\right)$ units of the regulated pollutant. In order to reduce emissions by a_i firm i incurs a cost $\theta_i C\left(e_i\right)$ with $C^{'}<0$, $C^{''}<0$, $e_i=e_o-a_i$ and where $\theta_i\in\left[0,+\infty\right[$ is a continuous cost parameter. Actual emissions e_i are equal to baseline emissions e_o subtracted by abated emissions a_i. Additionally, in order to have a convex total cost function, it is assumed that $F^{''}\geq\frac{C^{''}}{\overline{p}_i}$ with $\overline{p}_i\in\left\{\overline{p}_1,\overline{p}_2\right\}$ depending on the firm's compliance history.

3. Model

Firms choose their actual emissions e_{ti}, with index t indicating the time period, in order to minimise the total costs TC_i associated with the environmental standard:

$$\min_{e_{ti}} TC_{ti}=\min\left\{\sum_{t'=1}^{t}\theta_i C\left(e_{t'i}\right)+\overline{p}_i F\left(e_{t'i}^{m}\right)\right\} \tag{1}$$

and $\overline{p}_i\in\left\{\overline{p}_1,\overline{p}_2\right\}$ depending on the firm's compliance history.

The problem is solved through backward induction. First the regulatory scheme is discussed where fines are the only enforcement instrument available and next it is studied what happens if both warnings and fines can be used by the regulator.

3.1 Regulatory scheme 1: Fines

Period 2

The problem in the second period depends on the compliance history and is quite straightforward. Firm i chooses the emission level e_{ti} with index t indicating the period.

Firms minimise their environmental costs if:

$$-\theta_i C'\left(e_{2i}\right) = \overline{p}_i F'\left(e_{2i}^m\right)$$

This is the familiar result that, for an interior solution, marginal abatement costs equal the marginal expected fine. As is shown in figure 1, the marginal expected fine curves can be divided into three regions. If the firms' true emissions are below $\frac{\overline{e}}{1+\gamma}$, then the expected fine is zero since the firms will never be penalised. If the firms' emissions e_{ti} are between $\frac{\overline{e}}{1+\gamma}$ and $\overline{e}$, then they have a certain probability of being incorrectly fined and the marginal expected fine is $\overline{p}_i\, q\, F'\left(e_{ti}\left(1+\gamma\right)\right)$. If the firms truly violate the emission standard, $e_{ti} > \overline{e}$, then the marginal expected fine equals $\overline{p}_i\, q\, F'\left(e_{ti}\left(1+\gamma\right)\right) + \overline{p}_i\left(1-q\right)F'\left(e_{ti}\right)$.

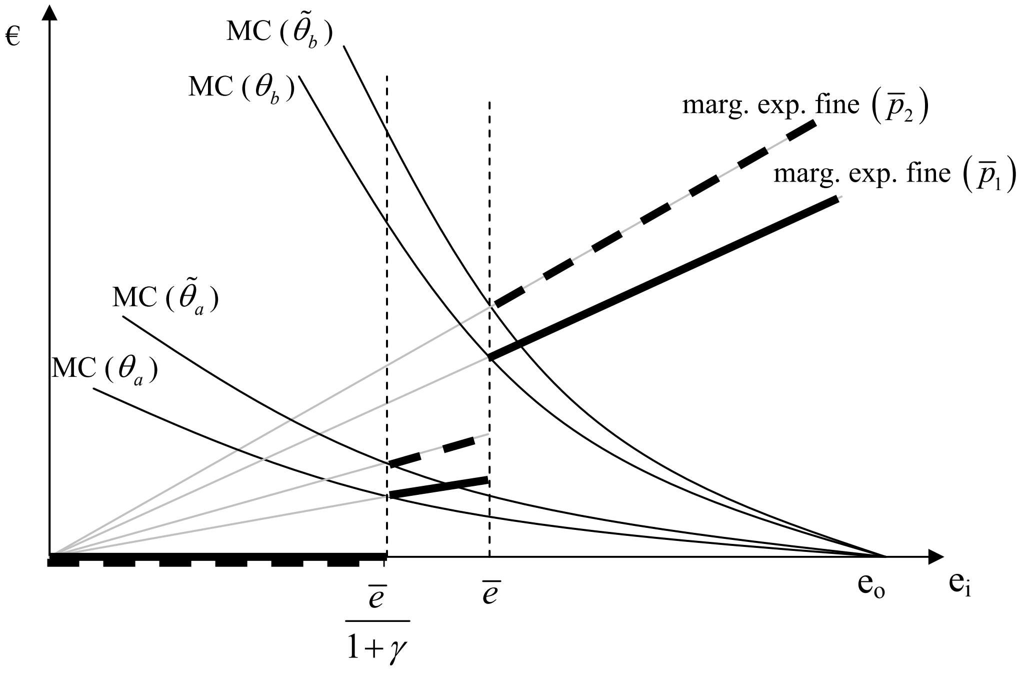


Figure 1: Abatement decision in period 2 with fines (scheme 1)

Due to the three different regions in the marginal expected fine curves, firms can be divided into three groups with similar behaviour depending on their cost parameter. The parameters e_i^a and θ_a are subsequently defined, where $^+$ denotes the right hand derivative in the point under consideration:

$$-\theta_a C'\left(\frac{\overline{e}}{1+\gamma}\right) = \overline{p}_1\, q\, F'\left(\overline{e}^+\right)$$

$$-\theta_i C'\left(e_i^a\right) = \overline{p}_1 q\, F'\left(e_i^a \left(1+\gamma\right)\right)$$

and e_i^b and θ_b are defined by:

$$-\theta_b C'\left(\overline{e}\right) = \overline{p}_1\left[\left(1-q\right)F'\left(\overline{e}^+\right) + q\, F'\left(\overline{e}\left(1+\gamma\right)\right)\right]$$

$$-\theta_i C'\left(e_i^b\right) = \overline{p}_1\left[\left(1-q\right)F'\left(e_i^b\right) + q\, F'\left(e_i^b\left(1+\gamma\right)\right)\right]$$

Analogously, $\tilde{\theta}_a$, $\tilde{\theta}_b$, $\tilde{e}_i^a$ and $\tilde{e}_i^b$ are defined with $\overline{p}_2$ instead of $\overline{p}_1$. This is also illustrated in figure 1, where e_o are the baseline emissions if the firms do not invest in abatement technology. For the firm with cost parameter θ_a $\left(\theta_b\right)$ its marginal abatement cost *MC* of reducing its emissions to level $\frac{\overline{e}}{1+\gamma}$ $\left(\overline{e}\right)$ exactly equals the marginal expected fine.

If the firm was not convicted in the first period, its emissions e_{2i} in period 2 are determined by the following equations:

$$\begin{array}{lll} \text{If } \theta_i \le \theta_a & \text{then} & e_{2i} = \dfrac{\overline{e}}{1+\gamma} \\ \text{If } \theta_a < \theta_i \le \theta_b & \text{then} & e_{2i} = \min\left[e_i^a, \overline{e}\right] \\ \text{If } \theta_b < \theta_i & \text{then} & e_{2i} = e_i^b \end{array} \qquad (2)$$

Low cost firms $\left(\theta_i \le \theta_a\right)$ overcomply with the emission standard. Medium cost firms $\left(\theta_a < \theta_i \le \theta_b\right)$ also comply but are sometimes incorrectly accused of violating the emission standard if measurement errors are present. Alternatively, these medium cost firms intend to comply but, due to managerial errors, they accidentally exceed the standard with probability *q*. High cost firms $(\theta_i > \theta_b)$ never comply.

If the firm was fined in the previous period, its emissions in the second period are:

$$\begin{array}{lll} \text{If } \theta_i \le \tilde{\theta}_a & \text{then} & e_{2i} = \dfrac{\overline{e}}{1+\gamma} \\ \text{If } \tilde{\theta}_a < \theta_i \le \tilde{\theta}_b & \text{then} & e_{2i} = \min\left[\tilde{e}_i^a ; \overline{e}\right] \\ \text{If } \tilde{\theta}_b < \theta_i & \text{then} & e_{2i} = \tilde{e}_i^b \end{array} \tag{3}$$

Since $\theta_a < \tilde{\theta}_a$ and $\theta_b < \tilde{\theta}_b$, all firms lower their emissions and more firms will comply if they have a past record of non-compliance because they will be inspected more frequently. This is the classical result found by Becker (1968); that an increase in expected penalty will reduce the level of crime.

Period 1

In the first period firms choose their emissions e_{1i} so as to minimise their total environmental costs over the two periods:

$$\min_{e_{1i}} \left\{ \theta_i C(e_{1i}) + \overline{p}_1 F\left(e_{1i}^m\right) + \delta\left[\theta_i C(e_{2i}) + \overline{p} F\left(e_{2i}^m\right)\right] \right\} \tag{4}$$

with $\delta \le 1$ the discount rate.

The optimal emission decisions, depending on the firms' cost parameters, are:

$$\begin{array}{lll} \text{If } \theta_i \le \theta_a & \text{then} & e_{1i} = \dfrac{\overline{e}}{1+\gamma} \\ \text{If } \theta_a < \theta_i \le \theta_b & \text{then} & e_{1i} = \min\left[e_i^a , \overline{e}\right] \\ \text{If } \theta_b < \theta_i & \text{then} & e_{1i} = e_i^b \end{array}$$

This expression is equivalent to the second period decision for a firm without a non-compliance record (see expression (2)). This myopic behaviour is only true for values of *q* that fulfil several conditions with the following general form (with $e_1 \le e_2 \le e^*$ and e^* is the optimum of $TC(e_i)$ for a given θ_i):

$$q \le \frac{TC(e_1) - TC(e^*)}{\delta\left(TC(e_2) - TC(e^*)\right)} = \frac{\theta_i C(e_1) + \overline{p}F(e_1) - \theta_i C(e^*) - \overline{p}F(e^*)}{\theta_i C(e_2) + \overline{p}F(e_2) - \theta_i C(e^*) - \overline{p}F(e^*)}$$

The second term is always greater than or equal to one given our assumption on the second derivatives of *F* and *C*, i.e. $C'' + \overline{p}_i F'' \ge 0$. And, since *q* must be smaller than one, these conditions always hold. The main reason behind this myopic behaviour is the fact that abatement efforts are only valid for one period and thus abatement costs return every period. The types of abatement costs under consideration are operating and maintenance costs that are necessary to minimise the emissions associated with the production process.

The firms' emission behaviour over the two periods can be described as (with $E[\ ]$ the expectation operator):

If $\theta_i \le \theta_a$

$$\text{then} \quad e_{1i} = \frac{\overline{e}}{1+\gamma} \qquad \text{and} \quad E[e_{2i}] = \frac{\overline{e}}{1+\gamma}$$

If $\theta_a < \theta_i \le \tilde{\theta}_a$

$$\text{then} \quad e_{1i} = \min\left[e_i^a, \overline{e}\right] \qquad \text{and} \quad E[e_{2i}] = (1 - \overline{p}_1 q)\min\left[e_i^a, \overline{e}\right] + \overline{p}_1 q\left(\frac{\overline{e}}{1+\gamma}\right)$$

If $\tilde{\theta}_a < \theta_i \le \theta_b$

$$\text{then} \quad e_{1i} = \min\left[e_i^a, \overline{e}\right] \qquad \text{and} \quad E[e_{2i}] = (1 - \overline{p}_1 q)\min\left[e_i^a, \overline{e}\right] + \overline{p}_1 q\left(\min\left[\tilde{e}_i^a, \overline{e}\right]\right)$$

If $\theta_b < \theta_i \le \tilde{\theta}_b$

$$\text{then} \quad e_{1i} = e_i^b \qquad \text{and} \quad E[e_{2i}] = (1 - \overline{p}_1)e_i^b + \overline{p}_1\left(\min\left[\tilde{e}_i^a, \overline{e}\right]\right)$$

If $\tilde{\theta}_b < \theta_i$

$$\text{then} \quad e_{1i} = e_i^b \qquad \text{and} \quad E[e_{2i}] = (1 - \overline{p}_1)e_i^b + \overline{p}_1\left(\tilde{e}_i^b\right)$$

Depending on their cost parameter firms can be grouped into five categories. The first group, lowest cost firms, always overcomplies while the last category, highest cost firms, always violates the environmental regulation.

3.2 Regulatory scheme 2: Fines and warnings

The regulator can now use warnings as well as fines in order to enforce the emission standard. A warning is a non-monetary sanction, which notifies the firm about a detected (small) violation and gives the manager the opportunity to remediate the situation. For this reason, a warning is a problem-solving rather than a penalising enforcement instrument. In this model a warning[4] is issued when the firm's measured emissions e_i^m lay between $\overline{e}$ and $\overline{e}(1+\gamma)$, and the firm was not previously given a warning or a fine. A fine $F(e_i^m)$ is directly applied for large detected violations, $e_i^m > \overline{e}(1+\gamma)$, or for small violations of previously sanctioned firms, $\overline{e} < e_i^m \leq \overline{e}(1+\gamma)$. If a firm was found in violation in the first period and a fine was levied or a warning was sent, it will face the higher probability of inspection in the second period, $\overline{p}_2 > \overline{p}_1$. As Eckert (2004) and Rousseau (2005) show warnings as well as fines are used by environmental inspection agencies to target firms for inspection.

Period 2

In the second period the abatement decision of the firm depends on its compliance history. The parameters θ_α, θ_β, e_i^α and e_i^β are defined in analogy to θ_a, θ_b, e_i^a and e_i^b (see figure 2). Firstly, I consider the decision process when the firm was not previously found in violation of the emission standard, $e_{1i}^m \leq \overline{e}$. This gives:

[4] If the government knows the size of the measurement error (γ), it might also decide to fine only firms with emissions larger than $\overline{e}(1+\gamma)$, cf. speeding violations. However, such a strategy would not allow the agency to target inspections using previous warnings and firms will have less incentives to reduce emission below $\overline{e}(1+\gamma)$.

$$\begin{aligned}
&If\ \theta_i \le \theta_\alpha && then \quad e_{2i} = \overline{e} \\
&If\ \theta_\alpha < \theta_i \le \theta_\beta && then \quad e_{2i} = \min\left[e_i^\alpha, \overline{e}(1+\gamma)\right] \\
&If\ \theta_\beta < \theta_i && then \quad e_{2i} = e_i^\beta
\end{aligned} \tag{5}$$

If the firm has low abatement costs, $\theta_i \le \theta_\alpha$, then it complies exactly with the emission standard in the second period. Medium cost firms, $\theta_\alpha < \theta_i \le \theta_\beta$, choose their emission levels such that they have a lower probability $(\overline{p}_1 q < \overline{p}_1)$ to incur a fine than high cost firms with $\theta_\beta < \theta_i$. Remark that $\theta_\alpha > \theta_a$ and $\theta_\beta > \theta_b$.

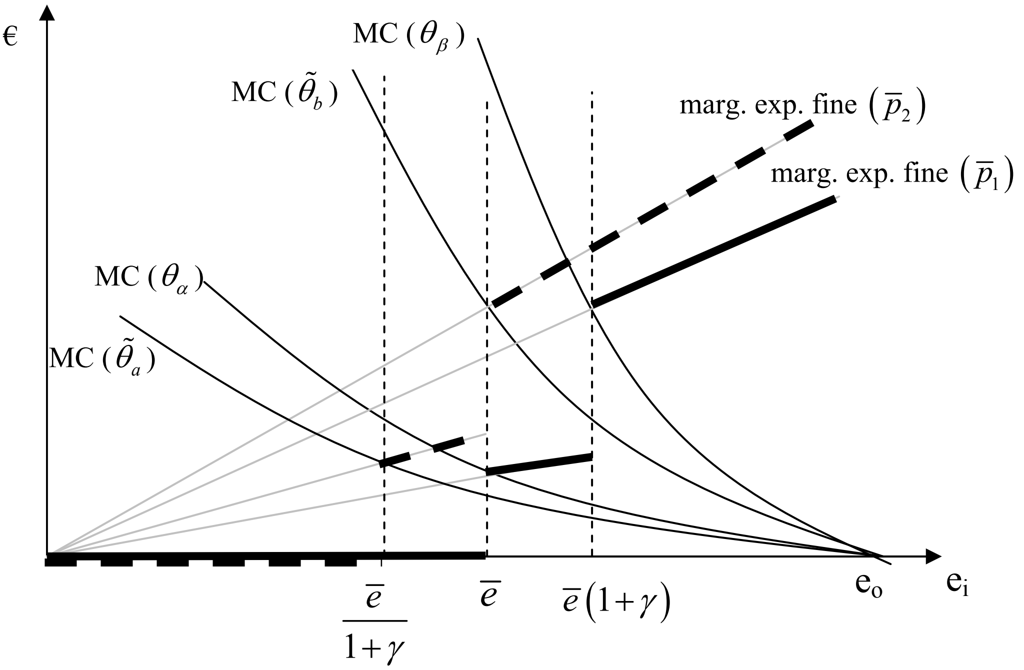


Figure 2: Abatement decision in period 2 with fines and warnings (scheme 2)

Secondly, I investigate what happens if the firm was found in violation in the first period, $e_{1i}^m > \overline{e}$. This gives:

$$\begin{aligned}
&If\ \theta_i \le \tilde{\theta}_a && then \quad e_{2i} = \frac{\overline{e}}{1+\gamma} \\
&If\ \tilde{\theta}_a < \theta_i \le \tilde{\theta}_b && then \quad e_{2i} = \min\left[\tilde{e}_i^a, \frac{\overline{e}}{1+\gamma}\right] \\
&If\ \tilde{\theta}_b < \theta_i && then \quad e_{2i} = \tilde{e}_i^b
\end{aligned} \tag{6}$$

Firms with a non-compliance record make the same emission decision in the second period irrespective whether they face fines or fines and warnings combined. After all, if the firm exceeded the emission limit in the first period, the environmental inspection agency will not use warnings anymore, not even for small abuses. Since, in the case of managerial errors the firm was given the opportunity to correct the situation, all detected violations in the second period are regarded as intentional and therefore punished by a fine. In the case of independent measurement errors, the probability that the firm's emissions are twice incorrectly measured above the emissions standard is positive but small since $q \in \left[0; \tfrac{1}{2}\right[$.

Period 1

In the first period firms again choose their emissions in order to minimise the total costs connected to the environmental regulation (see equation (4)):

$$\begin{array}{lll} \textit{If } \theta_i \le \theta_\alpha & \textit{then} & e_{2i} = \bar{e} \\ \textit{If } \theta_\alpha < \theta_i \le \theta_\beta & \textit{then} & e_{2i} = \min\left[e_i^\alpha, \bar{e}\left(1+\gamma\right)\right] \\ \textit{If } \theta_\beta < \theta_i & \textit{then} & e_{2i} = e_i^\beta \end{array}$$

This is equivalent to the second period decision if the firm was not previously fined.

If $\tilde{\theta}_a \le \theta_\alpha$ and $\tilde{\theta}_b \le \theta_\beta$, this is if $\dfrac{\bar{p}_2\ q\ F'\left(\bar{e}\right)}{C'\left(e_o - \dfrac{\bar{e}}{1+\gamma}\right)} \le \dfrac{\bar{p}_1\ q\ F'\left(\bar{e}\left(1+\gamma\right)\right)}{C'\left(e_o - \bar{e}\right)}$, then the firm's emission decision over the two periods can be described as:

If $\theta_i \le \tilde{\theta}_a$

$$\textit{then} \quad e_{1i} = \bar{e} \qquad \textit{and} \quad E\left[e_{2i}\right] = \left(1 - \bar{p}_1 q\right)\bar{e} + \bar{p}_1 q\left(\frac{\bar{e}}{1+\gamma}\right)$$

If $\tilde{\theta}_a < \theta_i \le \theta_\alpha$

$$\textit{then} \quad e_{1i} = \bar{e} \qquad \textit{and} \quad E\left[e_{2i}\right] = \left(1 - \bar{p}_1 q\right)\bar{e} + \bar{p}_1 q \min\left[\tilde{e}_i^a, \bar{e}\right]$$

$$
\begin{aligned}
&If\ \theta_\alpha < \theta_i \leq \tilde{\theta}_b \\
&\qquad then \quad e_{1i} = \min\left[e_i^\alpha, \overline{e}\left(1+\gamma\right)\right] \quad and \quad E\left[e_{2i}\right] = \left(1-\overline{p}_1\right)\min\left[e_i^\alpha, \overline{e}\left(1+\gamma\right)\right] + \overline{p}_1 \min\left[\tilde{e}_i^a, \overline{e}\right] \\
&If\ \tilde{\theta}_b < \theta_i \leq \theta_\beta \\
&\qquad then \quad e_{1i} = \min\left[e_i^\alpha, \overline{e}\left(1+\gamma\right)\right] \quad and \quad E\left[e_{2i}\right] = \left(1-\overline{p}_1\right)\min\left[e_i^\alpha, \overline{e}\left(1+\gamma\right)\right] + \overline{p}_1\left(\tilde{e}_i^b\right) \\
&If\ \theta_\beta < \theta_i \\
&\qquad then \quad e_{1i} = e_i^\beta \qquad\qquad\qquad and \quad E\left[e_{2i}\right] = \left(1-\overline{p}_1\right)e_i^\beta + \overline{p}_1\left(\tilde{e}_i^b\right)
\end{aligned}
$$

Else if $\tilde{\theta}_a > \theta_\alpha$ and $\tilde{\theta}_b > \theta_\beta$, the resulting emissions are calculated in a similar way. The illustration in section 4.3 is an example with $\tilde{\theta}_a > \theta_\alpha$ and $\tilde{\theta}_b > \theta_\beta$. The ranking of these cost parameters depends on the functional specification of the abatement costs and expected fine. It is impossible to have $\tilde{\theta}_a > \theta_\alpha$ and $\tilde{\theta}_b < \theta_\beta$ or $\tilde{\theta}_a < \theta_\alpha$ and $\tilde{\theta}_b > \theta_\beta$.

4. Results when firms' intended and measured emissions coincide

In order to compare the impact of both regulatory schemes, it is first necessary to define what happens if there is no uncertainty with respect to the measured emissions and measurements carried out by the inspection agency will correctly determine the firm's emissions. Managers know that, if they choose to exceed the emission standard and they are inspected, the violation will be detected with certainty. Likewise, managers can also be certain that, if they decide to comply with the regulation, they will not accidentally be found disobeying.

The firm's abatement decisions in the second period, if they are not fined in the first period, are described by:

$$
\begin{aligned}
&If\ \theta_i \leq \theta^* \qquad then \quad e_{2i} = \overline{e} \\
&if\ \theta_i > \theta^* \qquad then \quad e_{2i} = e_i^*
\end{aligned}
\tag{7}
$$

If the firm was previously found to exceed the emissions standard, its emission decision in the second period is represented by:

$$\begin{array}{lll} If\,\theta_i \le \tilde{\theta}^* & then & e_{2i} = \overline{e} \\ if\,\theta_i > \tilde{\theta}^* & then & e_{2i} = \tilde{e}_i^* \end{array}$$

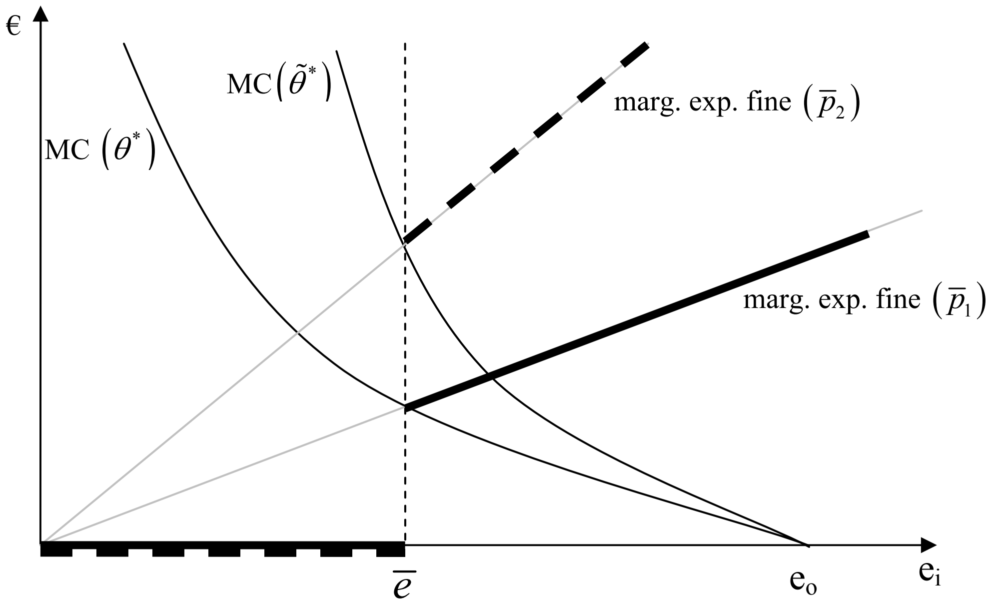


Figure 3: Abatement decision in period 2 with fines and under certainty

The firm's decision in the first period is equivalent to that in the second period if the firm was previously not fined (see equation (7)). This myopic behaviour occurs since firms prefer to incur the higher cost with a probability, $\overline{p}_i q \le 1$, in the second period rather than with certainty in the first period. The parameters θ^*, $\tilde{\theta}^*$, e_i^* and $\tilde{e}_i^*$ are defined in a similar way as before (see figure 3). Firms will obey the rules and emit exactly $\overline{e}$ if their abatement costs are sufficiently low. Otherwise they will violate the emission standard and the seriousness of the infraction depends on the level of their emission reduction costs.

5. Comparison

This section compares the emission decisions made under the different regulatory schemes, both when the results of the agency's emission measurements are certain and uncertain. Figure 4 illustrates that warnings alleviate the overdeterrence caused by the uncertainty with respect to the measured emissions. In the first (figure 4) and second period a similar picture emerges. If the emission levels on which the monetary sanction is based are uncertain, or equivalently if the expected value of the measured emissions is systematically higher than the intended or real emissions, warnings can provide a buffer to give firms time to return to compliance without having to pay monetary penalties. The use of non-monetary sanctions, such as warnings, thus counteracts the distortions caused by false positives or type II-errors as well as the overdeterrence caused by the uncertain measured emissions. It does, however, create some medium-cost firms, that are compliant under a fine system, to exceed the emissions standard since they will be underdeterred.

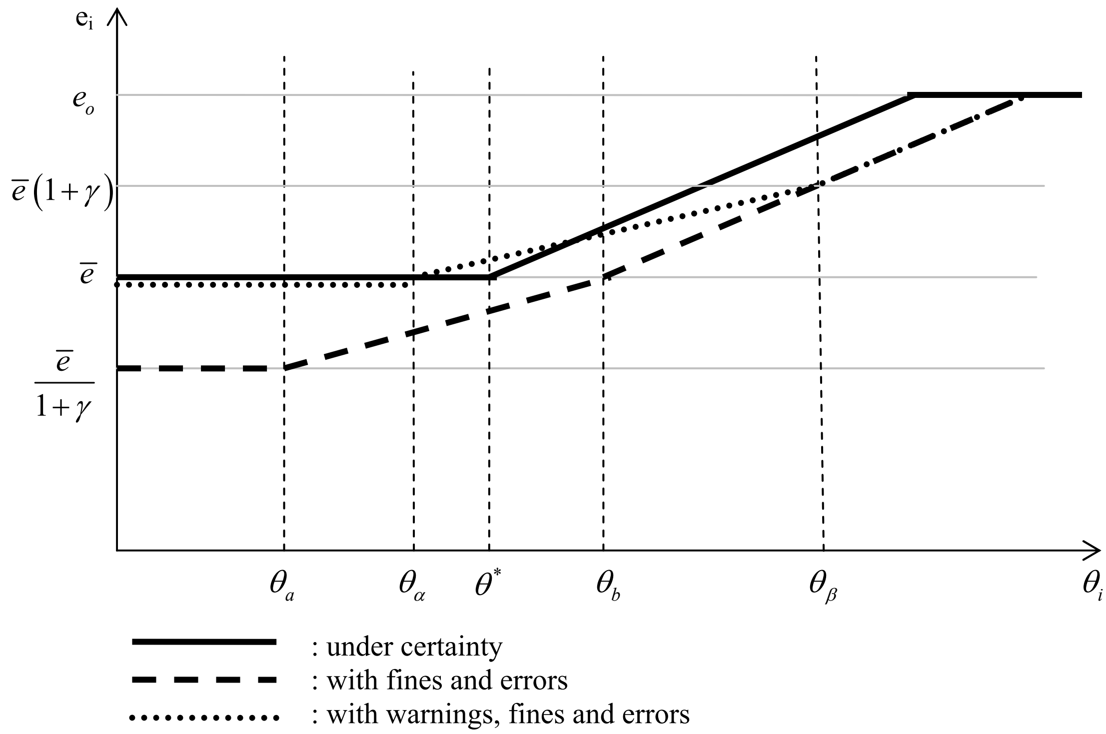


Figure 4: Emission levels with certain and uncertain measured emissions (period 1)

5. Illustration

In order to illustrate the impact of the different regulatory schemes, I specify the various parameters and functions for CO_2 regulation and calculate the associated welfare effects.

$$
\begin{aligned}
&\textit{Example}: && \overline{p}_1 = 0.1;\ \overline{p}_2 = 0.2;\ \overline{e} = 100 \text{ ton } CO_2;\ e_o = 200 \text{ ton } CO_2 \\
& && e_{mi} = e_i \quad \textit{with probability } 0.8 \\
& && \quad\ \ = e_i(1+0.1) \quad \textit{with probability } 0.2 \\
& && C_i = \theta_i \frac{(e_o - e_i)^2}{2} \\
& && F_i = 0 \quad \textit{if } e_{mi} \le \overline{e} \\
& && \quad\ = \frac{(e_{mi})^2}{2} \quad \textit{if } e_{mi} > \overline{e}
\end{aligned}
$$

Using these assumptions, the different thresholds for the cost parameter θ_i are:

$$
\begin{aligned}
&\theta_a = 0.0202; \quad \theta_b^{'} = 0.0242; \quad \theta_b = 0.1042; \\
&\tilde{\theta}_a = 0.0403; \quad \tilde{\theta}_b^{'} = 0.0484; \quad \tilde{\theta}_b = 0.2084; \\
&\theta_\alpha = 0.0242; \quad \theta_\beta^{'} = 0.0296; \quad \theta_\beta = 0.1247; \\
&\theta^* = 0.1; \quad \tilde{\theta}^* = 0.2
\end{aligned}
$$

The associated emission decisions for both regulatory schemes are described in tables 1 and 2.

$\theta_i \in$	*Period 1:* e_{1i}	*Period 2:* $E[e_{2i}]$
$[0, 0.0202]$	90.91	90.91
$]0.0202, 0.0242]$	$e_i^a = \frac{\theta_i 200}{\theta_i + 0.0242}$	$(1-0.22)e_i^a + 0.22(90.91)$
$]0.0242, 0.0403]$	100	$(1-0.22)100 + 0.22(90.91)$
$]0.0403, 0.0484]$	100	$(1-0.22)100 + 0.22\left(\frac{\theta_i 200}{\theta_i + 0.0484}\right)$
$]0.0484, 0.1042]$	100	$(1-0.22)100 + 0.22(100)$
$]0.1042, 0.2084]$	$e_i^b = \frac{\theta_i 200}{\theta_i + 0.08 + 0.0242}$	$(1-0.1)e_i^b + 0.1(100)$
$]0.2084, 0.25]$	e_i^b	$(1-0.1)e_i^b + 0.1\left(\frac{\theta_i 200}{\theta_i + 0.16 + 0.0484}\right)$

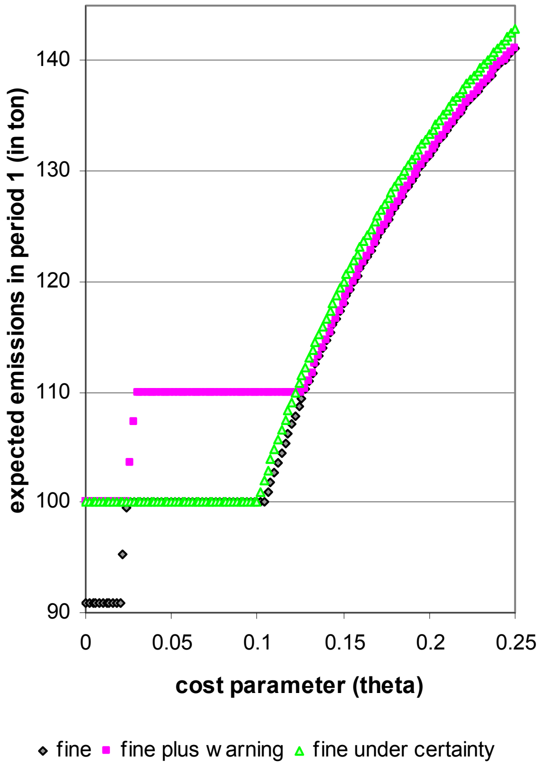
Table 1: Regulatory scheme 1: Fines

$\theta_i \in$	*Period 1:* e_{1i}	*Period 2:* $E\left[e_{2i}\right]$
$\left[0, 0.0242\right]$	100	$\left(1-0.22\right)100+0.22\left(90.91\right)$
$\left]0.0242, 0.0296\right]$	$e_i^{\alpha}=\dfrac{\theta_i 200}{\theta_i+0.0242}$	$\left(1-0.1\right)e_i^{\alpha}+0.1\left(90.91\right)$
$\left]0.0296, 0.0403\right]$	110	$\left(1-0.1\right)110+0.1\left(90.91\right)$
$\left]0.0403, 0.0484\right]$	110	$\left(1-0.1\right)110+0.1\left(\dfrac{\theta_i 200}{\theta_i+0.0484}\right)$
$\left]0.0484, 0.1247\right]$	110	$\left(1-0.1\right)110+0.1\left(100\right)$
$\left]0.1247, 0.2084\right]$	$e_i^{\beta}=\dfrac{\theta_i 200}{\theta_i+0.08+0.0242}$	$\left(1-0.1\right)e_i^{\beta}+0.1\left(100\right)$
$\left]0.2084, 0.25\right]$	e_i^{β}	$\left(1-0.1\right)e_i^{\beta}+0.1\left(\dfrac{\theta_i 200}{\theta_i+0.16+0.0484}\right)$

Table 2: Regulatory scheme 2: Warnings plus fines

Figure 5 compares the resulting emissions of these two enforcement options with the emissions obtained under certainty in the first and second period. Under a fine scheme, low cost firms, $\theta_i \leq 0.0202$, are overdeterred and will overcomply with the emission standard. Medium cost firms, $0.0202 < \theta_i \leq 0.1042$, will exactly comply, while high cost firms, $\theta_i > 0.1042$, will violate the environmental regulation. Under the regulatory scheme which combines warnings with fines, low cost firms, $\theta_i \leq 0.0242$, comply while medium and high cost firms exceed the standard. In order to compare both schemes, the overdeterrence of the low cost firms on the one hand must be weighted with the underdeterrence of the medium cost firms on the other hand and it is also necessary to value the social costs associated with false convictions.

In the second period more firms comply under both regulatory schemes. After all, firms that were found to be non-compliant in the first period will be inspected with a higher probability in the second period and will adjust their abatement decision accordingly.



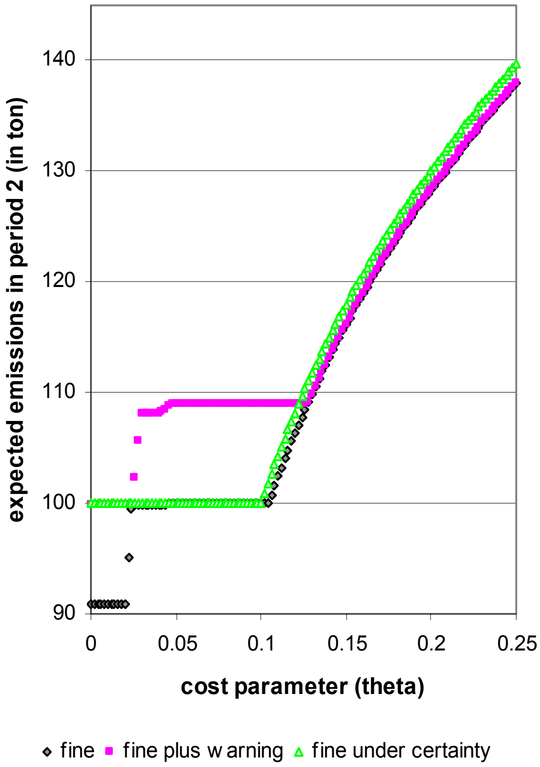


Figure 5: Comparison with the emissions obtained under certainty (period 1 and period 2)

In order to make a clear comparison, social welfare is calculated under each scenario with arbitrary parameter values. For illustrative purposes, the discount rate δ is 0.9, fines are costless transfers, the willingness-to-pay (WTP) for one tonne reduction in CO_2 is 5 euro, the cost of an inspection is negligible and the cost parameter θ_i is discretely uniformly distributed between zero and 0.25 (with 0.002 intervals). Social welfare then equals:

$$SW = -\sum_i \theta_i \frac{(e_o - e_{1i})^2}{2} + 5\sum_i (e_o - e_{1i}) - \Lambda \sum_i \text{Prob}\left[e_{1i}^m > \overline{e} \,\middle|\, e_{1i} \le \overline{e} \right]$$
$$+\delta\, E\left[-\sum_i \theta_i \frac{(e_o - e_{2i})^2}{2} + 5\sum_i (e_o - e_{2i}) - \Lambda \sum_i \text{Prob}\left[e_{2i}^m > \overline{e} \,\middle|\, e_{2i} \le \overline{e} \right] \right]$$

with $\Lambda \ge 0$ the social cost of fining innocent firms.

Social welfare with $\Lambda = 0$ when only fines are used as a regulatory instrument and uncertainty is present, equals 8693 euro. When also warnings are allowed, social welfare is increased to 9350 euro, i.e. an increase of 7.6%. The benchmark with fines under certainty leads to a social welfare level of 11790 euro. So, even if falsely levied fines do not reduce social welfare, social welfare under a warning-fine regime will be higher than social welfare under a fine regime since such a regime reduces the overdeterrence effect and saves on abatement expenditures. In the, more realistic, case where prosecuting innocent firms has a social cost, the difference in social welfare will be even more striking. This strong result depends on functional specifications of the abatement and fine functions as well as on the estimate of the willingness-to-pay for environmental improvement. Under other specifications the result might not be as clear but, if the social cost of falsely fining firms is high enough, then it will always pay off to use warnings as a complement to fines.

In this illustrative exercise, for $WTP \geq 5.67\,\text{euro/tonne}\,\text{CO}_2$ reduced and $\Lambda = 0$, social welfare of the fine scheme will always exceed that of the warning-fine scheme. If, for example, the WTP equals 10 euro per tonne CO_2 reduced, then the social cost Λ of incorrect fining will need to be larger than 2879 euro per incident to make warnings a socially beneficial enforcement instrument. Garcia-Quijano et al. (2005) mention that the expected world market price for tradable CO_2 permits is at present estimated between 5 and 20 euro per tonne CO_2. Furthermore, the closing prices of the European CO_2 emission trading market in November 2005 ranged between 21 and 23 Euro per tonne CO_2.

5. Conclusion

In my opinion the prevalent role of warnings in the daily policy of an inspection agency can be explained as a corrective measure when there is an imperfect match between the firm's emission decision and the agency's measured emissions. Introducing the use of warnings as a non-monetary enforcement instrument can thus increase social welfare when the results of emission measurements are uncertain. This uncertainty implies that abatement decisions taken by the firm's manager are not perfectly reflected in the level of emissions which could be measured by the inspection agency. Measured emissions can be biased upwards if, for example, the agency's measuring equipment does not work perfectly or if managers' decisions are poorly implemented by the workforce. In such a situation, warnings can, firstly, be used as a problem-solving device and as an alert to managers that communication within the company or employees' incentives might be improved. A warning-fine system allows firms to correct small accidental discharges or to investigate principal-agent relationships without monetary consequences. Even though it creates some underdeterrence of medium cost firms, such a system reduces the overdeterrence of low cost firms caused by the difference between intended and measured emissions. Secondly, warnings reduce the number of incorrect prosecutions in the case of measurement errors, which is also welfare enhancing.

The results of this study show theoretically that it is important to consider informal as well as formal enforcement instruments. Both types of instruments can not only be used as substitutes but also, and more importantly, as complements.

Acknowledgements

I gratefully acknowledge the financial support of the FWO project 'An economic approach to modelling the enforcement of environmental regulation'. I would also like to thank Eef Delhaye, Ronald Rousseau (KHBO, association K.U.Leuven) and Ellen Moons for their useful suggestions.

References

Becker, G.S.,1968. Crime and punishment: An economic approach. *Journal of Political Economy* 76(2), 169-217.

Bose, P., 1995. Regulatory errors, optimal fines and the level of compliance. *Journal of Public Economics* 56, 475-484.

Chu, C.Y.C., Sheng-cheng, H., Huang, T., 2000. Punishing repeat offenders more severely. *International Review of Law and Economics* 20(1), 127-140.

Cohen, M.A., 2000. Monitoring and enforcement of environmental policy. In: Tietenberg, T., Folmer, S. (eds.), *International Yearbook of Environmental and Resource Economics*, Volume III. Edward Elgar Publishers.

Eckert, H., 2004. Inspections, warnings, and compliance: The case of petroleum storage regulation. *Journal of Environmental Economics and Management* 47, 232-259.

Garcia-Quijano, J.F., Deckmyn, G., Moons, E., Proost, S., Ceulemans, R., Muys, B., 2005. An integrated decision support framework for the prediction and evaluation of efficiency, environmental impact and total social cost of domestic and international forestry projects for greenhouse gas mitigation: description and case studies. *Forest Ecology and Managemen*t 207, 245-262.

Garoupa, N., Klerman, D., 2004. Corruption and the optimal use of nonmonetary sanctions. *International Review of Law and Economics* 24, 219-225.

Gray, W.B.,Deily, M.E., 1996. Compliance and enforcement: Air pollution regulation in the US steel industry. *Journal of Environmental Economics and Management* 31, 96-111.

Harrington, W., 1988. Enforcement leverage when penalties are restricted. *Journal of Public Economics* 37, 29-53.

Laplante, B., Rilstone, P., 1996. Environmental inspections and emissions for the pulp and paper industry in Quebec. *Journal of Environmental Economics and Management* 31, 19-36.

Nyborg, K., Telle, K., 2004. The role of warnings in regulation: Keeping control with less punishment. *Journal of Public Economics* 88(12), 2801-2816.

Polinsky, A.M., Shavell, S., 2000. The economic theory of public enforcement of law. *Journal of Economic Literature* 37, 45-76.

Rousseau, S., 2005. Timing of environmental inspections: Survival of the compliant. In: Rousseau, S., *Selecting environmental policy instruments in the presence of incomplete compliance*. Doctoral dissertation. pp. 127-154.

Shavell, S., 1987. The optimal use of nonmonetary sanctions as a deterrent. *American Economic Review* 77(4), 584-592.

Stafford, S.L., 2002. The effect of punishment on firm compliance with hazardous waste regulations. *Journal of Environmental Economics and Management* 44, 290-308.

The Center for Economic Studies (CES) is the research division of the Department of Economics of the Katholieke Universiteit Leuven. The CES research department employs some 100 people. The division Energy, Transport & Environment (ETE) currently consists of about 15 full time researchers. The general aim of ETE is to apply state of the art economic theory to current policy issues at the Flemish, Belgian and European level. An important asset of ETE is its extensive portfolio of numerical partial and general equilibrium models for the assessment of transport, energy and environmental policies.

ETE WORKING PAPER SERIES
2005

N°2005-08	Rousseau S. (2005), The use of warnings when intended and measured emissions differ
N°2005-07	Proost S., Van der Loo S., de Palma A., Lindsey R. (2005), A cost-benefit analysis of tunnel investment and tolling alternatives in Antwerp
N°2005-06	de Palma A., Lindsey R. and Proost S. (2005), Research challenges in modelling urban road pricing: an overview
N°2005-05	Moons E., Rousseau S. (2005), Policy design and the optimal location of forests in Flanders
N°2005-04	Mayeres I., Proost S. (2005), Towards better transport pricing and taxation in Belgium
N°2005-03	Proost S., Sen A. (2005), URBAN Transport pricing reform with TWO levels of government
N°2005-02	Moons E., Saveyn B., Proost S., Hermy M. (2005), Optimal location of new forests in a suburban area
N°2005-01	Pepermans G., Willems B. (2005), The potential impact of cross-ownership in transmission: An application to the Belgian electricity market

ETE WORKING PAPER SERIES
2004

N°2004-16	Franckx L, D'Amato A., Brose I. (2004), Multi Pollutant Yardstick Schemes as Environmental Policy Tools
N°2004-15	Rousseau S., Proost S. (2004), The Relative Efficiency of Market-based Environmental Policy Instruments with Imperfect Compliance
N°2004-14	Eyckmans J., Finus M. (2004), An Almost Ideal Sharing Scheme for Coalition Games with Externalities