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Technology Choice and Environmental Regulation under Asymmetric Information

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Abstract

We analyze environmental standard setting and its consequences on a firm's incentives to invest in a cleaner technology. The regulated firm knows whether it is good or bad in employing the clean technology, but the regulator doesn't. We compare commitment (the regulator sets the standard first) to time consistency (the firm makes its investment choice first). With complete information, commitment always leads to the first best, but time consistency doesn't. Under asymmetric information, however, the regulator may be able to infer the firm's type from its investment decision, so that time consistency can lead to higher welfare than commitment.

Keywords: asymmetric information, commitment, time consistency, environmental policy

JEL classification: D62, D82, Q28

1 Introduction

Innovation is a crucial variable to be considered in the design of environmental policy. Since Downing and White [3] and Milliman and Prince [8], attempts have been made in the literature to compare the relative merits of different environmental policy instruments in terms of their dynamic efficiency properties.[1] Another relevant strand of the literature has focused, on the other hand, on the issue of whether the regulator should set environmental

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[1] See also the surveys in Jaffe et al. [5] and Requate [12].

policy dimensions before or after investment has actually taken place. In the first case we talk about *commitment*, while, in the second case, we are dealing with *time consistency*.

From its inception by Kydland and Prescott [6] and Fischer [4], the literature has almost unanimously found that with perfect information, commitment is always at least as good as time consistency. Recent papers, such as Amacher and Malik [1], Petrakis and Xepapadeas [10], Arguedas and Hamoudi [2] and Requate [11], concluded that time consistency can improve upon commitment in environmental policy. In Amacher and Malik's [1] time consistency scenario, the firm first invests in pollution abatement. Then the government sets an emission tax rate. With commitment, the following order of the actions is reversed. Finally, in both scenarios the firm sets its abatement level. Petrakis and Xepapadeas' [10] model can be seen as an extension of Amacher and Malik [1], considering multiple firms as well as the imperfectly competitive output market. In Arguedas and Hamoudi's [2] model, the firm can invest in a technology that reduces the damaging impact of its emissions on the environment. The regulator can inspect the firm and impose a fine if emissions exceed the standard. With time consistency, the firm first invests in technology and then the regulator sets the the standard and the probability of inspection. With commitment, the following order is reversed. Finally, in both scenarios, the firm sets its emission level and is potentially subjected to inspection and a fine. In Requate's [11] model, there is a single firm that can invest in R&D effort to make it more likely that it will find a new technology. If it does, it can sell the technology to the polluting industry. Requate [11] discusses several scenarios for the timing of environmental policy. None of the above papers, however, focuses on the impact of asymmetric information.

In this paper we analyze the welfare effects of commitment and time consistency for the regulation of a polluting firm that can invest in a cleaner technology. Our model is similar to Amacher and Malik's [1], with two main differences. First, we analyze the policy instrument of direct regulation rather than emission taxation. Secondly, we assume asymmetric information about technology. The firm knows its own cost of the new technology, but the regulator does not.

One of the first papers dealing with innovation and standard setting under asymmetric information is Yao [14]. The author examines the case where asymmetric information involves firms' innovation capacity. The game consists of two periods and involves a single player (the "industry"). In period one, the regulator sets the period-one emission standard. Then industry chooses a research investment level. This is not observable by the regulator, and neither is the industry's innovation capability. Industry research is either a failure or a success, so that its cost of meeting the standard is either high or low. The game is repeated in period two.

Yao's [14] regulatory scenario is a mix of commitment and time consistency. There is commitment in the sense that the regulator can commit to the period-i standard in period i, regardless of the outcome of R&D. There is time consistency in the sense that the regulator cannot commit to the period-two standard in period 1. As a result, the industry underinvests in period-one R&D effort in an attempt to reduce the regulator's confidence in its ability and to obtain a more lenient standard in period 2. The regulator partially counteracts this effect by setting a stricter standard in period 1.

Malik [7] compares commitment and time consistency for standard setting for a single firm in a two-period model where the period-two damage function is revealed in period 2. Under commitment (or precommitment, or permanent regulation, as Malik calls it), the regulator sets the standard for both periods at a time when only period-one damage is known. The firm then invests in abatement capital and complies with the period-one standard. Subsequently, period-two damage is revealed and the firm complies to the period-two standard. With time consistency (or discretion, or interim regulation, as Malik calls it), the regulator only sets the period-one standard in period one. The firm then invests in abatement capital and complies with the period-one standard. Now, the regulator sets the period-two standard after period-two damage is revealed. The advantage of time consistency is then that the regulator has perfect information when she sets the standards. The disadvantage is that the firm will underinvest in abatement capital in period 1 in order to obtain a more lenient period-2 standard. Malik [7] also takes the regulator's enforcement cost into account.

Tarui and Polasky [13] study a simplified version of Malik's game with only a single period and without costly enforcement. However, they analyze taxes as well as standards. With commitment (or rules, as Tarui and Polasky call it), the regulator first sets the tax rate or the standard. Then the firm invests in abatement capital. Uncertainty about environmental damage is resolved, and finally the firm makes its abatement decision. With time consistency (or discretion, as Tarui and Polasky call it), on the other hand, the regulator sets her policy after the firm has invested and damage has been revealed. Commitment would result in the first best if there were no uncertainty about damages, because the firm has a continuous investment decision. With time consistency, the result is again that the firm underinvests with standards and overinvests with taxes. Interestingly, when abatement costs and damage are quadratic, taxes are welfare-superior to standards.

Finally, Moledina et al. [9] compare taxes and tradable permits with grandfathering in a two-firm industry. The regulator does not know the firms' abatement cost and does not take into account that the firms will try to manipulate her beliefs and policy. In a two- as well as in a T-period model (where T may be infinite), Moledina et al. [9] show that firms will underabate under taxation in order to obtain a lower tax rate. The result for tradable permits is less clearcut. On the one hand, both firms benefit from a high permit price, because this will prompt the regulator to issue more permits. On the other hand, the permit buyer (seller) prefers a low (high) permit price.

In our paper, the game structure is close to the one in Tarui and Polasky [13], but in our case, as in Moledina et al. [9], asymmetric information is about abatement costs. We focus, however, on environmental standard setting and on its consequences on investment incentives of regulated firm. Asymmetric information is introduced in that the regulated firm can be good or bad in employing the good technology, if it invests. We focus on realistic contracts, not involving lump sum transfer, and show that under commitment the only possible equilibrium involves a pooling contract where the standard is set at an average level. On the other hand, time consistency might involve the same pooling contract, when investment costs are sufficiently low so that firms invest independently of their type, while it can imply that first best can be reached if fixed costs are sufficiently high to guarantee that only the efficient firm would invest. Indeed, in such a case time consistency implies that the firm's type is revealed by its investment behaviour. Further, in the latter case social welfare can be higher under time consistency than under commitment.

The paper is organized as follows: Section 2 shows the main structure of the model. Section 3 derives equilibria under commitment, while Section 4 derives equilibria under time consistency. Section 5 compares the results under the two regulatory structures.

2 The model

A regulated firm must choose whether or not to invest in a cleaner technology. We assume two technologies are available. Technology 0 is the "dirty" (high marginal costs) one, while technology 1 is the clean technology. Once the technology choice has been made, the firm chooses the abatement level in order to minimize compliance costs. Compliance costs of technology $i = 0, 1$ are given by:

$$C_i(a) = K_i + V_i(a)$$

where a is abatement, $V_i(a)$ are abatement costs related to technology i, while K_i are fixed costs related to the same technology. Fixed costs are higher for the clean technology 1, while marginal costs are assumed to be higher (for any given level of abatement) with the dirty technology 0. Further, abatement costs are increasing and convex.

We focus on specific functional forms, assuming:

$$C_1(a) = F + \frac{b_1}{2}a^2 \tag{1}$$

$$C_0(a) = 0 + \frac{b_0}{2}a^2 \tag{2}$$

where b_0 and b_1 are positive parameters, $b_0 > b_1 > 0$. Define b and θ such that $b_0 = b$ and $b_1 = \theta b$ with $0 < \theta < 1$.

The environmental regulator chooses the environmental standard in order to minimize social costs from production, given by:

$$SC_i = C_i(a) + D(a) \tag{3}$$

We assume specific functional forms also for the damage cost functions:

$$D(a) = \frac{d}{2}(e - a)^2 \tag{4}$$

where e denotes (exogenous) business as usual emissions.

Social costs under the dirty technology are, substituting (2) and (4) into (3):

$$SC_0 = \frac{ba^2}{2} + \frac{d\,(e-a)^2}{2} \tag{5}$$

Minimizing (5) with respect to a yields the first best abatement level a_0^*:

$$a_0^* = \frac{de}{b+d} \tag{6}$$

Substituting (6) into 5), we find "optimal" social costs under the dirty technology:

$$SC_0^* = \frac{d^2e^2}{2}\frac{b}{(b+d)} \tag{7}$$

Social costs under the clean technology are, substituting (1) and (4) into (3):

$$SC_1 = F + \frac{\theta ba^2}{2} + \frac{d\,(e-a)^2}{2} \tag{8}$$

Minimizing (8) with respect to a yields the first best abatement level a_1^*:

$$a_1^* = \frac{de}{b\theta + d} > a_0^* \tag{9}$$

Substituting (9) into 8), we find "optimal" social costs under the clean technology:

$$SC_1^*(\theta) = F + \frac{d^2e^2}{2}\frac{b\theta}{b\theta + d} \tag{10}$$

We assume that the cost parameter θ can take two values:

- a high one ($\theta = h$) with probability $1 - v$, implying that the firm is not good in using the new technology;
- a low one ($\theta = l$) with probability v, implying that the firm is efficient in using the new technology.

Of course, $l < h$.

The first best abatement level would be

$$a_h = \frac{de}{bh + d} \tag{11}$$

for the high-cost firm and

$$a_l = \frac{de}{bl + d} \tag{12}$$

for the low-cost one.

We see that $a_l > a_h$ *as* $l < h$. We can define $F_\theta,\ \theta = l, h$, as the level of fixed cost at which social cost with the clean technology ($SC_1^*(\theta)$ in (10) equals social cost with the dirty technolgy (SC_0^* in (7)):

$$F_h = \frac{be^2d^2}{2}\frac{(1-h)}{(b+d)(bh+d)} \tag{13}$$

$$F_l = \frac{be^2d^2}{2}\frac{(1-l)}{(b+d)(bl+d)} \tag{14}$$

Then $F_h < F_l$. We assume that social costs in the social optimum are strictly lower when the chosen technology is the cleaner one. This implies:

Assumption *We will focus, in what follows, on the case when it is first best for both types of firm to invest, implying* $F < F_h$

3 Symmetric Information

3.1 Commitment

Under commitment, the regulator sets the abatement target before the firm chooses whether to invest or not. Given that investment is always desirable, the regulator would like to impose a_l to the efficient firm and a_h to the inefficient one. This will be feasible only if the firm will indeed invest in reaction to the first best standard. This will happen if:

$$C_1^\theta(a_\theta) < C_0(a_\theta)$$

that is, if:

$$F < \frac{bd^2e^2}{2}\frac{(1-\theta)}{(b\theta+d)^2} = F_{co,s}^\theta$$

It is easily shown that $F_{co,s}^\theta > F_\theta$. Thus both types of firm will invest when the regulator sets a_θ: commitment always implements the first best under symmetric information.

3.2 Time Consistency

Under time consistency, the firm first decides whether or not to invest. Then the regulator observes the firm choice and sets the abatement target accordingly.

Assume that the firm anticipates that the regulator will set a_θ if it invests and a_0 if it does not. In order to understand whether first best is feasible, we must check whether firm of type θ will indeed invest under the first best standard. This will happen if

$$F < F^{\theta}_{tc,s}$$

where

$$F^{\theta}_{tc,s} = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{\theta}{(b\theta+d)^2}\right)$$

We see that $F^{\theta}_{tc,s} < F_\theta$. The firm will only invest if $F < F^{\theta}_{tc,s}$, in which case the first best is implemented. However, for $F^{\theta}_{tc,s} < F < F_\theta$ the firm will not invest and the first best is not achieved.

3.3 Comparisons

Comparing the threshold levels we get:

$$F^{\theta}_{tc,s} - F^{\theta}_{co,s} = \frac{bd^2e^2}{2}\left(\frac{1}{(b+d)^2} - \frac{\theta}{(b\theta+d)^2}\right) - \frac{bd^2e^2}{2}\frac{(1-\theta)}{(b\theta+d)^2} < 0$$

so that $F^{\theta}_{tc,s} < F^{\theta}_{co,s}$ for any θ. As a consequence, we can conclude that $F^{\theta}_{tc,s} < F_\theta < F^{\theta}_{co,s}$.

We can sum up results obtained so far as follows:

Proposition 1 *In the absence of asymmetric information:*

a. *commitment always implements the first best*

b. *time consistency implements the first best for firm θ if and only if $F < F^{\theta}_{tc,s}$. It does not implement the first best for $F^{\theta}_{tc,s} < F < F_\theta$. In the latter case, the firm does not invest, although investment is the first-best outcome.*

4 Asymmetric Information

4.1 Commitment

Also under asymmetric information the regulator would like to impose a_l to the efficient firm and a_h to the inefficient one. This is, however, not feasible due to the presence of adverse selection. Since $a_l > a_h$, the efficient firm would claim to be inefficient.

As a consequence, in the absence of the opportunity to make a transfer in favour of the efficient firm (which is the one that would benefit more from the investment in terms of lower costs) or a negative transfer damaging the inefficient firm (that would, after the new technology is introduced, have the highest marginal costs), regulation cannot take place by imposing differentiated standards. The environmental regulator will have, therefore, to impose a "pooling" regulation minimizing expected social costs.

Assuming that both types of firms will invest, from (8) we can conclude that the environmental regulator minimizes:

$$E(SC) = \frac{d}{2}(e-a)^2 + F + v\frac{lba^2}{2} + (1-v)\frac{hba^2}{2}$$

The first order condition is:

$$\frac{\partial E(SC)}{\partial a} = ablv + abh(1-v) + \frac{1}{2}d(2a-2e) = 0$$

Solving for the optimal abatement level a_m yields:

$$a_m = \frac{de}{d + blv + bh(1-v)} = \frac{de}{d + E(\theta)b} \tag{15}$$

where $E(\theta) \equiv lv + h(1-v)$. Clearly, $a_h < a_m < a_l$. The minimum expected social costs corresponding to a_m are given by:

$$SC_m^* = F + \frac{d}{2}(e - \frac{de}{d+E(\theta)b})^2 + v\frac{lb\left(\frac{de}{d+E(\theta)b}\right)^2}{2} + (1-v)\frac{hb\left(\frac{de}{d+E(\theta)b}\right)^2}{2}$$

Simplifying and using the definition of $E(\theta)$:

$$SC_m^* = F + \frac{bde^2}{2}\frac{E(\theta)}{d+E(\theta)b} \tag{16}$$

First of all, we need to check whether investment is, in this case, socially desirable. This happens when $SC_m^* < SC_0$, or from (7) and (16):

$$F < \frac{d}{2}\left((e-a_0)^2 - (e-a_m)^2\right) - \frac{b}{2}\left((vl + (1-v)h)a_m^2 - a_0^2\right)$$

The inequality is satisfied if and only if:

$$F < F_m \equiv \frac{1}{2}\frac{(1 - h(1-v) - lv)e^2bd^2}{(d + bh(1-v) + blv)(b+d)}$$

Given that,

$$\frac{(1-h)}{(bh+d)}-\frac{(1-h(1-v)-lv)}{(d+bh-b(h-l)v)}<0$$

so that $F_h < F_m$, and given our assumption that $F < F_h$ we have that *a fortiori* $F < F_m$.

This implies that, when first best is socially desirable, then also the average contract is always desirable.

Of course, we also need to check whether such pooling abatement level is feasible. In order for it to be feasible, we must have that the standard set is enough to force both firms to invest. This happens when, for each firm type,

$$C_1^\theta(a_m) < C_0(a_m)$$

with $\theta = h, l$. As

$$C_1^\theta(a_m) - C_0(a_m) = F + \frac{bd^2e^2}{2}\frac{\theta - 1}{(d+E(\theta)b)^2},$$

we can conclude that $C_1^\theta(a_m) < C_0(a_m)$ when

$$F < F_\theta^{co} \equiv \frac{bd^2e^2}{2}\frac{1-\theta}{(d+E(\theta)b)^2}$$

It is easily seen that $F_l^{co} > F_h^{co}$. Further, we assumed $F < F_h$. We can compare the two threshold levels:

$$F_h - F_\theta^{co} = \frac{bd^2e^2}{2}\left(\frac{(1-h)}{(bh+d)\,(b+d)} - \frac{1-\theta}{(d+E(\theta)b)^2}\right)$$

Given that $1 > h > E(\theta)$, we can conclude that $(bh+d)\,(b+d) > (E(\theta)b+d)^2$. Further, $1-h \leq 1-\theta$. As a consequence, $F_h < F_\theta^{co}$ for all θ. Imposing $F < F_h$ implies therefore $F < F_\theta^{co}$.

Both firms will, under our assumptions, choose to invest under the "average" contract under commitment. Thus the pooling contract (which is socially desirable) is always feasible under commitment.

4.2 Time consistency

Also under asymmetric information, the regulator observes the firm's choice about investment (but not its type) and sets the emission standard. As in the symmetric information case, we solve for the subgame perfect Bayesian Nash equilibrium by backward induction.

4.2.1 Second stage

Once the firm has chosen whether to invest or not, the regulator has to set the standard.

Suppose the firm did not invest; in this case the regulator will set abatement at the first best level a_0^* minimizing social costs (see (6)). When the firm has invested in stage one, the standard depends on the regulator's belief about the firm's type. If the regulator believes that both types would have invested, she would set the standard at a_m according to (15). If the regulator believes only the efficient firm would have invested, she would set the standard at a_l according to (12) if the firm invested and a_0 if the firm did not.

It is easily seen that there is no equilibrium in which the inefficient firm would invest and the efficient firm would not.

4.2.2 First stage

In case firm θ anticipates that the regulator will set a_m when it invests, it will invest for:

$$F < F_m^\theta \equiv \frac{b}{2}a_0^2 - \frac{\theta b}{2}a_m^2 \tag{17}$$

Obviously, $F_m^h < F_m^l$. When $F < F_m^h$, both types will invest.

If firm θ anticipates that the regulator will set a_l when it invests, it will invest for:

$$F < F_l^\theta \equiv \frac{b}{2}a_0^2 - \frac{\theta b}{2}a_l^2 \tag{18}$$

Again, $F_l^h < F_l^l$. When $F_l^h < F < F_l^l$, only the efficient type will invest.

4.2.3 Equilibrium

Note that $F_l^h < F_m^h$. On the other hand, F_l^l can be larger or smaller than F_m^h. From (17) and (18):

$$F_l^l - F_m^h = \frac{d^2e^2b}{2}\left(\frac{h}{(d+bE(\theta))^2} - \frac{l}{(d+bl)^2}\right) > 0$$

if and only if:

$$\frac{h}{l} > \left[\frac{d+bE(\theta)}{d+bl}\right]^2$$

Recall that we assumed $F < F_h$, to guarantee that investing is always first best for both firms.

Now let us compare F_m^θ and F_l^θ with F_h. It follows from (13) and (17) that:

$$F_m^\theta - F_h = \frac{(d+bE(\theta))^2 - \theta(b+d)^2}{(b+d)(d+bE(\theta))^2} - \frac{(d+bE(\theta))^2 - (d+bE(\theta))^2 h}{(d+bE(\theta))^2(bh+d)}$$

The above expression is always negative when $\theta = h$. In this case we can therefore conclude that $F_m^h < F_h$. On the other hand, when $\theta = l$ then we could have that either $F_m^l > F_h$ or $F_m^l < F_h$.

Turning to $F_l^\theta - F_h$, as $F_l^h < F_m^h$, then $F_l^h < F_m^h < F_h$. On the other hand, from (13) and (18):

$$F_l^l - F_h = \frac{be^2d^2}{2}\left(\frac{(d+bl)^2 - l(b+d)^2}{(b+d)^2(d+bl)^2} - \frac{(1-h)}{(b+d)(bh+d)}\right)$$

The sign of the above expression is not clear-cut. We can have therefore that either $F_l^l > F_h$ or $F_l^l < F_h$.

Summing up, we can distinguish three cases, each with two subcases. The equilibria of our game are then as follows (the regulator always sets a_0 if the firm does not invest):

1. $F_l^l < F_m^l < F_h$

   a. For $F_l^l < F_m^h$

   - if $F < F_l^h$: both types invest and the regulator sets a_m if the firm invests.
   - if $F_l^h < F < F_l^l$: there are two equilibria. In one equilibrium, both types invest and the regulator sets a_m if the firm invests. In the other equilibrium, only the efficient firm invests, and the regulator sets a_l if the firm invests.
   - if $F_l^l < F < F_m^h$: both firms invest and the regulator sets a_m if the firm invests.
   - if $F > F_m^h$: neither type invests.

   b. For $F_l^l > F_m^h$:

   - if $F < F_l^h$: both types invest and the regulator sets a_m if the firm invests.
   - if $F_l^h < F < F_m^h$: there are two equilibria. In one equilibrium, both types invest and the regulator sets a_m if the firm invests. In the other equilibrium, only the efficient firm invests, and the regulator sets a_l if the firm invests.

- if $F_m^h < F < F_l^l$: only the efficient firm invests and the regulator sets a_l if the firm invests.
- if $F > F_l^l$: neither type invests.

2. $F_l^l < F_h < F_m^l$

a. For $F_l^l < F_m^h$

- if $F < F_l^h$: both types invest and the regulator sets a_m if the firm invests.
- if $F_l^h < F < F_l^l$: there are two equilibria. In one equilibrium, both types invest and the regulator sets a_m if the firm invests. In the other equilibrium, only the efficient firm invests, and the regulator sets a_l if the firm invests.
- if $F_l^l < F < F_m^h$: both firms invest and the regulator sets a_m if the firm invests.
- if $F_m^h < F < F_h$: neither type invests.

b. For $F_l^l > F_m^h$:

- if $F < F_l^h$: both types invest and the regulator sets a_m if the firm invests.
- if $F_l^h < F < F_m^h$: there are two equilibria. In one equilibrium, both types invest and the regulator sets a_m if the firm invests. In the other equilibrium, only the efficient firm invests, and the regulator sets a_l if the firm invests.
- if $F_m^h < F < F_l^l$: only the efficient firm invests and the regulator sets a_l if the firm invests.
- if $F_l^l < F < F_h$: neither type invests.

3. $F_h < F_l^l < F_m^l$. Now itt can only be the case that $F_l^l > F_m^h$, as $F_m^h < F_h$ and, in this case, $F_h < F_l^l$.

- if $F < F_l^h$: both types invest and the regulator sets a_m if the firm invests.

- if $F_l^h < F < F_m^h$: there are two equilibria. In one equilibrium, both types invest and the regulator sets a_m if the firm invests. In the other equilibrium, only the efficient firm invests, and the regulator sets a_l if the firm invests.
- if $F_m^h < F < F_h$: only the efficient firm invests and the regulator sets a_l if the firm invests.

There are therefore three kinds of equilibria:

1. No firm invests, and the regulator sets a_0. In this case social welfare is:

$$SC_0^* = \frac{d^2e^2}{2}\frac{b}{(b+d)}$$

2. Both firms invest, and the regulator sets a_m. In this case (ex post) social welfare is the same as that resulting under commitment, that is:

$$SC_m^* = F + \frac{bde^2}{2}\frac{E(\theta)}{d+E(\theta)b}$$

3. The efficient firm invests and the inefficient one does not. The regulator, then, gains information concerning the firm's type, and is capable of setting the no investment standard if the firm is inefficient and a_l if the firm invests. Accounting for *a priori* probabilities, the corresponding *ex ante* expected social costs are given by:

$$E\left(SC_l^*\right) = vSC_l^* + (1-v)\,SC_0^*$$

with, as obvious,

$$SC_0^* < E\left(SC_l^*\right) < SC_l^*$$

and

$$\begin{aligned} E\left(SC_l^*\right) &= v\left(F + \frac{d^2e^2}{2}\frac{bl}{bl+d}\right) + (1-v)\left(\frac{d^2e^2}{2}\frac{b}{(b+d)}\right) = \\ &= vF + \frac{bd^2e^2}{2}\left(\frac{vl}{bl+d} + \frac{1-v}{(b+d)}\right) \end{aligned}$$

5 Comparisons

We already know that, under our assumptions,

$$SC_0^* < SC_m^* < SC_l^*$$

Proposition 2 *When investing is first best for both firms' type, time consistency might lead to "no investment" pure strategy equilibria and, therefore, to lower social welfare than commitment.*

We can now compare expected welfare from the second and the third type of pure strategy equilibrium. Given that

$$SC_0^* < E\left(SC_l^*\right) < SC_l^*$$

and that

$$SC_m^* < SC_l^*$$

it could be the case that either $SC_m^* < E\left(SC_l^*\right)$ or $SC_m^* > E\left(SC_l^*\right)$. It can be easily shown that

$$SC_m^* - E\left(SC_l^*\right) = (1-v)F + \frac{bde^2}{2}\frac{E(\theta)}{d+E(\theta)b} - \frac{bd^2e^2}{2}\frac{(d+bl-dv(1-l))}{(d+bl)\,(b+d)}$$

which is positive, implying higher expected social costs under the pooling contract if

$$F > \frac{bd^2e^2}{2(1-v)}\left(\frac{(d+bl-dv(1-l))}{(d+bl)} - \frac{dE(\theta)+bE(\theta)}{d\left(d+E(\theta)b\right)}\right) = \widehat{F}$$

Proposition 3 *When fixed costs are sufficiently high, we could have cases where time consistency leads to a higher ex ante expected social welfare than commitment.*

The intuition behind this result can be summed up as follows. Under commitment the regulator has no chance to "learn" the firm's type, as regulation is set before investment does indeed take place. On the other hand, under time consistency, and if fixed costs are such that only the efficient firm invests, the regulator has the chance to set the first best efficient type standard if the firm indeed invests. This leads to higher expected social welfare (lower social costs) than under commitment. On the other hand, social costs will be higher under time consistency if the firm does not invest. This implies that time consistency can lead to higher or lower *ex ante* expected social welfare depending on probabilities, cost differentials and fixed costs.

A numerical example can be provided to illustrate that the result summed up in Proposition 2 is indeed possible. Parameter values are set in such a way to be in case 3, where $F_h < F_l^l < F_m^l$. Further $\widehat{F} < F_l^h$ for all plausible values of v.[2] In such an example, when fixed costs are such that $F_m^h < F < F_h$, then the equilibrium implies that only the efficient firm invests, and the regulator sets a_l if the firm invests. As in the same circumstances, $F > \widehat{F}$, then *ex ante* social costs are lower under time consistency.

References

[1] Amacher, Gregory S. and Arun S. Malik (2002), "Pollution taxes when firms choose technologies", *Southern Economic Journal* 68: 891-906.

[2] Arguedas, Carmen and Hamid Hamoudi (2004), "Controlling pollution with relaxed regulations", *Journal of Regulatory Economics* 26: 85-104.

[3] Downing, Paul B. and Lawrence J. White (1986), "Innovation in pollution control", *Journal of Environmental Economics and Management* 13: 18-29.

[4] Fischer, Stanley (1980), "Dynamic inconsistency, cooperation and the benevolent dissembling government", *Journal of Economic Dynamics and Control* 2: 93-107.

[5] Jaffe, A.B., Newell, R.G., Stavins, R.N. (2003), "Technological change and the environment" in K.-G. Maler and J.R. Vincent (eds.), *Handbook of Environmental Economics*, Vol I, Ch. XI.

[6] Kydland, Finn E. and Edward C. Prescott (1977), "Rules rather than discretion: The inconsistency of optimal plans", *Journal of Political Economy* 85: 473-491.

[7] Malik, Arun S. (1991), "Permanent versus interim regulation: A game-theoretic analysis", *Journal of Environmental Economics and Management* 21: 127-139.

[2] This example involves the following parameter values: $d = 1, b = .1, q = 100, l = .6h, h = .8$

[8] Milliman, Scott R. and Raymond Prince (1989), "Firm incentives fto promote technological change in pollution", *Journal of Environmental Economics and Management* 17: 247-265.

[9] Moledina, Amyaz A., Jay S. Coggins, Stephen Polasky and Christopher Costello (2003), "Dynamic environmental policy with strategic firms: Prices versus quantities", *Journal of Environmental Economics and Management* 45: 356-376.

[10] Petrakis, Emmanuel and Anastasios Xepapadeas (2001), "To commit or not to commit: Environmental policy in imperfect markets", Department of Economics Working Paper, University of Crete.

[11] Requate, Till (2005a), "Timing and commitment of environmental policy, adoption of new technology, and repercussions on R&D", *Environmental and Resource Economics* 31: 175-199.

[12] Requate, Till (2005b), "Dynamic incentives by environmental policy instruments - a survey", *Ecological Economics* 54: 175-195.

[13] Tarui, Nori and Stephen Polasky (2005), "Environmental regulation with technology adoption, learning and strategic behavior", *Journal of Environmental Economics and Management* 50: 447-467.

[14] Yao, Dennis A. (1988), "Strategic responses to automobile emissions control: A game-theoretic analysis", *Journal of Environmental Economics and Management* 15: 419-438.