Pollution-Reducing Innovations under Taxes or Permits

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Abstract

This paper compares the effects of taxes and pollution permits when a pollution-reducing innovation is in prospect. When the government is not pre-committed into a fixed environmental policy but can freely adjust the level of taxes and permits after the innovation has been obtained, taxes and permits are fully equivalent. The equivalence breaks down, however, when the government can pre-commit. In this case, taxes give a higher incentive to invest in R&D than permits when the post-innovation output level is sufficiently high. The welfare ranking of taxes and permits is then analyzed. Loosely speaking, taxes are superior when the social damage associated with pollution is not too high.

1 Introduction

This paper develops a simple partial equilibrium framework where it is possible to compare the effects of effluent charges and pollution permits when an innovation is in prospect. In our model, a good is produced under perfect competition with a polluting technology exhibiting constant returns to scale. There is an innovator that can invest in R&D to obtain a pollution-reducing new technology. The innovation will then be licensed to firms operating in the downstream product market. The size of the reduction in effluent emissions depends on the level of R&D investment chosen by the innovator.

Because there is no uncertainty, taxes and permits would be fully equivalent in the absence of a technological innovation. Any difference in the effects of taxes and permits is due to the existence of an opportunity to improve the current technology. In the presence of a prospective innovation, taxes and permits actually perform two roles: on the one hand, they reduce effluent emission *via* a reduction in output, and on the other hand, they stimulate investment to obtain the pollution-reducing innovation. Unsurprisingly, it turns out that neither instrument delivers the first best social optimum. We then ask, which instrument is better.

When the government is not pre-committed into a fixed environmental policy but can freely adjust the level of taxes and permits after the innovation has been obtained, we show that taxes and permits are fully equivalent. The equivalence breaks down, however, when the government can pre-commit. In this case, when taxes and permits are set in such a way as to lead to the same level of post-innovation output, the level of profits accruing to the innovator is the same with the two instruments. However, the incentives to invest in R&D turn out to be different, because they are related to the marginal profit associated with an increase in R&D investment (and hence in the size of the innovation).

The ranking of taxes and permits according to the equilibrium R&D investment they lead to is related to the comparative statics of the two policy tools. As long as the incentive to innovate is increasing in the rate of effluent taxation, taxes give higher incentives to innovate than permits. When the tax is so high that output under competition is lower than the output level that would be chosen by an unregulated monopolist, however, an increase in the environmental tax will reduce the incentive to innovate. In this case, permits provide the highest incentive to innovate.

However, in order to determine the welfare ranking of taxes and permits, we cannot simply rely on the distinction between the two cases just described. That is, the ranking according to the incentives to innovate does not necessarily coincide with the welfare ranking of the two instruments, for post-innovation output is itself a choice variable from the point of view of a social planner. Nonetheless, conditions can be found, under which either taxes or permits are superior in welfare terms. The main result of the paper is that taxes are superior when the social cost of pollution is low, whereas permits are superior when pollution is very costly. A sufficient condition for taxes to be superior is that the output level that would be chosen by an unregulated monopoly be lower than the output level that would be socially optimal given the pre-innovation technology.

In this paper, by taxes we mean effluent fees which are fixed at a constant rate per unit of emission. By permits, we mean quantitative controls on the level of effluent emission. This can be performed by direct control, or by issuing marketable pollution permits; it does not matter whether permits are auctioned off or they are issued for free[1]. Since there is no uncertainty and all firms are identical, all these different ways of performing quantity controls have the same effects.

In the environmental economics literature, several papers have compared the incentives to innovate provided by different policy instruments – see Milliman and Prince (1989), Downing and White (1986), and the literature cited therein. We depart from this literature by analyzing explicitly the product market equilibrium associated with different environmental policies. Moreover, we do not confine our attention to the comparison of the incentives to do R&D but also analyze the welfare ranking of the two instruments.

By way of contrast, the literature so far has mainly looked at the level of profits accruing to an innovator under taxes or permits. This may be justified on the presumption that a) more investment in R&D is socially valuable, i.e. the market would tend to under-invest in R&D, and b) the incentive to innovate is correctly measured by the level of profits accruing to the innovator. We provide a rigorous proof of a), which is usually taken for granted. Concerning presumption b), it may be appropriate under certain circumstances, for instance when the size of the prospective innovation is fixed and the level of R&D investment influences only the timing of the innovation or the probability that the innovation is obtained. But, as this paper shows, things are different when the level of R&D investment can also affect the nature of the innovation and hence the reduction in effluent emissions that it entails. In this case, it is the marginal profit that matters to determine the innovator's incentive to invest.

In a recent paper, Laffont and Tirole (1996) have criticized the use of marketable permits in the presence of a prospective innovation on the ground that, when the government cannot pre-commit, they provide insufficient incentives to invest in R&D – in their admittedly extreme example, no incentive at all. However, we show that the same problem is faced by taxes; indeed, in our model marketable permits and taxes are fully equivalent in the absence of pre-commitments. Only when the government can pre-commit, their effects are different.

[1] That is, this han only a purely redistributive effect. Likewise, the allocation of pollution permits across firms is irrelevant in the aggregate since the technology exhibits constant returns to scale; however, it may affect individual output and profits.

Proposition 7 *There exists a critical value of α, $\hat{\alpha}$, such that taxes are superior to permits for $\alpha < \hat{\alpha}$ and permits are superior to taxes if $\alpha > \hat{\alpha}$. When $\alpha = \hat{\alpha}$, the two instruments lead to the same level of social welfare in the second best.*

Proof. From Propositions 5 and 6 it follows that taxes and permits can lead to the same level of social welfare in the second best only if point H lies below the $W_X = 0$ locus and above the $W_b = 0$ locus. Figure 6 illustrates. The continuous social indifference curve corresponds to the critical value of $\alpha, \hat{\alpha}$. The slope of the social indifference curve is:

$$\frac{dX}{db} = -\frac{W_b}{W_X},$$

and it clearly must be positive both at points T and P, where the same social indifference curve is tangent to the TT and the PP curves, respectively. In particular, at both points it must be $W_X > 0$ and $W_b < 0$.

Next suppose that α increases above $\hat{\alpha}$. Note that the derivative of the slope of the social indifference curve with respect to α is:

$$\frac{d}{d\alpha}\left(-\frac{W_b}{W_X}\right) = -\frac{W_{b\alpha}W_X - W_b W_{X\alpha}}{(W_X)^2} > 0,$$

where $W_{b\alpha} = -XD'(bX) < 0$ and $W_{X\alpha} = -bD'(bX) < 0$. Thus, when α increases, the social indifference curve becomes steeper, which means that the new indifference curve passing through P will now correspond to a level of social welfare higher than that associated with the new social indifference curve passing through T. These are the dotted social indifference curves in figure 6. By the envelope theorem, the total welfare effect of a change in α (that is, after re-optimizing) will equal the direct effect. This implies that with $\alpha > \hat{\alpha}$ permits yield a level of social welfare higher than taxes. The opposite holds for $\alpha < \hat{\alpha}$. ■

8 Conclusion

In the presence of a pollution-reducing innovation, taxes and permits are no longer equivalent when the government can pre-commit, even if there is no uncertainty, constant returns to scale prevail, and the output market is perfectly competitive. The non-equivalence result rests on the size of the environmental innovation being sensitive to the amount invested in R&D. Under these assumptions, we have shown that taxes are better than permits when the environmental externality is small, while permits are superior when it is large.

References

[1] Arrow, K., 1962, Economic welfare and the allocation of resources for invention, in R. Nelson, ed., *The rate and direction of innovative activity*, Princeton, Princeton University Press.

will then stick to the pre-innovation level $P = c + at$, output will also stick to $X(c + at)$, and the innovator's revenue will be[3]:

$$V^T = t(a - b)X(c + at) \tag{1}$$

Permits

Suppose the government issues N pollution permits. We assume $P\left(\frac{N}{a}\right) > c$, so that all permits will be used in equilibrium[4]. Output will be $X = N/b$ and price $P(\frac{N}{b})$. The value of a permit is therefore given by the price-cost margin multiplied by the output level that each permit allows a firm to produce, i.e.:

$$z = \frac{1}{a}\left[P\left(\frac{N}{b}\right) - c\right].$$

The patentee will then charge a royalty fee which makes producers just indifferent between using the new and the old technology. If a firm uses the new technology, its cost will be $(c + bz + v)$, where v is the royalty fee per unit of product, whereas if it uses the old technology the cost is $c + az$. It follows that the optimal unit royalty fee is $v = (a - b)z$ or:

$$v = (a - b)\frac{P\left(\frac{N}{b}\right) - c}{a}.$$

[3]When the innovator directly engages in production, assuming Bertrand competition, the price will stick to the pre-innovation level and the innovator will produce the whole industry output. Under taxes, price will be $P = c+at$ and output $X(c+at)$. The innovator's production cost is $c + bt$, hence the innovator's profits (gross of R&D costs) are:

$$V^T = t(a - b)X(c + at)$$

like in the case of licensing.

[4]As will become clear presently, the innovator will never invest in R&D so as to reach a level of b such that $P\left(\frac{N}{b}\right) \leq c$, so all permits will be used in the post-innovation equilibrium as well.

7 Second best policy with pre-commitments

We start this section establishing that with pre-commitments, there cannot be over-investment in R&D[18].

Proposition 4 *Both under taxes and under permits, there is always under-investment in R&D with respect to the first best social optimum.*

Proof. Let us first re-arrange the first order conditions for the first best social optimum. Combining (4) and (12) we get:

$$X\frac{P(X)-c}{b}+C'(b)=0. \tag{13}$$

Now, comparing (13) with the equation that defines the TT locus, we see immediately that, since $b \leq a$, for any given level of X, the value of b that solves (13) is lower that the value of b that solves (9). Thus, the first best social optimum S lies to the left of the TT locus.

On the other hand, rewrite (10) as

$$\bar{X}\frac{P(\bar{X})-c}{b}+\bar{X}^2\left(\frac{1}{b}-\frac{1}{a}\right)P'(\bar{X})+C'(b)=0. \tag{14}$$

Again, the value of b that solves (13) is clearly lower, for any given X, than the value that solves (14). Thus, point S will also lie to the left of the PP locus. ■

Propositions 3 and 4 imply that if taxes and permits are set in such a way as to lead to the same level of post-innovation output $\bar{X}$, taxes are welfare superior to permits if and only if $\bar{X} > X^M$, and permits are superior if $\bar{X} < X^M$. However, if t and N are set optimally, they need not lead to the same post-innovation output. Thus, even if we know that there will be under-investment in the second best, we cannot conclude that the instrument that provides the highest incentive to invest in R&D is superior in welfare terms. For, from the viewpoint of the social planner, post-innovation output is itself a policy variable.

To analyze the welfare ranking of taxes and permits, we must therefore consider the second best social optimum. In a second best problem, the government no longer directly controls both X and b. Instead, it can either fix a tax t or a number of pollution permits N, with X and b determined by the market equilibrium conditions. With taxes, this is equivalent to choosing a point on the TT locus; with permits, the government is effectively choosing a point on the PP locus. Performing a welfare comparison of taxes and permits then means finding which locus affords the highest social welfare.

It is clear that, depending on the shape of the social indifference curves, either taxes or permits can be preferred. Consider figure 4. If the point H where the TT

[18] It can be shown that without pre-commitments either over or under-investment may occur.

The interpretation of (4) is straightforward. It says that production must be pushed to the point where price equals the sum of marginal production cost and marginal environmental damage. Equation (4) implicitly defines a function $X^*(b)$ that gives, for each fixed level of b, the socially optimal output level. With permits, this will be obtained by setting $N^* = bX^*(b)$, whereas with taxes it must be

$$t = \frac{b}{a}\alpha D'\left[bX^*(b)\right].$$

Inserting these conditions into (1) and (2) one gets:

$$V^T = V^P = \frac{b}{a}(a-b)X^*(b)\alpha D'\left[bX^*(b)\right].$$

Thus taxes and permits are fully equivalent when the government is not committed to a pre-specified environmental policy, but adjusts it after the innovation has been obtained.

Proposition 1 *In the absence of pre-commitments, taxes are equivalent to permits.*

This conclusion may help put some of Laffont and Tirole's (1996) conclusions in perspective. In their analysis of permits in the absence of pre-commitments, they focus on the special case where the innovation completely eliminates effluent emission ($b = 0$)[7]. They claim that under permits there would be no incentive to innovate because the innovator perceives that the government will issue enough permits after the innovation has occurred so as to reduce its value to zero. As Proposition 1 makes it clear, the same outcome would occur under taxes. After the innovation, the optimal tax with $b = 0$ would be $t = 0$ and therefore there would be no incentive to innovate. One cannot discriminate between taxes and permits in the case where pre-commitments are not feasible.

4 Non-equivalence under pre-commitments

In the rest of the paper, we assume that the government can commit itself to a fixed environmental policy. That is, before the innovator invests C and develops the new technology, and in the anticipation of that, the government either sets a tax at rate t per unit of effluent emission, or it issues tradeable permits in amount N. To this environmental policy the government will stick thereafter[8]. We assume that the government knows the innovator's R&D technology, and therefore can

[7] The special case $b = 0$ is ruled out in this paper by (A1), but it is clear that the equivalence result would carry over to this case.

[8] The pre-commitment hypothesis is standard in the industrial organization literature. The very existence of the patent system may be considered as evidence that governments can pre-commit, for once an innovation has been obtained, it would be socially optimal to enforce perfect dissemination of the new technology.

Since $C''(b) > 0$ by assumption, b decreases when t is increased if and only if the numerator of this derivative is positive. It can be easily seen that this condition is equivalent to:

$$P(\bar{X}) - c + \bar{X}P'(\bar{X}) < 0. \tag{11}$$

Given (A3), condition (11) says that the output level is higher than the one chosen by an unregulated monopoly, i.e. $\bar{X} > X^M$. ■

We now turn to the comparison of the equilibrium R&D effort under taxes or permits. Since when (11) holds the middle term in (10) is negative, comparing (9) and (10) we see immediately that in this case the incentive to innovate is higher under taxes. The opposite result obtains when inequality (11) is reversed so that the middle term in (10) is positive. Thus we have:

Proposition 3 *If $\bar{X} > X^M$, R&D investment under taxes is higher than under permits that lead to the same post-innovation output. If $\bar{X} < X^M$, the incentive to innovate is higher under permits. Only when $\bar{X} = X^M$ the two policy instruments lead to the same equilibrium R&D investment.*

Figure 2 represents in the space (b, X) the two loci corresponding to the innovator's first order condition under taxes (9) and under permits (10). Let us call TT the first locus and PP the second one. Since $C'(a) = 0$ by (A1), the TT locus intersects the $b = a$ vertical line at $X = 0$ and at $P(X) - c = 0$. The TT locus is increasing when $X > X^M$ and decreasing when $X < X^M$. The minimum level of b (that is, the maximum amount of R&D investment), $b^T_{\min}$, is reached at $X = X^M$.

The PP locus also intersects the $b = a$ vertical line at $X = 0$ and at $P(X) - c = 0$; it intersects the TT locus at $X = X^M$ and reaches the minimum level of b, $b^P_{\min}$, at a value of X which is lower than X^M. By Proposition 4, the PP locus lies to the right of the TT locus for $X > X^M$, and to the left of it when $X < X^M$. The two loci intersect at point H, whose co-ordinates are $(b^T_{\min}, X^M)$. Notice also that the maximum amount of R&D investment that can be reached with permits is higher than the maximum R&D investment that can be reached under taxes, i.e. $b^P_{\min} < b^T_{\min}$[15].

Proposition 3 has a simple corollary that concerns the comparison of taxes and permits that lead to the same level of post-innovation total effluent emissions bX. Clearly, the iso-emission curves are rectangular hyperboles in the (b, X) plane. At point H, total post-innovation emissions are $b^T_{\min}X^M$. Note also that total effluent emissions (which equal the number of permits N) decrease as one moves downward along the PP curve so that each iso-emission curve intersects the PP locus only once. An iso-emission curve corresponding to post-innovation

[15]This may be confirmed by noting that when it intersects the TT curve, the PP curve is still increasing.

Inserting (7) into the innovator's first order condition under taxes (5) we get:

$$\bar{X}\frac{P(\bar{X})-c}{a}+C'(b)=0, \tag{9}$$

whereas inserting (8) into (6) we get:

$$\bar{X}\frac{P(\bar{X})-c}{a}+\bar{X}\left(\frac{1}{b}-\frac{1}{a}\right)\left[P(\bar{X})-c+\bar{X}P'(\bar{X})\right]+C'(b)=0. \tag{10}$$

Comparing (9) and (10) we immediately see that the first order conditions differ and therefore generally speaking equilibrium R&D investment will be different under taxes and permits. Thus, when they lead to the same level of output, taxes and permits result in innovations of different size. And, conversely, if they are set so as to lead to the same R&D investment, they will result in different post-innovation output levels. This establishes the non-equivalence of the two instruments in the pre-commitment case.

To understand the source of this non-equivalence, note that inserting (7) into (1) and (8) into (2) we get:

$$V^T=V^P=(a-b)\bar{X}\frac{P(\bar{X})-c}{a}.$$

Thus, the level of profits accruing to the innovator under taxes would be the same as under permits, provided the post-innovation level of output is kept constant. However, R&D investment is determined by the marginal increase in profits associated with an increase in R&D expenditure. Though we have $V^T=V^P$ when (7) and (8) hold, the derivatives of V^T and $V^P$with respect to b are different. In particular, with taxes the private value of a reduction in effluent emission is constant. With permits, instead, the value of a reduction in effluent emission is a function of b, as is clear from (2). The reason is that under permits, the innovator anticipates the change in the aggregate value of the permits $X\left[P(X)-c\right]$ that a change in b brings about, and keeps this into account in calculating its optimal R&D investment[12]. This explains the presence of the middle term in (10).

This effect would not arise if the size of the innovation did not depend on R&D investment. For instance, in models where the level of R&D investment only affects the timing or the probability that an innovation is obtained, but the size of the innovation is fixed, the incentive to innovate would be correctly

[12]Of course, the aggregate value of permits is relevant to the innovator, because its profit is just a fraction $(1-b/a)$ of this value, as can be seen rewriting (2) as:

$$V^P=\left(1-\frac{b}{a}\right)X\left[P(X)-c\right].$$

When b decreases, X increases and the aggregate value of permits changes.

measured by the *level* of profits accruing to the innovator. In this case, taxes and permits would be equivalent even under pre-commitments. The non-equivalence result emerges when the size of the innovation is not fixed and depends on R&D expenditure[13].

5 Comparative statics

Having established that taxes are no longer equivalent to permits under pre-commitments, the problem arises as to which instrument is superior. Before proceeding to compare taxes and permits on welfare grounds, however, we perform a comparative statics analysis of the two instruments.

To begin with, we ask under what circumstances an increase in the tax t leads to an increase in R&D investment, and hence in a reduction of b. To address this problem, the following regularity assumption is made:

(A3) The function $g(X) \equiv X\left[P(X) - c\right]$ is strictly quasi-concave.

This assumption guarantees that the profit maximizing level of output that would be chosen by an unregulated monopoly is the unique solution to the first order condition:

$$g'(X) = P(X) - c + XP'(X) \leq 0$$

with $X = 0$ when a strict inequality holds. Denote by X^M the level of output that would be chosen by an unregulated monopoly. Assumption (A3) implies that $P(X) - c + XP'(X) < 0$ when $X > X^M$ and $P(X) - c + XP'(X) > 0$ when $X < X^M$.

Proposition 2 *An increase in the tax rate leads to an increase in the equilibrium R&D investment, and hence to a decrease in b, if and only if $\bar{X} > X^M$*[14].

Proof. By implicit differentiation of (9) one gets:

$$\frac{db}{dt} = -\frac{X(c+at) + atX'(c+at)}{C''(b)}$$

[13] Our assumption of deterministic and instantaneous innovation is admittedly quite crude. However, even in a more general model in which the timing and the probability of the innovation depended on R&D investment, similar results would hold as long as the size of the innovation is also related to R&D expenditure.

[14] The comparative statics for the case of permits is more complicated. However, the following strengthening of assumption (A3) guarantees that if $\bar{X} > X^M$, an increase in the number of permits reduces the equilibrium R&D effort:

(A3′) The function $g(X)$ is strictly concave, i.e. $2P'(X) + XP''(X) < 0$.

Proceeding like in the proof of Proposition 2, it can be shown that if (A3′) holds, an increase in the number of permits reduces the equilibrium R&D effort, and therefore leads to an increase in b, if $\bar{X} > X^M$. Note that while Proposition 2 gives a necessary and sufficient condition for R&D effort to increase when taxes are increased, this result provides only a sufficient condition. That is, db/dN could be positive even if $\bar{X} \leq X^M$.

anticipate the effects of its policy choices on R&D investment. In this scenario, taxes and permits actually perform two roles: they reduce effluent emission *via* a reduction in output, and at the same time they stimulate investment to obtain the pollution-reducing innovation. Both roles must be taken into account by the government in choosing the environmental policy.

Let us re-consider the innovator's problem in this new context. A crucial difference with respect to the pre-commitment case is that now the innovator treats t or N as given when choosing the level of R&D investment. Specifically, under taxes, the innovator maximizes

$$\pi = V^T - C(b)$$

taking t as given, which yields the following first order condition[9]:

$$tX(c + at) + C'(b) = 0. \tag{5}$$

Under permits, the objective function is

$$\pi = V^P - C(b),$$

and the corresponding first order condition, taking now N as given, is[10]:

$$\frac{N}{b}\frac{P(N/b) - c}{a} + \frac{N}{b^2}\frac{a-b}{a}\left[P(N/b) - c + \frac{N}{b}P'(N/b)\right] + C'(b) = 0. \tag{6}$$

For the two instruments to be equivalent, the incentive to invest in R&D provided by taxes and permits that lead to the same level of post-innovation output should be equal[11]. Let $\bar{X}$ denote a given level of post-innovation output and suppose that taxes and permits are set in such a way as to lead to output $\bar{X}$ in the post-innovation equilibrium. With taxes, output sticks to $X(c + at)$, so that we must have:

$$t = \frac{P(\bar{X}) - c}{a}. \tag{7}$$

With permits, post-innovation output is N/b, and therefore we must have:

$$N = b\bar{X}. \tag{8}$$

[9]The second order condition is always satisfied since $C''(b) > 0$ by (A1).

[10]We assume that the second order condition:

$$\frac{1}{b^2}\frac{N}{b}\left[-2\left(P - c + \frac{N}{b}P'\right) - \left(1 - \frac{b}{a}\right)\frac{N}{b}\left(2P' - \frac{N}{b}P''\right)\right] - C''(b) < 0$$

is always satisfied.

[11]Since with both type of instruments only the new technology will be used after the innovation, the level of effluent emission would then also be constant if the investment in R&D were the same under taxes and permits.

emissions higher than $b^T_{\min}X^M$ would therefore intersect the PP and the TT curves above point H, whereas an iso-emission curve corresponding to post-innovation emissions lower than $b^T_{\min}X^M$ would cut the PP and TT curves below point H. By inspection of figure 2, it is then immediate to conclude:

Corollary 1 *If post-innovation emissions are larger than $b^T_{\min}X^M$, R&D investment under taxes is higher than under permits that lead to the same post-innovation total effluent emissions. If post-innovation emissions are smaller than $b^T_{\min}X^M$, the incentive to innovate is higher under permits. Only when post-innovation emissions are equal to $b^T_{\min}X^M$, the two policy instruments lead to the same equilibrium R&D investment.*

6 The social problem

In this section we shall consider the social problem and determine the first best social optimum which is achieved when the government directly controls both output X and R&D investment C (and hence b). The aim of the government is to maximize the social welfare function $W(b, X)$ given by (3). We assume:

(A4) The social welfare function $W(b, X)$ is concave.

Since $W_{XX} = P'(X) - b^2\alpha D''(bX) < 0$ and $W_{bb} = -X^2\alpha D''(bX) - C''(b) < 0$, assumption (A4) is in fact equivalent to $W_{XX}W_{bb} - (W_{bX})^2 \geq 0$ (where $W_{Xb} = -\alpha D'(bX) - bX\alpha D''(bX) < 0$).

The first order conditions for a maximum[16] are $W_X = 0$ (i.e., equation (4)) and:

$$W_b = -X\alpha D'(bX) - C'(b) = 0. \tag{12}$$

This condition says that, at the margin, the cost of R&D investment should be equal to the reduction of environmental damage.

Figure 3 depicts in the (b, X) space the two loci $W_X = 0$ (or, equivalently, $X^*(b)$) and $W_b = 0$. Since $W_{XX} < 0$ and $W_{Xb} < 0$, the locus $W_X = 0$ is decreasing. It intersects the vertical axis at $P(X) - c = 0$ and the $b = a$ vertical line at $X^*(a)$, which is implicitly defined by $P(X) - c - a\alpha D'(aX) = 0$. That is, $X^*(a)$ would be the socially optimal output level in case no innovation was anticipated.

The $W_b = 0$ locus is also decreasing, as $W_{bb} < 0$ and $W_{Xb} < 0$. It intersects the $b = a$ vertical line at $X = 0$ and grows without limit as b goes to 0. The two loci intersect at a point S, which is the first best social optimum[17].

Figure 3 also depicts the social indifference curves in the (b, X) space. They are closed orbits around the first best social optimum point S.

[16]Given (A4), these conditions are sufficient.

[17]Multiple intersections are ruled out by (A4), that guarantees that the slope of the $W_X = 0$ curve (whose absolute value is W_{bX}/W_{XX}) is always smaller than the slope of the $W_b = 0$ curve (W_{bb}/W_{bX}).

Thus, the innovator's revenue $V^P = vX$ will be[5]:

$$V^P = \frac{N}{b}(a-b)\frac{P\left(\frac{N}{b}\right)-c}{a}. \qquad (2)$$

3 Equivalence of taxes and permits under no commitment

When the government has not the ability to commit to a fixed environmental policy, the innovator perceives that the tax rate t or the number of permits N will be adjusted after the innovation has been obtained. Therefore, the innovator will try to anticipate the environmental policy that is chosen by the government, and will determine its R&D effort accordingly.

Let $\alpha D(bX)$ denote the monetary value of the social damage associated with effluent emission bX. Here $\alpha > 0$ is a shift parameter that measures to what extent pollution is socially costly. We assume:

(A2) $\qquad D(0) = 0; \qquad D'(bX) > 0; \qquad D''(bX) \geq 0.$

Then, social welfare is

$$W(b, X) = \int_0^X P(s)ds - cX - \alpha D(bX) - C(b). \qquad (3)$$

After the innovation has been obtained, with b given, the government faces an entirely standard optimization problem. Using either instrument, it is clear that the government can effectively control the output level X, so the socially optimal output level will be chosen. The first order conditions for a maximum is[6]:

$$W_X = P(X) - c - b\alpha D'(bX) = 0. \qquad (4)$$

[5]Suppose the innovator directly engages in production, and pollution permits are marketable. In the ensuing Bertrand equilibrium, only the innovator would produce and the price would be $P\left(\frac{N}{b}\right)$. The value of a permit to a firm that uses the old technology would therefore be

$$z = \frac{1}{a}\left[P\left(\frac{N}{b}\right) - c\right].$$

and this is the price that the innovator will have to pay for each pollution permit bought from other firms. Then its gross profits would be:

$$\frac{N}{b}\left[P\left(\frac{N}{b}\right) - c\right] - \frac{N}{a}\left[P\left(\frac{N}{b}\right) - c\right],$$

and therefore coincide with V^P. Obviously this argument requires that pollution permits be marketable. Also, we are assuming that the amount of permits initially owned by the innovator is negligible.

[6]Clearly, the second order condition is satisfied given (A2).

locus intersects the PP locus, lies below the $W_b = 0$ curve, then clearly taxes are welfare superior to permits. The next proposition provides a sufficient condition for this case to occur.

Proposition 5 *If the output that would be socially optimal when no innovation is in prospect is higher than the unconstrained monopoly output, i.e.* $X^*(a) > X^M$*, then taxes are superior to permits.*

Proof. Let us evaluate W_b at point H, where $X = X^M$ and $b = b^T_{\min}$. We have:

$$W_b = -X^M \alpha D'(bX^M) - C'(b),$$

which using (9) becomes:

$$W_b = \frac{X^M}{a}\left[-a\alpha D'(bX^M) + P(X^M) - c\right],$$

whence

$$W_b \geq \frac{X^M}{a}\left[-a\alpha D'(aX^M) + P(X^M) - c\right].$$

Next, notice that if $X^*(a) > X^M$ it must be

$$-a\alpha D'(aX^M) + P(X^M) - c > 0$$

so that we can conclude that $W_b > 0$ at point H. Since $W_{bX} < 0$, this implies that point H lies below the $W_b = 0$ curve. ∎

Note that Proposition 5 provides a sufficient condition for the superiority of taxes that does not depend on the shape of the R&D cost function $C(b)$.

Next consider figure 5. If point H lies above the $W_X = 0$ curve, then clearly permits are welfare superior to taxes. The next Proposition simply restates this observation.

Proposition 6 *If the output level that would be socially optimal at* $b^T_{\min}$ *is lower than the unconstrained monopoly output, i.e.* $X^*(b^T_{\min}) < X^M$*, then permits are superior to taxes.*

The general message that emerges from these results is that taxes are superior when the correction of the environmental externality does not require a very large output contraction, whereas permits may be preferable when the environmental externality is so high that, even taking into account the environmental innovation, output must be considerably reduced to correct for the environmental externality.

This suggests that taxes are superior for low values of parameter α, which measures the social cost of pollution, whereas permits are superior for high values of α. This is shown formally in the next Proposition, that concludes our welfare analysis and is the main result of the paper.

The layout of the paper is as follows. In section 2, we set up the model. Section 3 analyzes the case when the government can pre-commit. The rest of the paper focus on the no-pre-commitment case. Section 4 derives the equilibrium conditions for the innovator. In section 5, the incentives to innovate under taxes and permits are compared. Section 6 describes the first best social optimum. Section 7 analyzes the social problem and the welfare ranking of taxes and permits. Section 8 concludes.

2 The model

The analysis is partial equilibrium in nature. A good is produced under constant returns to scale in a perfectly competitive industry. Let c denote the unit production cost, and $P(X)$ the demand function, where P is price and X is aggregate output. $X(P)$ denotes the inverse demand function. It is assumed that $P(X)$ is twice continuously differentiable with $P' < 0$ whenever $P > 0$.

Under the current technology, which is freely available to all firms in the industry, each unit of output entails effluent emission at rate a. There is one innovator, that at time $t = 0$ may decide to invest in R & D in order to obtain a new production technology. The new technology does not affect the unit production cost c, but it reduces effluent emission to a new level $b \in (0, a)$. It is assumed that the size of the innovation is related to the level of R & D investment, so that it costs $C(b)$ to develop the new technology, where:

(A1) $\quad C(a) = 0; C'(b) < 0; C'(a) = 0; C'(0) = -\infty; C''(b) > 0.$

Figure 1 illustrates the R & D technology. The innovator is awarded an infinitely long patent, and no imitation is allowed. Moreover, we assume that no further innovation is in prospect.

The patentee can either license the new technology, setting the royalty fee in an optimal way, as in Arrow's (1962) classic analysis, or it can directly engage in production. In the latter case, following Dasgupta and Stiglitz (1980), we assume there is Bertrand competition in the product market. Then, the innovator will engage in limit pricing and obtain a positive profit. It turns out that Arrow's assumption leads to the same outcome as Dasgupta and Stiglitz's[2].

To proceed, we determine the post-innovation market equilibrium. To fix ideas, we shall consider the case of licensing. The case where the innovator directly engages in production leads to similar conclusions and is treated in footnotes.

Taxes

If there is a tax at rate t per unit of effluent emission, the royalty fee will be optimally set at a level (slightly lower than) $(a - b)t$. The equilibrium price

[2] This, however, requires that pollution permits be marketable. See footnote 5 below.

[2] Dasgupta, P., and J. Stiglitz, 1980, Uncertainty, industrial structure and the speed of R & D, *Bell Journal of Economics and Management Science*, **11**, 1-28.

[3] Downing P.B. and L.J. White, "Innovation in pollution control", *Journal of Environmental Economics and Management*, **13** (1986), 18-25.

[4] Laffont J.J. and J. Tirole, "Pollution permits and environmental innovation", *Journal of Public Economics*, **62** (1996), 127-140.

[5] Milliman S.R. and R. Prince, "Firm incentives to promote technological change in pollution control", *Journal of Environmental Economics and Management*, **17** (1989), 247-265.

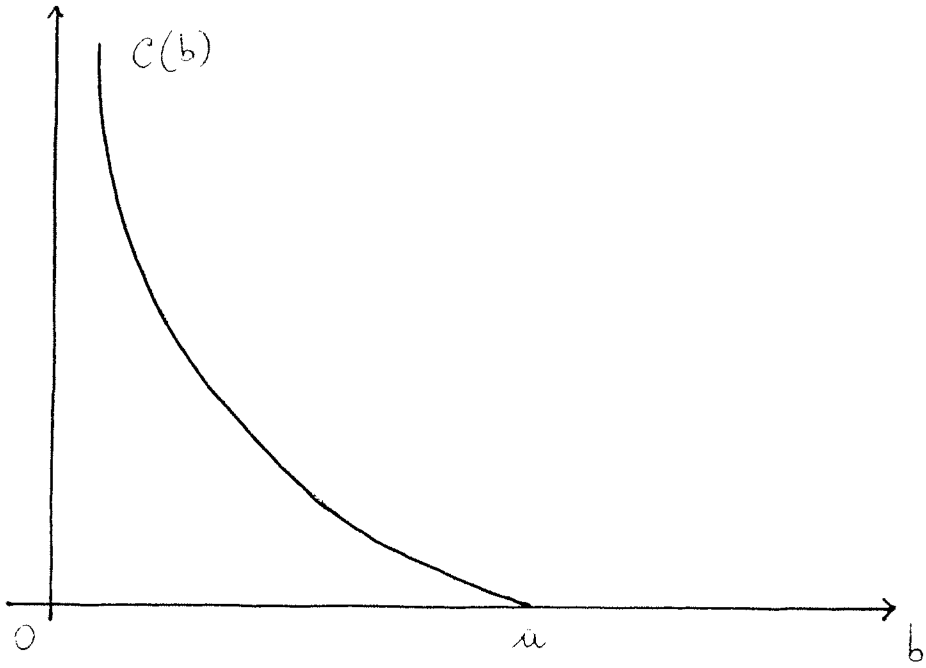

FIGURE 1

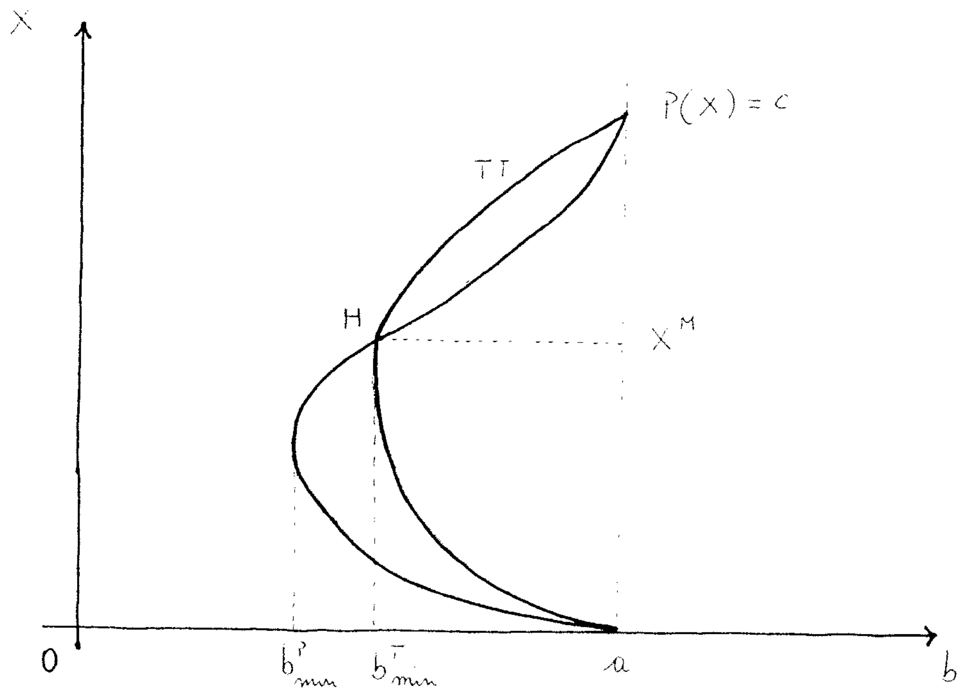

FIGURE 2

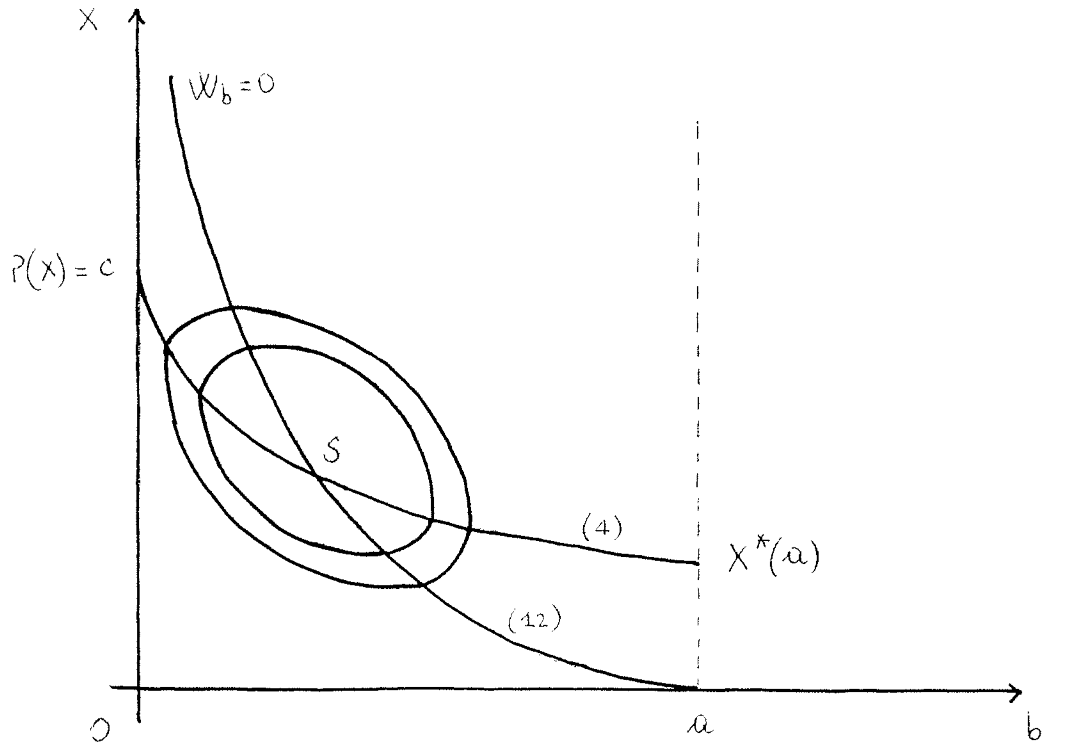

FIGURE 3

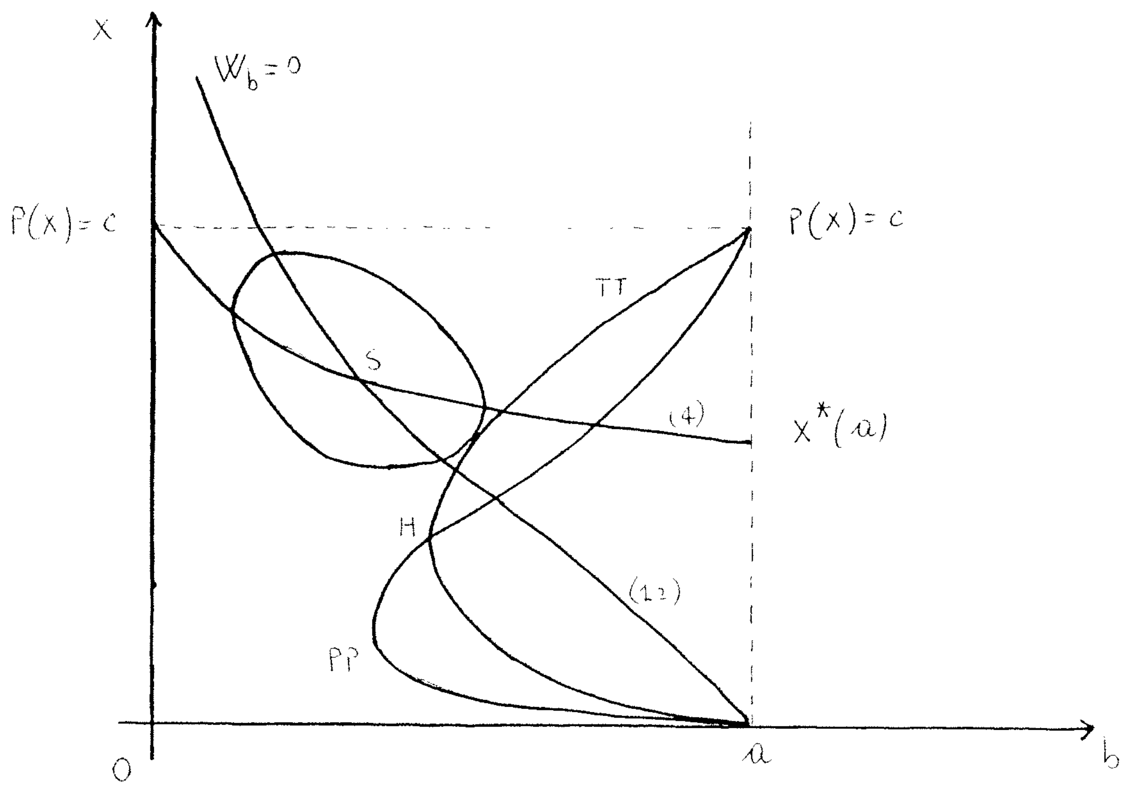

FIGURE 4

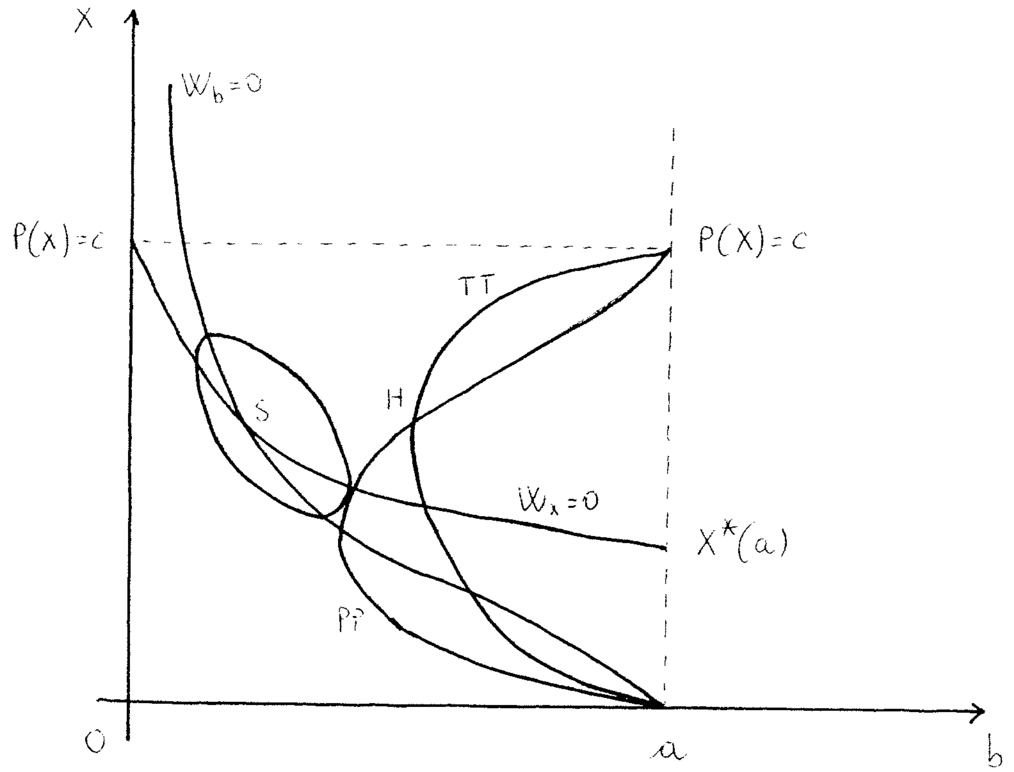

FIGURE 5

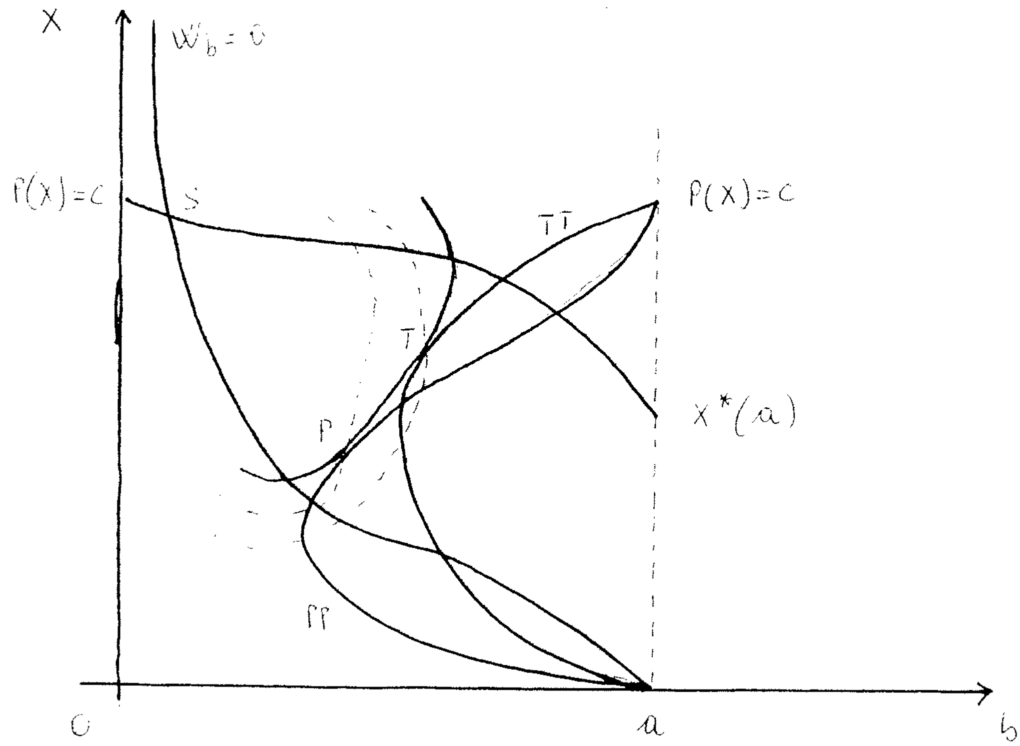

FIGURE 6