A General Approach to Firm Incentives for Technological Change in Pollution Control

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October 31, 2002

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*Thanks to Gardner Brown, Robert Halvorsen, and Karl Seeley for helpful comments on this paper.

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Abstract

This paper examines firm incentives for technological change under various pollution control policies. Our approach is based on Milliman and Prince [6] but uses a more general algebraic model. We find that Milliman and Prince's conclusions are reversed if the innovation increases demand for emissions at the margin. Such a result is not possible for innovations in end-of-pipe abatement technologies, but it is possible for production process innovations such as those that enhance resource productivity.

1 Introduction

The standard approach for analyzing incentives for innovation in pollution control is that taken in Milliman and Prince [6]. (See also [2, 4] and others.) Technological change is divided into three stages: innovation (a single firm develops a new technology), diffusion (the new technology spreads across the industry), and optimal agency response (the regulatory body responds, e.g., by adjusting the rate of a Pigovian tax).

Milliman and Prince calculate the impact on firms of the transition from one stage to the next, and of various combinations of the stages. Most notably, they analyze the impact of the entire three-stage process and find that "emissions taxes and auctioned permits provide the highest firm incentives to promote technological change" (p. 247).

This paper examines the extent to which Milliman and Prince's conclusions carry over to a more general model of innovation. Motivation for this more general treatment comes from two sources. First is a recent paper by McKitrick [5] which shows that discontinuities are likely in marginal abatement cost curves, thereby highlighting the dangers of making assumptions about marginal abatement cost curves. Although Milliman and Prince do not assume continuous abatement cost curves, they do follow Downing and White [2] and others in assuming that innovation uniformly reduces marginal abatement costs. This paper explores the ramifications of relaxing that assumption.

The second source of motivation is that pollution clean-up is no longer the center of attention; equal or greater attention is being paid to production process innovations such as those that enhance resource productivity (e.g., generate more electricity from each ton of coal). In some instances this is due to the difficulties of mitigating pollution after the fact, as with carbon dioxide and other greenhouse gases. In other instances this is due to the success of previous end-of-pipe efforts; the "low-hanging fruit" may have already been picked, as with point source emissions of sulphur dioxide. In any case, the focus of pollution control discussions is shifting attention away from end-of-pipe abatement technologies such as scrubbers and toward production process innovations such as combined-cycle gas turbines.

The Milliman and Prince approach is limited in its applicability to these changing focal points. Bauman and Seeley [1] show that their geometric approach is appropriate for innovations in end-of-pipe abatement technology but cannot be extended to production-process innovations. Together with McKitrick's analysis, this indicates the need for a more general approach. Abatement cost curves do not have to be well-behaved, and the effect of innovation on abatement costs can be counter-intuitive: enhancements in resource productivity can *increase* marginal abatement costs *at all* margins.[1] These situations are a poor fit for the standard approach.

The structure of this paper is as follows. Section 2 describes our approach, which is an algebraic analogue of Milliman and Prince's geometric analysis. Sections 3, 4, and 5 use this approach to calculate the gains from innovation, diffusion, and optimal agency response, respectively. The conclusion compares our results with those of Milliman and Prince and discusses opportunities for future research and implications for public policy.

[1]Intuitively, this is because the marginal cost of abatement is also the marginal benefit of emissions, which is the smaller of (1) the extra profits available from decreasing end-of-pipe abatement by one unit and (2) the extra profits available from increasing output by an amount corresponding to one unit of emissions. This latter quantity increases as a result of resource-enhancing innovations; absent cost-effective end-of-pipe measures, such innovations will therefore increase marginal emission benefits.

2 The Model

Following Milliman and Prince, we consider a competitive market with N identical profit-maximizing firms and divide the process of technological change into innovation, diffusion, and optimal agency response.

The baseline stage ($i = 0$) describes the situation prior to innovation. There are n potential inputs, $K_1, \ldots, K_n$, with prices $w_1, \ldots, w_n$. Each firm's production technology transforms these inputs into a good output $G = G^0(K_1, \ldots, K_n)$, with market price p_G, and a waste product $W = W^0(K_1, \ldots, K_n)$. Note that the inputs are *potential* inputs; for notational convenience, we include inputs that are useless under the current technology but may prove useful after innovation. Also note that the list of potential inputs includes those that may be used in end-of-pipe abatement efforts. Such efforts (if they exist) are subsumed within the function W, i.e., $W^0(\cdot) = E^0(\cdot) - A^0(\cdot)$ where $E^0(\cdot)$ is initial emissions and $A^0(\cdot)$ is end-of-pipe abatement.

If there were no environmental regulations, the waste product would be unpriced and the firm's profits would be given by

$$\pi = p_G G - \sum w_i K_i. \tag{1}$$

We can now consider imposing a limit on emissions and define $\pi^*(W)$ to be the firm's maximum profits subject to the constraint that emissions cannot exceed W. The derivative $\dfrac{d\pi^*}{dW}$ measures the firm's marginal emissions benefits, an example of which is shown in Figure 1. Note that reflecting this curve around the line $W = W^{\max}$ yields the firm's marginal abatement cost curve: the cost

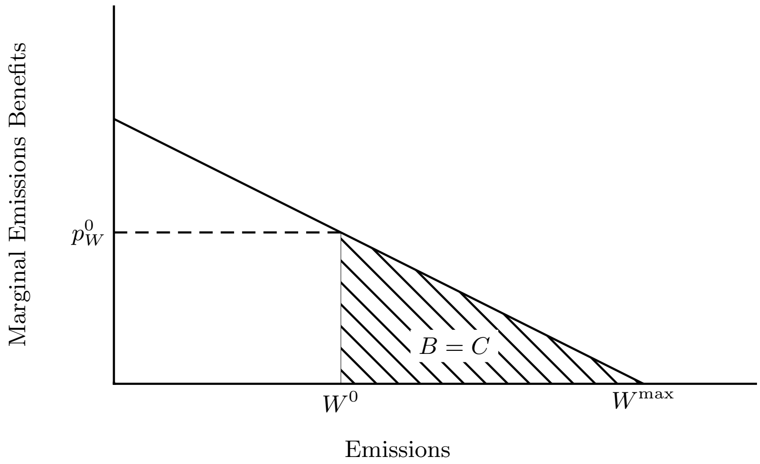

Figure 1: A marginal emissions benefit curve. The shaded area represents the total benefits B of extending an emissions limit from W^0 to $W^{\max}$ or, equivalently, the total costs C of reducing emissions from $W^{\max}$ to W^0. A firm facing a Pigovian tax of p_W^0 would choose to emit W^0 units of waste.

C of reducing emissions from $W^{\max}$ to W^0 is logically equivalent to the benefit B of being allowed to increase emissions from W^0 to $W^{\max}$.

The regulatory body maximizes social welfare by equating the social marginal benefit of emissions with the social marginal cost of emissions. The regulator's policy options are command-and-control emissions limits (abbreviated "C&C"), Pigovian subsidies ("sub"), free permits grandfathered in equal amounts to all firms ("gra"), auctioned permits ("auc"), and Pigovian taxes ("tax").

We assume that all of the policies are "properly designed" at stage 0, meaning that each firm produces the same (socially optimal) amount of waste—say,

W^0—under the various policies. In order for this result to hold, the command-and-control limit must be W^0, the number of tradable permits issued or auctioned to each firm must be W^0, and the market price of these permits must be equal to the level of the Pigovian tax or subsidy (say, p_W^0).[2]

In the innovation stage ($i = 1$), a single firm (the "innovating firm") adopts a new technology. The firm is assumed to be small enough that its actions have no impact on industry-wide variables such as the prices and aggregate amounts of inputs and outputs. In particular the firm is assumed to have no effect on aggregate emissions or on the market price of pollution permits if such a market exists.

We define an "innovation" to be any change in the firm's technology, modelled as a change in the production functions from $G^0(\cdot)$ and $W^0(\cdot)$ to $G^1(\cdot)$ and $W^1(\cdot)$.[3] This definition may be overly general in other contexts, but it serves our purposes well. It includes innovations in end-of-pipe abatement efforts (which are subsumed within the function W) as well as innovations in production processes (which will likely affect both G and W). It also includes innovations that are not specifically "environmentally related," or even environmentally related at all. This means that our results can be used to analyze the

[2]We assume throughout this paper that the baseline $\overline{W}$ used for calculating the Pigovian subsidy is sufficiently high, e.g., $\overline{W} \geq W^{\max}$ in the example shown in Figure 1. This ensures that the policy always provides the appropriate marginal incentives.

[3]Recall that the potential inputs $K_1, \ldots, K_n$ include all relevant inputs for these production technologies.

role of environmental policy in promoting non-environmental innovations.[4]

In the diffusion stage ($i = 2$), the other firms in the industry (the "non-innovating firms") adopt the innovation. (We treat the innovation as non-patentable, i.e., as a public good.[5]) Diffusion may change industry-wide variables relating to emissions, such as aggregate emissions and the market price of pollution permits. However, we assume that no other industry-wide variables are affected: other input and output prices remain constant, and firms do not enter or exit the industry. Though restrictive, these assumptions follow those made explicitly or implicitly in Milliman and Prince. (Indeed, one of the points of this paper is to make those assumptions more explicit.)

The final stage ($i = 3$) is optimal agency response. Here the regulatory agency becomes aware of the new technology and responds with an appropriate policy adjustment, e.g., a change in the Pigovian tax rate that re-equates the social marginal benefit and social marginal cost of emissions. (As at stage 0, the various policies are "properly designed" at stage 3 in that each firm produces the socially optimal amount of waste—say, W^3—under the various policies.) Again following Milliman and Prince, we allow this change in regulatory policy to affect industry-wide variables relating to emissions but assume that other

[4]Since most innovations are likely to have environmental impacts, the concept of "environmental" or "environmentally related" innovation may in fact be of limited value. Is an innovation that allows more electricity to be generated from each ton of coal an "environmental" innovation or not, and is the distinction relevant?

[5]Milliman and Prince consider the case of patentable innovations, but this paper does not.

industry-wide variables remain constant.

The next three sections consider innovation, diffusion, and optimal agency response, respectively. Our analysis is based on calculating profit differentials between the various stages. For example, $\Delta\pi_I^{01}$ measures the change in the innovating firm's profits between stages 0 and 1, i.e., the change in profits resulting from innovation. (The subscript I denotes the innovating firm; N denotes a non-innovating firm.) Similarly, $\Delta\pi_I^{12}$ measures the change in the innovating firm's profits resulting from diffusion.

Although we break down technological change into different stages, there is no explicit discount rate and (as in Milliman and Prince) our model is fundamentally atemporal.[6] The various stages of innovation are best thought of not as points in time but as different "worlds" or scenarios: $\Delta\pi_I^{01}$ measures the change in innovator profits between the "before innovation" scenario and the "after innovation" scenario; $\Delta\pi_I^{12}$ measures the change in innovator profits between "innovation only" and "innovation plus diffusion"; and $\Delta\pi_I^{02}$ measures the change in profits between the baseline and "innovation plus diffusion." It follows that multi-stage profit differentials can be broken down additively, e.g., $\Delta\pi_I^{02} = \Delta\pi_I^{01} + \Delta\pi_I^{12}$.

The atemporal nature of our model leads to the following important result,

[6] Given a discount rate and assumptions about the duration of the various stages, it would be possible to create a temporally accurate model to compare the discounted present value of firm profits under the different policies. Such a model could also incorporate entry and exit, since entry or exit would effectively neutralize whatever gains or losses existed prior to that point.

which we will make frequent use of.

Proposition 1 *The gains from innovation plus diffusion are identical for innovating and non-innovating firms,*[7] *and the same is true for the gains from innovation plus diffusion plus optimal agency response, i.e.,*

$$\Delta\pi_I^{02} = \Delta\pi_N^{02} \overset{\text{call}}{=} \Delta\pi^{02} \tag{2}$$

$$\Delta\pi_I^{03} = \Delta\pi_N^{03} \overset{\text{call}}{=} \Delta\pi^{03} \tag{3}$$

Proof. There is no difference between innovating and non-innovating firms at stage 0 (before innovation, at which point nobody has the new technology), stage 2 (after diffusion, at which point everybody has the new technology), or stage 3 (after optimal agency response, at which point everybody is subject to the new regulatory policy). It follows that innovating and non-innovating firms will have identical profits in each of these three stages, and therefore that their profit differentials will be identical. As a result, we will remove the subscripts and simply call these profit differentials $\Delta\pi^{02}$ and $\Delta\pi^{03}$. ■

3 Innovation

In this section we examine a single firm that develops an innovation. We assume that the firm is small enough relative to the industry that industry-wide variables will be unaffected by the innovation. For simplicity, we assume that

[7] Although Milliman and Prince do not explicitly point out this result, it can be seen from their results in Tables I and II.

there are no R&D costs or other fixed costs associated with the innovation.[8]

If we define $R(W)$ to be the regulatory cost of emitting W units of waste,[9] then a profit-maximizing firm would choose $K_1, \ldots, K_n$ to maximize

$$\pi = p_G G - R(W) - \sum w_i K_i. \tag{4}$$

If $\pi^0_{\max}(x)$ and $\pi^1_{\max}(x)$ are, respectively, the innovator's maximum profits before and after innovation under policy x, then the gain from innovation under policy x is the difference between these terms:

$$\Delta\pi^{01}_I(x) = \pi^1_{\max}(x) - \pi^0_{\max}(x). \tag{5}$$

We can immediately establish two results.

Proposition 2 *Incentives for innovation are identical under a variety of properly designed economic instruments (taxes, subsidies, and tradable permits):*

$$\Delta\pi^{01}_I(\text{tax}) = \Delta\pi^{01}_I(\text{sub}) = \Delta\pi^{01}_I(\text{auc}) = \Delta\pi^{01}_I(\text{gra}) \overset{\text{call}}{=} A.$$

As described in Section 2, "properly designed" means Pigovian taxes with tax rate p^0_W, Pigovian subsidies with subsidy rate p^0_W, and auctioned or grandfathered tradable permits with market price p^0_W; all of these induce the pre-innovation firm to emit W^0 units of waste.

[8] More generally, what we will be calculating is the gain from innovation *exclusive of fixed R&D costs*; this is the approach taken by Milliman and Prince.

[9] A command-and-control limit of W^0 can be represented by $R(W) = 0$ for $W \leq W^0$ and $R(W) = \infty$ for $W > W^0$. A Pigovian subsidy with baseline $\overline{W}$ and subsidy rate p^0_W corresponds to $R(W) = p^0_W(W - \overline{W})$, i.e., to a negative cost. As noted in Section 2, we assume that $\overline{W}$ is sufficiently high to avoid complications.

Proof. All of these policies have the form $R(W) = p_W^0 W + c$, where c is some constant. Pigovian taxes correspond to $c_{\text{tax}} = 0$, as do auctioned permits; W^0 grandfathered permits correspond to $c_{\text{gra}} = -p_W^0 W^0$; Pigovian subsidies with baseline $\overline{W}$ correspond to $c_{\text{sub}} = -p_W^0 \overline{W}$.

Since the constant term c doesn't affect the firm's profit-maximizing choices of $K_1, \ldots, K_n$, any differences in firm profits between these various policies at stages 0 or 1 can be attributed entirely to differences in the magnitude of c. For example, we have

$$\pi^1_{\max}(\text{tax}) = \pi^1_{\max}(\text{gra}) - p_W^0 W^0 \tag{6}$$

$$\pi^0_{\max}(\text{tax}) = \pi^0_{\max}(\text{gra}) - p_W^0 W^0 \tag{7}$$

Subtracting the second equation from the first yields $\Delta\pi_I^{01}(\text{tax}) = \Delta\pi_I^{01}(\text{gra})$, which is one of the desired results. The other results follow from identical proofs: the constant c drops out when we compute $\Delta\pi_I^{01}$ for the various policies. ■

Proposition 3 *The incentive for innovation under properly designed direct controls is less than or equal to the incentive under the economic instruments discussed previously:*

$$\Delta\pi_I^{01}(\text{C\&C}) = A - B \text{ for some } B \geq 0.$$

As described in Section 2, "properly designed" direct controls means an emission limit of W^0 *that corresponds to the other policies at stage 0.*

Proof. Intuitively, this is true because firms facing economic instruments can always mimic the behavior of firms facing direct controls; deviations from this mimicry offer the possibility of higher payoffs.

Mathematically, we assume for simplicity that under direct controls the profit-maximizing choice for the post-innovation firm is to emit the maximum allowable amount of pollution, W^0.[10] The post-innovation firm could choose to emit W^0 units of emissions under a Pigovian tax, too; calling the resulting profits $\pi^1_{W^0}(\text{tax})$, we have

$$\pi^1_{\max}(\text{C\&C}) = \pi^1_{W^0}(\text{tax}) + p^0_W W^0. \tag{8}$$

Next: because the policies are "properly designed" at stage 0, we have

$$\pi^0_{\max}(\text{C\&C}) = \pi^0_{\max}(\text{tax}) + p^0_W W^0. \tag{9}$$

Subtracting the second equation from the first produces

$$\begin{aligned} \pi^1_{\max}(\text{C\&C}) - \pi^0_{\max}(\text{C\&C}) &= \pi^1_{W^0}(\text{tax}) - \pi^0_{\max}(\text{tax}) \qquad (10)\\ &\leq \pi^1_{\max}(\text{tax}) - \pi^0_{\max}(\text{tax}), \qquad (11) \end{aligned}$$

i.e., $\Delta\pi^{01}_I(\text{C\&C}) \leq \Delta\pi^{01}_I(\text{tax})$. The crucial inequality here arises tautologically: $\pi^1_{\max}(\text{tax})$ is by definition the maximum profit under a Pigovian tax. ■

3.1 Summary

The results are shown in Table 1. We can see that direct controls never provide a greater incentive than economic instruments, and in fact provide an equal incentive if and only if $B = 0$. Proposition 3 shows that $B = 0$ if and only if $\pi^1_{W^0}(\text{tax}) = \pi^1_{\max}(\text{tax})$, i.e., if and only if the innovation doesn't change the

[10]The same result can be reached without this assumption via a similar but notationally cumbersome proof.

	C&C	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A - B$	A	A	A	A
Rank	5	1	1	1	1

Table 1: The gains from innovation. For clarity, the relative ranking assumes that the inequality constraint $B \geq 0$ is a strict inequality.

firm's optimal level of pollution under a Pigovian tax. For the relative rankings we have assumed that the inequality $B \geq 0$ is a strict inequality.

4 Diffusion

In this section we examine the diffusion of an innovation across an entire industry. We assume that patents are not available, so that the innovation becomes a public good that is adopted by all of the firms in the industry. Although the innovation may change industry-wide variables relating to emissions (e.g., the market-clearing price for pollution permits), we follow Milliman and Prince in assuming that other industry-wide variables (e.g., output price) are unaffected. The results are given in the next three propositions.

Proposition 4 *The innovating firm is unaffected by diffusion under taxes, subsidies, or direct controls. Under these policies, non-innovating firms make a gain from diffusion equal to the innovating firm's gain from innovation:* $A - B$ *under direct controls,* A *under taxes or subsidies.*

Proof. The innovating firm is not affected by diffusion under taxes, subsidies, or direct regulations, i.e., $\Delta\pi_I^{12} = 0$. Its profit differentials $\Delta\pi^{02}$ under these policies are therefore A, A, and $A-B$, respectively. We can now apply Proposition 1 to assert that the same profit differentials $\Delta\pi^{02}$ accrue to non-innovating firms. Since the gain from innovation for non-innovating firms is zero ($\Delta\pi_N^{01} = 0$), it follows that $\Delta\pi_N^{12} = \Delta\pi_I^{01}$ under taxes, subsidies, or direct controls. ■

Proposition 5 *Under grandfathered permits, the non-innovating firm's gain from diffusion is $A - B$. It follows that the innovating firm suffers a loss of B from diffusion.*

Proof At stages 0 and 2 all the firms are identical, so there will be no permit trades. If each firm receives W^0 permits, this situation is identical to the direct control policy whereby each firm is given an emissions limit of W^0. So tradable permits and direct controls are equivalent policies at stages 0 and 2, meaning that $\Delta\pi^{02}(\text{gra}) = \Delta\pi^{02}(\text{C\&C})$, which the previous proposition showed to be equal to $A - B$. Since the non-innovating firms make no gain from innovation, they must gain $A - B$ from diffusion. We can then use Propositions 1 and 2 to back out the impact of diffusion on the innovating firm: innovation produces a gain of $\Delta\pi_I^{01} = A$, and innovation plus diffusion produces a gain of $\Delta\pi^{02} = A - B$, so diffusion must yield $\Delta\pi_I^{12} = -B$.[11] ■

Proposition 6 *Under auctioned permits, the non-innovating firm's gain from diffusion is $A - B \pm C$ for some $C \geq 0$. It follows that the innovating firm's*

[11] We discuss the intuition behind this result at the end of this section.

gain from diffusion is $-B \pm C$.

Proof If p_W^2 is the market price of permits at stage 2, profits under grandfathered and auctioned permits at stage 2 are related by

$$\pi_{\max}^2(\text{auc}) = \pi_{\max}^2(\text{gra}) - p_W^2 W^0. \tag{12}$$

Similarly,

$$\pi_{\max}^0(\text{auc}) = \pi_{\max}^0(\text{gra}) - p_W^0 W^0. \tag{13}$$

Subtracting the second equation from the first yields

$$\begin{aligned} \Delta\pi^{02}(\text{auc}) &= \Delta\pi^{02}(\text{gra}) + (p_W^0 - p_W^2)W^0 && (14)\\ &= A - B \pm \left|p_W^0 - p_W^2\right| W^0 && (15)\\ &\overset{\text{call}}{=} A - B \pm C. && (16) \end{aligned}$$

Since the non-innovating firms make no gain from innovation, this must be their gain from diffusion. The innovating firm has a gain of A from innovation, so we can use Proposition 1 to back out $-B \pm C$ as its gain from diffusion. ■

4.1 Summary

Table 2 summarizes these results. The table lists the innovation results $\Delta\pi_I^{01}$ from Table 1, and then lists (for two different cases) the innovator's gains from diffusion ($\Delta\pi_I^{12}$) and from the combined effect of innovation plus diffusion ($\Delta\pi^{02}$). Since non-innovating firms are unaffected by innovation, their gain from diffusion is $\Delta\pi_N^{12} = \Delta\pi^{02}$.

The two cases concern the impact of diffusion on the market price (or shadow price) of permits. If, under grandfathered or auctioned permits, the permit price falls ($p_W^2 < p_W^0$), the results are shown in the middle rows of Table 2; intuitively, this can be thought of as the case in which the innovation *decreases* demand for pollution. If the permit price rises ($p_W^2 > p_W^0$), the results are shown in the bottom rows of Table 2; intuitively, this can be thought of as the case in which the innovation *increases* demand for pollution.[12]

The relative rankings (which assume strict inequalities) are established in the following proposition.

Proposition 7 *Auctioned permits provide either the maximum or the minimum incentive for innovation plus diffusion.*

Proof. Since the various policies are "properly designed" at stage 0, profits under taxes and auctioned permits are equal at stage 0:

$$\pi_{\max}^0(\text{auc}) = \pi_{\max}^0(\text{tax}). \tag{17}$$

At stage 2, however, the price of auctioned permits diverges from the Pigovian tax rate. If the permit price goes down ($p_W^2 < p_W^0$), Equation 4 confirms what intuition suggests: firm profits are higher under auctioned permits than under Pigovian taxes:

$$\pi_{\max}^2(\text{auc}) > \pi_{\max}^2(\text{tax}). \tag{18}$$

[12] If the permit price stays the same, all the policies are equal because $B = C = 0$. Intuitively, this corresponds to the case in which the innovation produces no change in the demand for pollution.

	C&C	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A-B$	A	A	A	A
Rank	5	1	1	1	1
$p_W^2 < p_W^0$ ("Decreased demand" for emissions)					
$\Delta\pi_I^{12}$	0	0	$-B$	$-B+C$	0
Rank	2	2	5	1	2
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B+C$	A
Rank	4	2	4	1	2
$p_W^2 > p_W^0$ ("Increased demand" for emissions)					
$\Delta\pi_I^{12}$	0	0	$-B$	$-B-C$	0
Rank	1	1	4	5	1
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B-C$	A
Rank	3	1	3	5	1

Table 2: The gains from innovation, diffusion and innovation plus diffusion. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

Subtracting the first equation from the second yields $\Delta\pi^{02}(\text{auc}) > \Delta\pi^{02}(\text{tax})$, i.e., $A - B + C > A$. We can conclude that auctioned permits provide the greatest incentive if diffusion reduces the permit price.

On the other hand, if the permit price goes up ($p_W^2 > p_W^0$) then the gain under auctioned permits is $A - B - C$, which is lower than $A - B$ or A. ■

One result that is common to the two cases is the consistently poor performance of free permits in terms of diffusion. Free permits always provide either the lowest or the second-lowest incentive for diffusion ($\Delta\pi_I^{12} = -B$). To see the intuition behind the unambiguous loss for the innovating firm, recall that at stage 2 (after diffusion) all of the firms will be the same, so there will not be any trades and the innovating firm will simply use its allotted permits to earn profits of, say, $\hat{\pi}$. At stage 1 (after innovation but before diffusion), the innovating firm could also choose to not make any trades, and if it did so it would earn profits of $\hat{\pi}$. Any trades that the innovating firm makes at stage 1, then, must raise its profits above $\hat{\pi}$. Diffusion eliminates those trading opportunities, and therefore hurts the firm regardless of whether the innovating firm is a net buyer of permits or a net seller of permits at stage 1.

5 Optimal Agency Response

In this section we examine optimal agency response and then consider all three steps—innovation, diffusion, and optimal agency response—together. Following Milliman and Prince, we allow the agency's response to change industry-wide variables relating to emissions (e.g., the market-clearing price for pollution permits), but assume that other industry-wide variables (e.g., output price) are unaffected. We also assume that the benchmark for pollution subsidies—the emissions level below which emissions reductions are subsidized—remains unchanged, and is high enough that all emissions reductions are subsidized. Finally, we follow Milliman and Prince in assuming that entry and exit are not allowed.

As the previous section suggests, the results will depend on the impact of innovation and diffusion on the "demand" for pollution, i.e., on the market price (or shadow price) of permits. In the subsections below we address the two cases,[13] both of which make use of the following result.

Proposition 8 *The combined effect $\Delta\pi^{03}$ of innovation, diffusion, and optimal agency response under direct controls must be equal to that under free permits, and the combined effect under Pigovian taxes must be equal to that under auctioned permits.*

Proof All firms are identical at stages 0 and 3, so there are no permit trades. Since the regulator is behaving optimally at both stages under the various policies, the number of free permits it issues at either stage must be equal to the limit established under direct control, and the price and quantity of auctioned permits must be equal to the results under taxes. ■

5.1 Reduced demand for pollution control

First assume that innovation and diffusion reduce the demand for pollution control, by which we mean that the intersection of the marginal environmental damage curve and the marginal emissions benefit curve occurs at a lower price. Figure 2 shows an example, with MEB^0 and MEB^2 representing industry-level marginal emissions benefits with the old and new technologies, respectively, and MED representing marginal environmental damage.[14] The social optimum

[13] As discussed in Footnote 12, all policies are identical if the demand for pollution is unchanged by innovation and diffusion.

[14] This innovation can be thought of as a technology that allows the firm to substitute low-sulphur coal for high-sulphur coal, thereby "front-loading" the benefits of emissions onto the

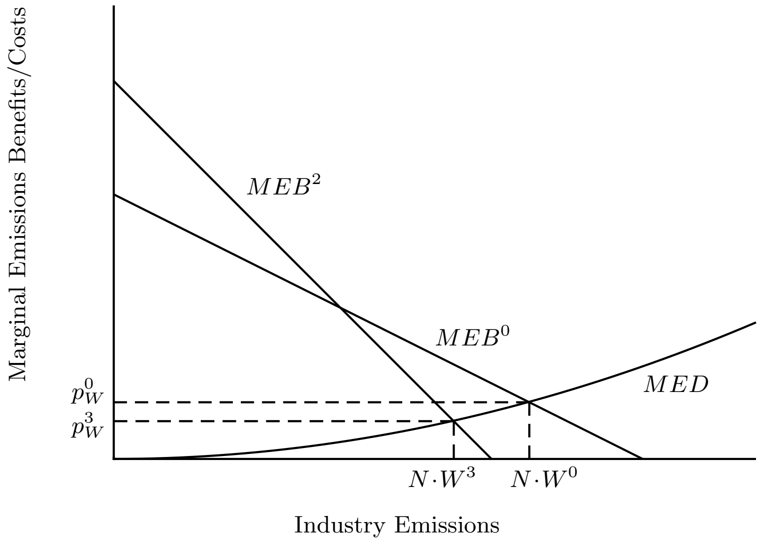

Figure 2: An innovation that *decreases* demand for pollution at the margin. The curves represent marginal environmental damages and marginal emissions benefits at stages 0 (before innovation) and 2 (after diffusion).

with the old technology features emissions of W^0 per firm (and so $N \cdot W^0$ for the entire industry) and a shadow price for emissions of p_W^0. The social optimum with the new technology features emissions of $W^3 < W^0$ per firm and a shadow price for emissions of $p_W^3 < p_W^0$.

Accordingly, the optimal agency response is to tighten direct controls, re-

initial units of emissions. Similar shifts would occur in the demand for gasoline in the case of a consumer who switches to a car with high gas mileage, or in the demand for electricity in the case of a consumer who switches to compact fluorescent lights. Thanks to Karl Seeley for suggesting this graph and its interpretation.

duce the number of permits issued or auctioned, or lower the rate for emissions taxes or subsidies. These adjustments will harm the firms in the industry under all policies except emissions taxes. If we let $-D < 0, -E < 0$, and $F > 0$ be the impacts of agency response under direct controls, subsidies, and taxes, respectively, then the previous proposition (Proposition 8) yields all of the results in Table 3 (at the top of page 24). We will discuss the ambiguity concerning the relative ranking of subsidies and direct controls/free permits at the end of this section.

5.2 Increased demand for pollution control

Now assume that innovation and diffusion increase the demand for emissions, by which we mean that the intersection of the marginal environmental damage curve and the marginal emissions benefit curve occurs at a higher price. An example is shown in Figure 3.

The optimal agency response in this case is to loosen direct controls, increase the number of permits issued or auctioned, or increase the rate for emissions taxes or subsidies. These adjustments will benefit the firms in the industry under all policies except emissions taxes. If we let $D > 0, E > 0$, and $-F < 0$ be the impacts on each firm of agency response under direct controls, subsidies, and taxes, respectively, then Proposition 8 yields all of the results in Table 4 (at the bottom of page 24) except the following:

Proposition 9 *Auctioned permits and taxes provide the weakest incentive for innovation, diffusion, and optimal agency response.*

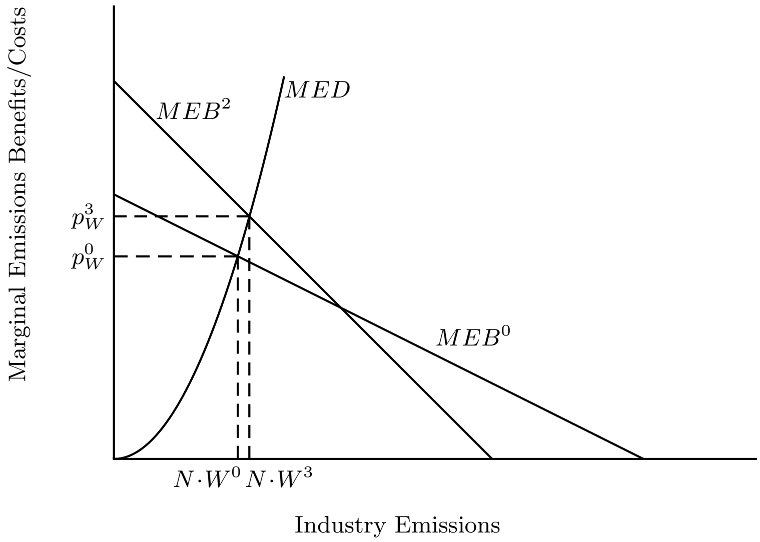

Figure 3: An innovation that *increases* demand for pollution at the margin. The curves represent marginal environmental damages and marginal emissions benefits at stages 0 (before innovation) and 2 (after diffusion).

Proof. Auctioned permits are clearly inferior to subsidies because $A-F < A+E$ for $E > 0$ and $F > 0$. Proposition 8 now shows that the desired result will follow if we can show that auctioned permits (which are equivalent to taxes) are inferior to grandfathered permits (which are equivalent to direct controls). Intuitively, this makes sense because auctioned permits impose an additional cost on firms, namely, the higher price of permits. Mathematically we have

$$\pi^3_{\max}(\text{gra}) = \pi^3_{\max}(\text{auc}) + p^3_W W^3 \tag{19}$$

$$\pi^0_{\max}(\text{gra}) = \pi^0_{\max}(\text{auc}) + p^0_W W^0. \tag{20}$$

Subtracting the second equation from the first and rearranging yields

$$\Delta\pi^{03}(\text{gra}) - \Delta\pi^{03}(\text{auc}) = p_W^3 W^3 - p_W^0 W^0. \tag{21}$$

The right hand side here is positive since $p_W^3 > p_W^0$ and $W^3 > W^0$. We can conclude that auctioned permits provide the weakest incentive. ■

5.3 The relative ranking of subsidies

As shown in Tables 3 and 4, subsidies cannot be definitively ranked above or below direct controls (or free permits) in terms of the entire process of technological change. Our next proposition shows that the subsidy baseline $\overline{W}$ is the key in determining the incentive effects of Pigovian subsidies.

Proposition 10 *If the subsidy baseline $\overline{W}$ is relatively large compared to a firm's optimal choice of emissions, subsidies will provide a lower incentive than direct controls if $p_W^3 < p_W^0$ and a higher incentive if $p_W^3 > p_W^0$. The reverse is true if the baseline is relative small.*

Proof. Direct controls and subsidies are related by

$$\pi_{\max}^3(\text{C\&C}) = \pi_{\max}^3(\text{sub}) - p_W^3(\overline{W} - W^3) \tag{22}$$

$$\pi_{\max}^0(\text{C\&C}) = \pi_{\max}^0(\text{sub}) - p_W^0(\overline{W} - W^0) \tag{23}$$

Subtracting the second equation from the first and rearranging yields

$$\Delta\pi^{03}(\text{C\&C}) - \Delta\pi^{03}(\text{sub}) = p_W^3 W^3 - p_W^0 W^0 + (p_W^0 - p_W^3)\overline{W}. \tag{24}$$

If the benchmark $\overline{W}$ is very large, the subsidy payment term $(p_W^0 - p_W^3)\overline{W}$ will dominate the right hand side. If the subsidy rate decreases ($p_W^3 < p_W^0$),

	C&C	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A-B$	A	A	A	A
Rank	5	1	1	1	1
$\Delta\pi_I^{12}$	0	0	$-B$	$-B+C$	0
Rank	2	2	5	1	2
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B+C$	A
Rank	4	2	4	1	2
$\Delta\pi^{23}$	$-D$	$-E$	$-D$	$B-C+F$	F
Rank	2–5	2–5	2–5	2–5	1
$\Delta\pi^{03}$	$A-B-D$	$A-E$	$A-B-D$	$A+F$	$A+F$
Rank	3–5	3–5	3–5	1	1

Table 3: The gains from innovation, diffusion, optimal agency response, and combinations of the three, assuming that diffusion *decreases* demand for pollution. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

	C&C	Subsidy	Free permits	Auctioned permits	Tax
$\Delta\pi_I^{01}$	$A-B$	A	A	A	A
Rank	5	1	1	1	1
$\Delta\pi_I^{12}$	0	0	$-B$	$-B-C$	0
Rank	1	1	4	5	1
$\Delta\pi^{02}$	$A-B$	A	$A-B$	$A-B-C$	A
Rank	3	1	3	5	1
$\Delta\pi^{23}$	$+D$	$+E$	$+D$	$B+C-F$	$-F$
Rank	1–4	1–4	1–4	1–4	5
$\Delta\pi^{03}$	$A-B+D$	$A+E$	$A-B+D$	$A-F$	$A-F$
Rank	1–3	1–3	1–3	4	4

Table 4: The gains from innovation, diffusion, optimal agency response, and combinations of the three, assuming that diffusion *increases* demand for pollution. For clarity, the relative ranking assumes that all inequality constraints are strict inequalities.

subsidies will provide less of an incentive than direct controls; Table 2 shows that subsidies will then provide the weakest incentive of all the instruments. If the subsidy rate increases ($p^3_W > p^0_W$), subsidies will provide more of an incentive than direct controls; Table 3 shows that subsidies will then provide an intermediate level of incentives (greater than direct controls, less than taxes).

The reverse is true if the subsidy baseline is small. For example, if the innovation reduces demand for pollution and $\overline{W} = W^0 = \max\{W^0, W^3\}$ then Equation 24 simplifies to

$$\Delta\pi^{03}(\text{C\&C}) - \Delta\pi^{03}(\text{sub}) = p^3_W(W^3 - W^0) < 0, \tag{25}$$

showing that in this case subsidies provide a stronger incentive than direct controls. If the innovation increases demand for pollution and $\overline{W} = W^3 = \max\{W^0, W^3\}$ then Equation 24 simplifies to

$$\Delta\pi^{03}(\text{C\&C}) - \Delta\pi^{03}(\text{sub}) = p^0_W(\overline{W} - W^0) > 0, \tag{26}$$

showing that in this case subsidies provide a weaker incentive than direct controls. ■

6 Conclusion

This paper makes four contributions to the literature on innovation in pollution control. First, the algebraic alternative we provide is more general than the geometric model of Milliman and Prince. It therefore allows us to determine the conditions under which Milliman and Prince's analysis of end-of-pipe innovations extends to, e.g., production-process innovations. A quantitative comparison of the two approaches is difficult because one is algebraic while the other is geometric.[15] Qualitatively, however, our results (e.g., in terms of relative rankings) for the innovation stage (i.e., $\Delta\pi_I^{01}$) agree exactly with those in Milliman and Prince, and our results for diffusion and optimal agency response are in agreement in cases where the innovation *lowers* the demand for emissions at the margin. These are significant extensions of the results that Milliman and Prince find with regard to innovation in end-of-pipe abatement technology. As long as the innovation in question lowers demand for emissions at the margin, our results hold for all types of environmental innovations—most notably, production-process innovations—as well as for "non-environmental" innovations that nonetheless affect emissions levels.

Where our results for diffusion and optimal agency response differ from those in Milliman and Prince are cases where the innovation *increases* the demand for emissions at the margin. Here we find almost the reverse of Milliman and Prince's conclusion. For example, Table 4 shows that taxes and auctioned permits provide the weakest incentive for the entire process of technological change.

Under what circumstances is innovation likely to increase demand for emissions at the margin? Most obvious is the case of innovations which enhance resource productivity, e.g. by increasing the amount of electricity that can be

[15]The two approaches should yield identical quantitative results as long as the innovation is limited to end-of-pipe abatement technologies and results in an everywhere-lower marginal abatement cost curve.

produced from each ton of coal. As long as end-of-pipe abatement efforts are not cost-effective, resource-enhancing innovations will increase the benefit of emissions at all margins.

But other types of production process innovations can also increase demand for emissions at some margins, and therefore have the potential to lead to situations in which Milliman and Prince's conclusions are reversed. For example, consider an innovation that "front-loads" the benefits of emissions onto the initial units of emissions, such as the use of low-sulphur coal instead of high-sulphur coal or compact fluorescent lights instead of incandescent. Such an innovation is pictured in Figures 2 and 3, both of which show the same shift in the industry marginal emissions benefit curve. But taxes and auctioned permits provide the strongest incentive for technological change in Figure 2 and the weakest incentive in Figure 3. The difference is the location of the marginal environmental damage curve: MED is relatively low in Figure 2 and relatively high in Figure 3.

This example touches on the second contribution of this paper: our analysis highlights the hitherto unexamined role of marginal environmental damages in determining the incentive effects of different policies. In the case of "front-loading" innovations, for example, taxes and auctioned permits will be good instruments for providing incentives if and only if marginal emissions damages are relatively small.

A third contribution is that our algebraic alternative to the standard geometric model makes more explicit the assumptions underlying both types of analyses. Two in particular are worth pointing out: there is no entry or exit, and there are fixed prices for all inputs and outputs except (in the case of tradable permits) the price of pollution permits. These assumptions restrict the applicability of these results to public policy; they also identify opportunities for further research. The role of patent protection would also be a promising area for future work.[16]

A final contribution of our analysis is its suggestion that the study of "environmental" innovations can be integrated more closely with the study of innovations more generally. This is another promising area for future research, especially when the topic under consideration is *socially optimal* incentives rather than simply *maximal* incentives. Social welfare gains can come from both "environmental" and "non-environmental" innovations, suggesting that a socially optimal incentive structure must balance the rewards for these different types of innovation [3, p. 23] [7, p. 14]. Efforts to examine this issue must be able to address various types of innovation is a common language; the model described in this paper provides one such common language.

[16] The issue of entry and exit may have an easy solution in the absence of patents: entry and exit should bring this market back into equilibrium with the rest of the economy, so any stages *after* entry and exit should generate gains of zero for all firms. If entry and exit occur after innovation but prior to diffusion, the innovating firm will be the only one to benefit from technological change. A logical extension of this matches up with the intuitive notion that not even the innovating firm will benefit if innovation is *immediately* followed by diffusion *and* entry or exit.

References

[1] Yoram Bauman and Karl Seeley. Limitations in the standard approach to innovation in pollution control. Unpublished working paper, http://students.washington.edu/yoram, 2001.

[2] Paul B. Downing and Lawrence J. White. Innovation in pollution control. *Journal of Environmental Economics and Management*, 13:18–29, 1986.

[3] Adam B. Jaffe, Richard G. Newell, and Robert N. Stavins. Technological change and the environment. NBER working paper 7970, 2000.

[4] Chulho Jung, Kerry Krutilla, and Roy Boyd. Incentives for advanced pollution abatement technology at the industry level: an evaluation of policy alternatives. *Journal of Environmental Economics and Management*, 30:95–111, 1996.

[5] Ross McKitrick. A derivation of the marginal abatement cost curve. *Journal of Environmental Economics and Management*, 37:306–314, 1999.

[6] Scott R. Milliman and Raymond Prince. Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management*, 17:247–265, 1989.

[7] Ian W.H. Parry. On the implications of technological innovation for environmental policy. *Environment and Development Economics*, forthcoming.