Policy Persistence in Environmental Regulation

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Abstract

We study the optimal emission standards under uncertain pollution damages and transaction costs associated with policy changes. We show that in many situations, the authority should avoid or reduce the scale of a policy change in the presence of future transaction costs. Then policy persistence is a rational response of forward-looking policy makers to future transaction costs, rather than a passive outcome of the current political process.

Economists have long taught that the efficient level of effluent (or more generally any externality) occurs when the marginal benefits and costs of pollution are equated. Despite this clear policy advice, there is considerable agreement that economists' influence on environmental policy making has been modest (Hahn (2000)). Rather, there is a strong sense that many times it is the political process, in particular the interaction of interest groups, that shapes the final design of environmental policy and any changes in that policy over time (Maloney and McCormick (1982), Keohane, Revesz and Stavins (forthcoming) and Yandle (1989)).

An important reason for this belief is the predominant presence of policy persistence; the fact that policies such as pollution standards tend to change slowly if at all. Significant agreement is emerging in the literature concerning the difficulty of reversing a policy once it has been established. For example, Coate and Morris (1999) shows that the introduction of a policy invites agents to undertake actions that allow them to benefit from the policy. These benefits, in turn, create incentives for these agents to protect their interests in the form of political pressure and lobbying. Likewise, Dixit (1996) argues that "policy acts shape the future environment by creating constituencies that gain from the policy, who will then fiercely resist any changes that take away these gains." Different voting rules (Fernandez and Rodrik (1991) and Alesina and Drazen (1991)) and aggregation methods (Sen (1977)) can also lead to different forms of policy inertia. In these papers, policy persistence is seen to be an outcome of the political process, replacing economic efficiency as the determinant of a policy such as an emission standard.

But, suppose the environmental authority is uncertain of the damages of the effluent and is cognizant of the transaction costs engendered by the political process associated with a future change in policy. How should the environmental authority set a standard that may need to be changed when additional information becomes available, when it knows those changes are costly? This is the question addressed by this paper. Specifically, we study the optimal pollution standard under uncertain damages and transaction costs associated with policy changes. We show that in many situations, the authority would avoid or reduce the scale of a policy change, in response to *future* transaction costs. The resulting policy persistence is over and above that induced by the *current period* transaction costs.

In investigating the consequences of transaction costs on efficient emission levels, we recognize that there are many causes of adjustment costs.[1] Various forms of political lobbying and interest group behavior can generate adjustment costs, although these political groups and their actions have many additional consequences that cannot be fully captured by the generic modeling of transaction costs. Further, there are sources of transaction costs that have little or nothing to do with the political process (such as those related to monitoring and reporting). Thus, although our model and results complement the work on political economy in environmental economics, the main contribution is a better understanding of the dynamic consequences of transaction costs, in all its facets.

In a world of certainty, transaction costs are easily incorporated into setting the efficient standard, resulting in a standard that is closer to the starting point than in a situation without transaction costs. Thus, the presence of current period transaction costs provides some efficiency basis for policy persistence. Stavins (1995) examines explicitly how the form of transaction costs affects the solution in the context of emission permits. Here, we investigate the consequences of these transaction costs in an explicitly dynamic environment, exploring whether the intertemporal effects further perpetuate policy persistence.

Transaction costs induced by political pressures may be either symmetric or asymmetric. Symmetric costs may occur when it is equally difficult (costly) to further relax or tighten the new standard. This may happen if the standard is highly controversial and both sides (environmental-

[1] We use "adjustment" costs and "transaction" costs interchangeably throughout the paper.

ists and industry for example) can be expected to lobby hard for (or against) changes in opposite directions.

In contrast, asymmetric costs may occur if it is difficult to reverse a policy once it is set, but not particularly difficult to make further changes in the same direction. Thus, if a new policy is more strict than the current standard, then the agency would expect high transaction costs to loosen the standard in the future, but relatively low costs to further tighten it. The arguments of Coate and Morris (1999) and Dixit (1996) indicate the existence of this type of asymmetric costs.

In considering the consequences of transactions costs for the efficient standard, we find that if the costs are symmetric, the optimal new standard depends on the relative probability of future adjustments in the two directions. In this case, the added effect of uncertainty is unclear and depends on the parameters of the model. As uncertainty rises, the policy may demonstrate persistence in one direction, but not in the other.

However, under asymmetric transaction costs, uncertainty unambiguously enhances the degree of policy persistence. If the new standard is more strict than the current one, the action of setting the new standard creates a "policy trend" of tightening standards that will be difficult to reverse. Anticipating this trend, the policy maker will be "cautious" in reducing the allowed emission, and this caution translates into the new standard being even closer to the existing one. That is, the current policy becomes more persistent and the starting position matters more under uncertainty.

Essentially when a policy trend already exists, the regulatory agency's optimal choice of the standard resembles that of an investor conducting irreversible investment under uncertainty, as illustrated by Arrow and Fisher (1974), Dixit and Pindyck (1994), and Kolstad (1996). There is an option value associated with delaying setting the new policy for the agency to gather more information, but if the agency is forced to act today (possibly due to a legislative mandate), it will set the policy closer to the starting (i.e. existing) policy level to compensate for the lost option value. Thus the policy path consists of a sequence of relatively small adjustments, rather than a few instances of radical shifts. When currently there is not a policy trend, but a change in policy will set a trend that cannot be reversed, the agency will become even more cautious, and is more reluctant to move away from the current position.

In this paper we focus on policy irreversibility, rather than ecological or economic irreversibility that is usually studied in the real options literature. We broadly define ecological or economic irreversibility as difficulty in reversing one's action due to physical or economic laws, for instance extinction of species or investment in equipment that has little or no scrap value. Standard real option theory shows that when a policy leads to ecologically or economically irreversible actions, the efficient timing and scale of the policy are affected by uncertainty and future information (Arrow and Fisher (1974) and Kolstad (1996)). Pindyck (1998) showed that similar results also hold for policy irreversibility: uncertainty tends to delay the timing of the new policy. In the only other piece dealing with policy irreversibility, Farrow and Morel (1999) argued that the way individuals perceive pollution and frame their decision problems implies different directions of policy irreversibility, and consequently the timing of the policy. In this paper, we show how uncertainty affects the *scale* of the new policy when the agency has to act today. Further, we study the optimal policy choice when the irreversibility is not pre-imposed, but rather is induced by a policy change.

The paper is organized as follows. In Section 1, we lay out the basic problem faced by the regulatory authority, and the different forms of adjustment costs. We then develop a simple, stylized model in Section 2 where policy changes in both directions incur symmetric adjustment costs. We first study a simple case where the regulatory authority is uncertain about environmental damages in the current period, but where all of that uncertainty will be resolved in the second period. We then extend the model to the more realistic situation where additional information becomes available in each period, but the uncertainty is never completely resolved. We study asymmetric policy inertia in Sections 3 and 4, and in Section 5, we conclude with a discussion of the implications of these results generally for policy.

1 Model Setup and Alternative Forms of Adjustment Costs

To focus on policy irreversibility, we assume away ecological and economic irreversibility and consider a flow pollutant that causes environmental damage only in the period it is emitted. Let e_t be the emission standard, and consequently the actual emission level[2] in period t, with damage given by $D(e_t) = \theta_t d(e_t)$, $d' \geq 0$, $d'' > 0$, $d(0) = 0$ and $d'(0) = 0$. The damage coefficient θ_t is a random variable that is observed at the beginning of period t. The benefit of emitting e_t (i.e. the saved abatement cost) is given by $B(e_t)$, with $B'' < 0$, $B(0) = 0$ and $B'(0) > 0$. The information process facing the regulatory agency is described by the stochastic process $\{\theta_t\}$, $t \geq 0$.

The regulatory agency chooses a standard for per period emissions to maximize social welfare. If the policy is not rigid so that the agency can change the standard costlessly, it can simply set the current period standard as $\arg\max_e B(e) - \theta_t d(e)$. If future information renders this standard inappropriate, the authority can then set a new standard based on the new information.[3] That is, the agency's problem is essentially static. However, if the current standard is costly to change in the future, the agency's problem is dynamic: the current standard should be set to maximize the expected present value of net payoffs, subject to the amount of information available and transaction costs associated with future adjustments to the standard.

We consider two forms of adjustment costs. Under symmetric costs, the adjustment cost for both more and less strict policy changes is given by $c(\cdot)$, defined on $[0, \infty)$, with $c(0) = 0$, $c' > 0$ and $c'' \geq 0$. The argument of $c(\cdot)$ measures the absolute value of the policy change. For example,

[2] Throughout the paper, we assume that the policy standard is binding: firms will emit up to the allowed level.

[3] Excluding economic irreversibility implies that we assume away any possible adjustment costs the firms may incur responding to policy changes.

if the current standard is e_0 and the new standard is e_1, then the adjustment cost is $c(|e_1 - e_0|)$.

We study an extreme form of asymmetric adjustment costs where a policy trend, once set, cannot be reversed at any cost. In particular, if the policy trend is toward tighter pollution control, the policy maker faces the following constraint: $e(t_1) \geq e(t_2)$ for $t_2 > t_1$. Similarly, if the trend is toward loosening control, the constraint is $e(t_1) \leq e(t_2)$ for $t_2 > t_1$. The assumption of absolute irreversibility is not critical to our results, but greatly simplifies the analysis.

We distinguish between two scenarios under the asymmetric inertia: one where the policy trend has been set, and one where the new policy change establishes a future trend. We will show that the agency is more cautious in changing the current policy under the second scenario.

For both the symmetric and asymmetric adjustment cost cases, we first consider a simpler problem of full uncertainty resolution in discrete time, where the uncertainty about θ is fully resolved in period two. This simple case provides much of the intuition for our general results. Specifically, in period one, the agency knows that θ is Bernoulli: it takes $\theta_L > 0$ and $\theta_H > \theta_L$ with equal probability, thus the expected value of θ is $\bar{\theta} = \frac{\theta_L + \theta_H}{2}$. In period two, the agency observes the true value of θ. Let $\delta = \frac{\theta_H - \theta_L}{2}$, so that $\theta_H = \bar{\theta} + \delta$ and $\theta_L = \bar{\theta} - \delta$. The parameter δ is monotonically related to the variance of θ and measures the degree of uncertainty.

We then extend the model to the more realistic setup of continuous time with partial uncertainty resolution to study the likely policy path overtime. For many environmental problems, uncertainty about pollution damages may never be fully resolved: human preferences and populations are ever changing; thus, even as some sources of uncertainty are resolved, new ones arise. A process for θ that has successfully captured this idea and has been widely used (see for example Dixit and Pindyck (1994)) is described by a Geometric Brownian Motion:

$$d\theta_t = \alpha \theta_t dt + \sigma \theta_t dz_t, \tag{1}$$

where dz_t is the increment of the Wiener process. That is, $dz_t = x(t)\sqrt{dt}$, where $x(t) \sim N(0,1)$ with $cov(x(t_1), x(t_2)) = 0$ for $t_1 \neq t_2$. The parameter α measures the "trend" of the future values of θ, and σ measures the level of uncertainty. According to this formulation, uncertainty about the future change in θ always remains. New information arrives in the form of an observed θ value that affects the expected future level of θ.

2 Symmetric Adjustment Costs

Some policies face transaction costs to induce change in either direction. It is not uncommon for the government to be criticized on both fronts when it announces a new regulation. For example, when the U.S. government announced its new policy to protect the west coast salmon and steelhead, property owners criticized that the policy went too far, while environmentalists considered the policy inadequate and announced plans to sue the government (New York Times, 2000).

2.1 Full Uncertainty Resolution

Suppose the current standard is e_0. Then the risk neutral agency's decision problem is

$$\begin{aligned}\max_{e, e_H, e_L} \; & B(e) - \bar{\theta} d(e) - c(|e - e_0|) \\ & + \frac{1}{2}\left[\frac{B(e_L) - \theta_H d(e_L)}{r} - \frac{c(e - e_L)}{1+r}\right] + \frac{1}{2}\left[\frac{B(e_H) - \theta_L d(e_H)}{r} - \frac{c(e_H - e)}{1+r}\right],\end{aligned} \tag{2}$$

where e measures the new policy in period one, e_H is the emission level from period two on if the realized damage coefficient θ is low at θ_L, and e_L is that if θ is high at θ_H. Since there is no uncertainty after period two, we assume that the standard will not be changed.[4] Note that we used the condition $e_L \leq e \leq e_H$ which can be verified from the first order conditions of e_L and e_H.

[4]Since the adjustment cost function is convex, the policy maker may prefer to adjust the standard gradually. That is, based on the new information in period two, instead of changing the standard to e_H or e_L immediately, the agency may choose to make the changes over a number of periods. The optimal adjustment rate depends on the trade off between the saved adjustment cost and the net loss from the suboptimal standard. We assume the gradual adjustment away since it does not affect our conclusion regarding the effects of uncertainty.

Obviously the departure of the optimal standard e from that without adjustment costs and uncertainty depends on the functional forms. Without uncertainty, standard Coastian results apply: the new standard e is closer to the starting policy as the adjustment cost increases. Our interest is to investigate whether uncertainty reduces the starting level effect, i.e. whether it implies a further change from the status quo than the static transaction costs result, or whether it makes the existing policy more persistent.

Applying the implicit function theorem to the first order conditions, we find that regardless of whether $e > e_0$ or $e < e_0$, i.e., whether the new standard is more or less strict than the initial standard, the following condition always holds:

$$\frac{de}{d\delta} \propto \frac{c''(e_H - e)d'(e_H)}{-A_H} - \frac{c''(e - e_L)d'(e_L)}{-A_L}, \tag{3}$$

where $A_H = B''(e_H) - \theta_L d''(e_H) - \frac{r}{1+r}c''(e_H - e) < 0$ and $A_L = B''(e_L) - \theta_H d''(e_L) - \frac{r}{1+r}c''(e - e_L) < 0$ are the second order coefficients of e_H and e_L respectively. Thus the effects of uncertainty depend in part on the future adjustments needed. For example, if $e_H - e$ is sufficiently big, i.e. if the standard would need to be raised significantly in the future if $\theta = \theta_L$, the current optimal standard should also be raised as uncertainty increases. Further, as long as $de/d\delta \neq 0$, uncertainty enhances policy persistence in one direction and reduces it in the opposite direction. For example, if $de/d\delta > 0$, high initial standards become more persistent than low ones: the agency is more willing to raise the standard. We will show later that under asymmetric policy inertia, uncertainty enhances persistence in both directions.

Equation (3) indicates that the sign of $de/d\delta$ depends directly on the functional forms of $B(\cdot)$, $d(\cdot)$, and $c(\cdot)$, and indirectly on the starting standard e_0 through the optimal e. If $B(\cdot)$, $d(\cdot)$ and $c(\cdot)$ are all quadratic, we can verify that $\frac{de}{d\delta} > 0$. In this case, the agency is more willing to increase than to decrease e as uncertainty increases. The *symmetric* adjustment cost seems to favor adjustment toward higher emission levels and creates persistence against reducing e. On the other hand, if $c(\cdot)$ is quadratic, $d(\cdot)$ is $\epsilon-$linear[5] and $B''' > 0$, then $\frac{de}{d\delta} < 0$. The policy becomes more persistent against increasing standards. In other cases, the sign of $de/d\delta$ may depend on the level of the initial standard. It is possible that $\frac{de}{d\delta} > 0$ at some starting standard levels and $\frac{de}{d\delta} < 0$ at other levels.

2.2 Partial Uncertainty Resolution

Suppose the initial standard is e_0. In period t, the agency observes the value of θ_t and chooses the new standard for this period. Let I_t measure the magnitude of the policy change. Then the agency's optimal decision problem is

$$\begin{aligned} J(\theta_0, e_0) \equiv \max_I E \int_0^\infty & \left[B(e_\tau) - \theta_\tau d(e_\tau) - c(|I_\tau|)\right] e^{-r\tau} d\tau \\ \text{s.t.} \quad d\theta_\tau &= \alpha\theta_\tau d\tau + \sigma\theta_\tau dz_\tau \\ \dot{e}_\tau &= I_\tau, \qquad e_0 \quad \text{given.} \end{aligned} \tag{4}$$

From Bellman's Principle of Optimality and Ito's Lemma, we know the optimal policy adjustment I_t satisfies

$$rJ(\theta_t, e_t) = \max_{I_t} \left\{ B(e_t) - \theta_t d(e_t) - c(|I_t|) + \alpha\theta_t J_\theta + \frac{1}{2}\sigma^2\theta_t^2 J_{\theta\theta} + J_e I_t \right\}. \tag{5}$$

Thus the first order condition on I_t is

$$\begin{aligned} c'(I_t) &= J_e(\theta_t, e_t) \quad \text{if } I_t \geq 0 \\ c'(-I_t) &= -J_e(\theta_t, e_t) \quad \text{if } I_t < 0. \end{aligned} \tag{6}$$

Uncertainty affects the optimal policy I_t through changing J_e. Again, I_t changes in the same direction as σ^2 increases, regardless of whether $I_t > 0$ or $I_t < 0$. For example, if higher uncertainty σ raises the marginal value of pollution $J_e(\theta, e)$, then more pollution should be allowed, resulting in a bigger increase in e_t if $I_t > 0$ or a smaller decrease in e_t if $I_t < 0$. Thus, uncertainty enhances

[5] The convex function $d(\cdot)$ is $\epsilon-$linear if $0 < d''(\cdot) < \epsilon$.

policy persistence in one direction and weakens it in the other direction.

3 Asymmetric Adjustment Costs: Full Uncertainty Resolution

The key feature of asymmetric adjustment costs is that the initial policy change sets a trend that is difficult to reverse. That is, future adjustment costs are endogenously determined by setting today's standard. Thus even when the starting policy level is the same, the optimal new policies will differ depending upon whether the policy trend is already set, and, if so, on its direction. To simplify the analysis, we restrict ourselves to the special case where the policy trend is absolutely irreversible, while setting a new policy along the trend does not incur any adjustment costs. These assumptions do not affect our major results.[6]

Suppose the policy trend has already been set. Then the decision maker can only change the standard in the direction of the trend. When new information calls for such a change, we would expect that she will be reluctant to make the entire change because it cannot be reversed if future new information proves that the change has been too much. That is, we expect more gradual changes than without the constraint of the policy irreversibility. This observation is directly parallel to the conclusions of real option theory on optimal investment decisions. Consider now the scenario where the policy trend has not been set, but will be once the standard is changed. Then the agency will be even more reluctant to change the policy since not only can she not reverse the change in face of new information, but she will be setting a trend that cannot be reversed in the future. Only particularly strong information will induce her to change the current policy.

We first study the case of full uncertainty resolution. Partial information will be dealt with in the next section. Let $e_H^* = \arg\max_e B(e) - \theta_L d(e)$ be the optimal emission level, without any

[6] We solved the model for a special form of the adjustment cost function that is linear in the policy change, with the marginal cost higher when the trend is reversed. We obtained similar results, although the resulting conditions can only be analyzed by numerical methods. This special case is available from the authors upon request.

policy trend constraint, if θ turns out to be θ_L, and $e_L^* = \arg\max_e B(e) - \theta_H d(e)$ be the optimal level if θ turns out to be θ_H. Further, we assume that the current emission standard $e_0 \in [e_L^*, e_H^*]$. Continuity of the payoff function implies that any optimal policy will be in the interval $[e_L^*, e_H^*]$.

To solve for the government's optimal policy, we employ the logic of Pindyck (1988) and focus on the efficient *marginal* unit of emissions. In particular, given that $B''(\cdot) < 0$ and $d''(\cdot) > 0$, if in any period it is optimal to emit the xth unit of the pollutant, it must also be optimal to emit all of the yth units, for $y < x$. Therefore, we only need to identify the *last* unit of the pollutant that should be emitted. If the agency is indifferent between emitting this unit and waiting for more information, then all earlier units should be emitted.

3.1 Optimal Policy Under a Pre-Set Trend

We call the policy trend a *polluting trend* if the emission standard can only increase, and a *cleaning trend* if the emission standard can only decrease. Consider first the polluting trend. Suppose the current standard is $e \in (e_L^*, e_H^*)$, and we consider whether it is optimal to raise e by one unit. If we do so, one unit of emission will be added in all future periods since the policy cannot be reversed. Then the expected present value of the added net benefit over all future periods is $du_0^p(e) = \frac{B'(e)-\bar{\theta}d'(e)}{r}$. If the government waits one more period and observes that the pollution damage is low with $\theta = \theta_L$, then the added benefit of raising one unit of emission is $\frac{B'(e)-\theta_L d'(e)}{r}$. Since $e < e_H^*$, the definition of e_H^* means that $B'(e) - \theta_L d'(e) > 0$. Thus the agency should raise the emission level (note that there is no transaction cost for doing this). However, if the damage is high with $\theta = \theta_H$, the added benefit is $\frac{B'(e)-\theta_H d'(e)}{r}$, which is negative since $e > e_L^*$. The optimal decision is not to raise the emission level, and the added net payoff is zero. Thus the present value of the expected added benefit of waiting is $du_1^p(e) = \frac{1}{2}\frac{1}{1+r}\frac{B'(e)-\theta_L d'(e)}{r}$. Equating $du_0^p(e)$ with $du_1^p(e)$, we get

$$\frac{B'(e^p)}{d'(e^p)} = A^p\bar{\theta}, \tag{7}$$

where $A^p = \frac{2r+\theta_H/\bar{\theta}}{2r+1} > 1$, and e^p is the unique emission level where the agency is indifferent between setting the standard now (at e^p) and waiting for more information. It is straightforward to verify that $du_0^p(e)$ decreases faster in e than $du_1^p(e)$ (see also Figure 2). Thus for $e < e^p$, $du_0^p(e) > du_1^p(e)$ and the agency should adopt the new policy e. If $e > e^p$, $du_0^p(e) < du_1^p(e)$ and the agency should wait. The optimal standard should be set at e^p if e^p is higher than the current standard. Otherwise, the current standard is not changed.

Note that without the possibility of future information, the optimal standard satisfies $B'(e^*)/d'(e^*) = \bar{\theta}$. With future information, $A^e > 1$ and $e^p < e^*$. Therefore, if the agency has to increase the standard now, policy irreversibility means that it will choose a standard that is more strict than without future information. That is, the agency is reluctant to move away from the current policy facing uncertainty and an irreversible trend. Further, A^p is increasing, and consequently e^p is decreasing, in $\theta_H/\bar{\theta}$ or the level of uncertainty: Uncertainty thus enhances policy persistence. A^p is decreasing in r, and in the extreme, if $r = 0$ (i.e. without discounting), $B'(e^p)/d'(e^p) = \theta_H$, or $e^p = e_L^*$. So without discounting (or the cost of waiting), the agency acts as if the pollutant is causing the most possible damage, and the current policy e_0 ($\geq e_L^*$) will not be changed until full information becomes available.

Now consider the cleaning policy trend. Given the current standard $e \in (e_L^*, e_H^*)$, we consider reducing the emission standard by one unit. The present value of the expected net benefit of abating one more unit permanently is $du_0^c(e) = (\bar{\theta}d'(e) - B'(e))/r$. If the agency waits one period and θ turns out to be θ_L, the payoff of abating one more unit is $\left[\theta_L d'(e) - B'(e)\right]/r < 0$, and the standard should not be reduced. If $\theta = \theta_H$, then the payoff is $(\theta_H d'(e) - B'(e))/r > 0$ and the unit should be reduced.

Thus the expected present value of waiting one period is $du_1^c(e) = (\theta_H d'(e) - B'(e))/(2r(1+r))$. Equating $du_0^c(e)$ and $du_1^c(e)$, we get

$$\frac{B'(e^c)}{d'(e^c)} = A^c\bar{\theta}, \tag{8}$$

where $A^c = \frac{2r+\theta_L/\bar{\theta}}{2r+1} < 1$. Thus the optimal policy is e^c if it is lower than the current emission standard. Otherwise, it is optimal to maintain the current standard.

Since $A^b < 1$, we know $e^c > e^*$. If the agency decides to reduce the current standard, it will reduce it by a smaller magnitude due to uncertainty and irreversibility. Again, a higher uncertainty level implies more policy persistence: A^c is decreasing and e^c is increasing in uncertainty. If $r = 0$, $B'(e^c)/d'(e^c) = \theta_L$ and $e^c = e_H^*$: without the cost of waiting, the agency acts as if the pollutant is causing the least possible damage, and does not change the current standard until full information becomes available.

Figure 1 shows the effects of uncertainty on e^p and e^c: they start at the same level e^* when $\sigma = 0$, and e^p decreases while e^c increases as σ rises. The arrows indicate allowed policy changes under each trend. Even though the regulatory agency has the same payoff function, its optimal policies are different due to the different directions of policy rigidity and future learning. For example, if the starting condition is at point A, the standard should be raised to e^p under the polluting trend, and should not be changed under the cleaning trend. If the starting condition is at B, the standard should not be changed under either trend. Note that higher uncertainty leads to increased likelihood that the current policy is not changed, and smaller scale of change if the change does occur.

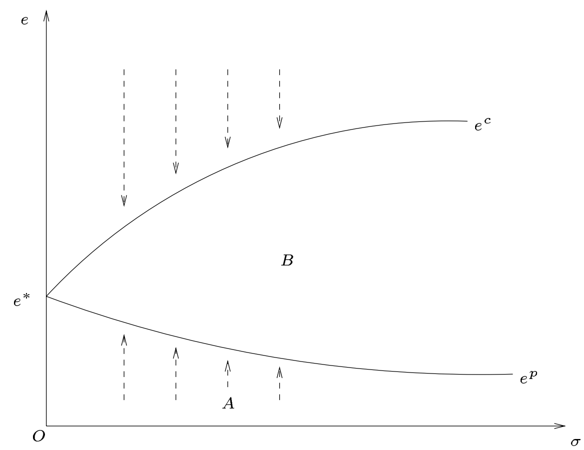

Figure 1: Effects of Uncertainty Under Different Policy Trends

3.2 Optimal Trend-setting Policy

Suppose currently a policy trend does not exist, but the new standard, if different from the current one, will set a trend that cannot be reversed. This may be the case if a long-standing policy is to be changed. Given a current standard e, if the government raises it by one unit, the policy trend will be a polluting trend, and the standard raised cannot be reversed. Then the (marginal) expected net payoff is $du_0^p(e)$, as defined in the last section. Similarly, if the government reduces the standard by one unit, the (marginal) expected payoff is $du_0^c(e)$.

If the government waits one more period and finds that $\theta = \theta_L$, the optimal standard is $e_H^* > e$. Thus it *will* raise the standard by this unit and the marginal benefit is $\frac{B'(e)-\theta_L d'(e)}{r}$. If $\theta = \theta_H$, it will reduce the standard by this unit and the marginal benefit is $\frac{\theta_H d'(e)-B'(e)}{r}$. Then the expected marginal benefit of waiting is

$$du_w(e) = \frac{1}{2}\frac{1}{1+r}\left[\frac{B'(e)-\theta_L d'(e)}{r} + \frac{\theta_H d'(e)-B'(e)}{r}\right] = \frac{1}{2}\frac{1}{1+r}\left[\frac{(\theta_H-\theta_L)d'(e)}{r}\right]. \tag{9}$$

Equating $du_0^p(e)$ and $du_w(e)$, we obtain the optimal standard *if* the government decides to increase the pollution level, given implicitly by

$$\frac{B'(\tilde{e}^p)}{d'(\tilde{e}^p)} = \tilde{A}^p\bar{\theta}, \tag{10}$$

where $\tilde{A}^p = \frac{r+\theta_H/\bar{\theta}}{r+1} > 1$. We can verify that $\tilde{A}^p > A^p$, thus $\tilde{e}^p < e^p$. Equating $du_0^c(e)$ and $du_w(e)$ gives the optimal standard if the government decides to decrease the pollution level:

$$\frac{B'(\tilde{e}^c)}{d'(\tilde{e}^c)} = \tilde{A}^c\bar{\theta}, \tag{11}$$

where $\tilde{A}^c = \frac{r+\theta_L/\bar{\theta}}{r+1} < 1$. We can verify that $\tilde{A}^c < A^c$ so that $\tilde{e}^c > e^c$.

Figure 2 illustrates the optimal choices $\tilde{e}^p$ and $\tilde{e}^c$ relative to the optimal policy without irreversibility, e^*. It also compares the optimal policies with those under pre-set policy trends. If the current standard $e_0 < \tilde{e}^p$, the optimal policy is to increase the standard to $\tilde{e}^p$. If $e_0 > \tilde{e}^c$, the optimal policy is to reduce the allowed emission to $\tilde{e}^c$. If $\tilde{e}^p \leq e_0 \leq \tilde{e}^c$, the agency should not change the current policy. Further, $\tilde{e}^p < e^p$ and $\tilde{e}^c > e^c$: when the new policy sets a trend, the government is more likely to stick to the current policy, and reduce the size of the policy change when a change is needed. The reason is that the expected payoff from immediately changing the current policy is the same regardless of whether the policy trend has been set or not. However, the expected payoff from waiting until period two is higher when the policy trend is not set: $du_w(e) = du_1^p(e) + du_1^c(e)$. Again, from (9), we know $du_w(e)$ increases as the uncertainty level increases, reducing $\tilde{e}^p$ and raising $\tilde{e}^c$. The current policy becomes more persistent as uncertainty increases.

4 Asymmetric Adjustment Costs: Partial Uncertainty Resolution

The analysis becomes more complicated with gradual information arrival. Working with this more realistic case allows us to obtain additional insight about the possible "paths" of environmental policy: a typical path consists of a sequence of small adjustments, rather than a few instances of big changes.

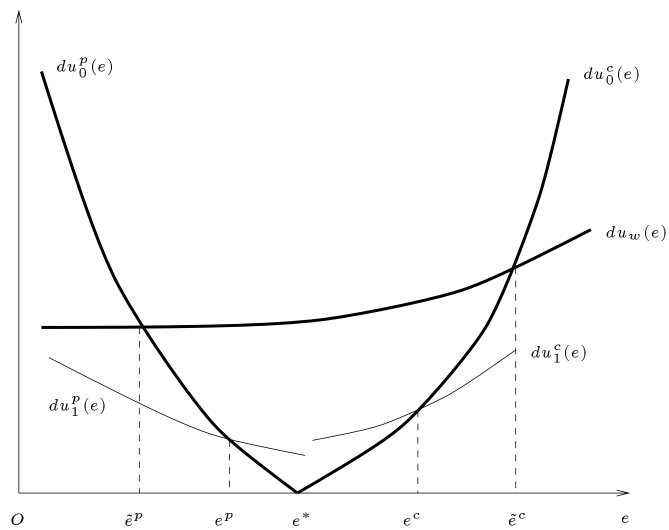

Figure 2: Optimal Policies Before and After the Policy Trend is Set

4.1 Optimal Policy Under Pre-Set Trend

Given the direction of policy irreversibility, finding the best policy is again similar to the optimal capacity problem discussed in Pindyck (1988). For each level of pollution coefficient θ, we identify an optimal level of emission. The current emission is compared with and adjusted to equate this optimal standard, if the required adjustment is allowed by the policy trend.

Consider first the polluting trend so that the emission level can only be raised. Suppose the current emission is e and the authority is deciding whether or not to raise the emission by one unit. The expected benefit of raising this unit now is

$$dv_0^p(\theta) = E_\theta \int_0^\infty e^{-rt}[B'(e) - \theta_t d'(e)]dt = \frac{B'(e)}{r} - \frac{\theta d'(e)}{r-\alpha}, \tag{12}$$

where (1) is substituted for θ_t. Let $dv_1^p(\theta)$ be the expected value of waiting, given θ. Applying dynamic programming and Ito's Lemma to $dv_1^p(\theta)$, we know $dv_1^p(\cdot)$ satisfies

$$\frac{1}{2}\sigma^2\theta^2 dv_1^{p\prime\prime}(\theta) + \alpha\theta dv_1^{p\prime}(\theta) - r dv_1^p(\theta) = 0, \tag{13}$$

where the (single and double) primes stand for the (first and second order) derivatives with respect to θ. As shown in Dixit and Pindyck (1994), the solution to (13) is

$$dv_w^p(\theta) = A_1\theta^{\beta_1} + A_2\theta^{\beta_2}, \tag{14}$$

where A_1 and A_2 are two constants to be determined by the boundary conditions, and $\beta_1 > 1$ and $\beta_2 < 0$ are the two solutions to the fundamental quadratic:

$$\frac{1}{2}\sigma^2\beta(\beta-1) + \alpha\beta - r = 0. \tag{15}$$

We can show that β_1 decreases and β_2 increases in the uncertainty level of θ, σ^2.

If $\theta = \infty$, the emission causes too much damage and the proposed increase in the standard will never be adopted. Then $dv_1^p(\theta)$ is the relevant measure of the agent's payoff and the expected payoff from waiting is zero. Thus $dv_1^p(\infty) = 0$, which implies that $A_1 = 0$. To determine A_2 and the critical θ^p at which the authority is indifferent between increasing the standard and waiting, we use the value matching and smooth pasting conditions, $dv_1^p(\theta^p) = dv_0^p(\theta^p)$ and $dv_1^{p\prime}(\theta^p) = dv_0^{p\prime}(\theta^p)$:

$$A_2(\theta^p)^{\beta_2} = \frac{B'(e)}{r} - \frac{\theta^p d'(e)}{r-\alpha} \tag{16}$$

$$A_2\beta_2(\theta^p)^{\beta_2-1} = -\frac{d'(e)}{r-\alpha}. \tag{17}$$

Solving (16) and (17), we obtain

$$\theta^p(e) = \frac{\beta_2}{\beta_2-1}\frac{B'(e)/r}{d'(e)/(r-\alpha)}, \quad A_2 = \frac{B'(e)}{r(1-\beta_2)(\theta^p(e))^{\beta_2}}. \tag{18}$$

Note that $dv_0^p(\theta)$ is decreasing and linear and $dv_1^p(\theta)$ is decreasing and convex in θ. If the observed damage coefficient θ falls in the "continuation" region, i.e. $\theta \geq \theta^p(e)$, $dv_1^p(\theta)$ dominates $dv_0^p(\theta)$ and the agency should not raise e (i.e. it should wait). If, however, $\theta < \theta^p(e)$, $dv_0^p(\theta)$ is the relevant measure of value, and the agency should raise e (see also Figure 4). Note that as e is raised, $\theta^p(e)$ decreases because $B''(e) < 0$ and $d''(e) > 0$. Thus when the observed damage coefficient θ is lower than $\theta^p(\theta)$, the standard e should be increased until $\theta^p(e) = \theta$. Figure 3 graphs $\theta^p(e)$ and a sample policy path: starting at point A, whenever the observed pollution damage coefficient θ

decreases, the standard e should be increased so that $\theta^p(e)$ is reduced to the level of the current θ. If, however, θ increases, the policy remains unchanged.

Since β_2 is negative and increasing in σ^2, we know $\frac{\beta_2}{\beta_2-1} < 1$ and decreases in σ^2. Higher uncertainty reduces $\theta^p(e)$, or enhances persistence of the current policy: from Figure 3, we see that if the $\theta^p(e)$ curve shifts down, it is more likely that the current policy is not changed, and if changed, the change will be at a smaller scale.

Under the cleaning trend, suppose the current emission level is e and consider the decision of *reducing* the standard by one unit. The expected present value of adopting the policy now is

$$dv_0^c(\theta) = \frac{\theta d'(e)}{r-\alpha} - \frac{B'(e)}{r}. \tag{19}$$

The expected value of waiting, $dv_1^c(\theta)$, satisfies the following differential equation:

$$\frac{1}{2}\sigma^2\theta^2 dv_1^{c\prime\prime}(\theta) + \alpha\theta dv_1^{c\prime}(\theta) - r dv_1^c(\theta) = 0. \tag{20}$$

The solution of (20) is $dv_1^c(\theta) = D_1\theta^{\beta_1} + D_2\theta^{\beta_2}$ where $\beta_1 > 1$ and $\beta_2 < 0$ are the two roots of (15). If $\theta = 0$, the pollution causes no damage and the proposed reduction will never be adopted. If we wait until the next period, no action will be undertaken. The expected marginal value of waiting is zero: $du_1^c(0) = 0$ which implies that $D_2 = 0$. From the value matching and smooth pasting conditions, we obtain $D_1 = \frac{B'(e)}{r(\beta_1-1)(\theta^c)^{\beta_1}}$, and the critical level θ^c:

$$\theta^c(e) = \frac{\beta_1}{\beta_1 - 1}\frac{B'(e)/r}{d'(e)/(r-\alpha)}, \tag{21}$$

where $\beta_1 > 0$ and is decreasing in σ^2. The concavity of $B(\cdot)$ and convexity of $d(\cdot)$ implies that $\theta^c(e)$ is decreasing in e.

Equation (21) indicates the following decision rule: given any realization of θ, if the current standard level is such that $\theta > \theta^c(e)$, the emission standard should be reduced so that the new critical θ^c equals θ. If the current standard level is sufficiently low such that $\theta^c(e) \geq \theta$, the standard

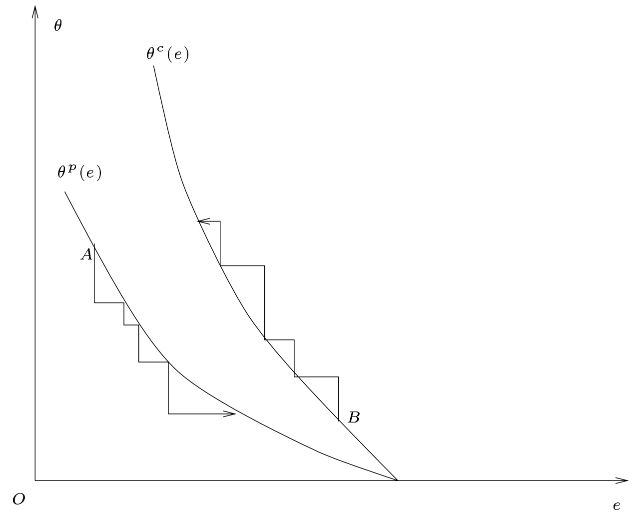

Figure 3: Optimal Policies Under Pre-Set Trends

is not changed. Figure 3 shows $\theta^c(e)$ and a sample policy path starting at point B. As σ^2 increases, both $\frac{\beta_1}{\beta_1-1}$ and $\theta^c(e)$ increases. Again, higher uncertainty enhances the policy persistence.

4.2 Optimal Trend-setting Policy

When the policy trend is not set, given the current standard e and information θ, the expected payoff of increasing the emission standard by one unit is given by $dv_0^p(\theta)$, and that of decreasing the standard is given by $dv_0^c(\theta)$. Using the same procedure in deriving (13) and (14), the expected payoff of waiting is given by

$$dv_w(\theta) = F_1\theta^{\beta_1} + F_2\theta^{\beta_2}, \tag{22}$$

where F_1 and F_2 are two constants to be determined that are independent of θ (but depend upon e).

Let $\tilde{\theta}^p(e)$ be the critical θ level for a given e such that the agency is indifferent between increasing the standard from e and waiting, and $\tilde{\theta}^c(e)$ be the indifference level between decreasing from e and

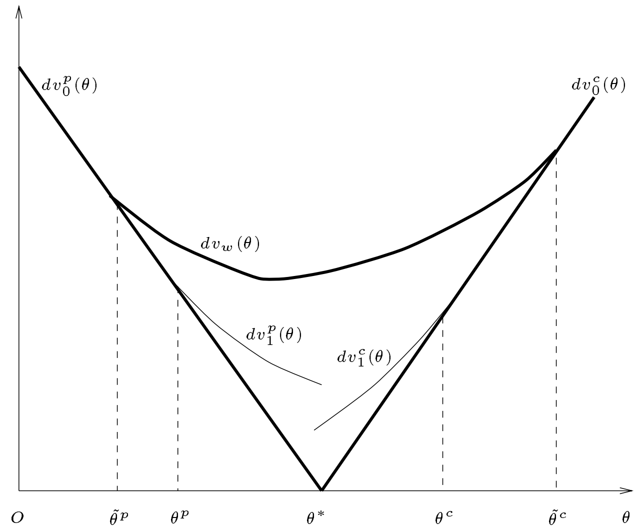

Figure 4: Optimal Policies Before and After the Policy Trend is Set

waiting. Then value matching and smooth pasting conditions are

$$dv_0^p(\tilde{\theta}^p) = dv_w(\tilde{\theta}^p); \quad dv_0^{p\prime}(\tilde{\theta}^p) = dv_w{}'(\tilde{\theta}^p) \tag{23}$$

$$dv_0^c(\tilde{\theta}^c) = dv_w(\tilde{\theta}^c); \quad dv_0^{c\prime}(\tilde{\theta}^c) = dv_w{}'(\tilde{\theta}^c). \tag{24}$$

The functions in (23) and (24) are well behaved and we expect that a unique solution exists. However, the equations cannot be solved analytically. We use a graphical approach similar to Figure 2 to illustrate the solution. The expected benefits of acting now ($dv_0^p(\theta)$ and $dv_0^c(\theta)$) are the same with and without the pre-set policy trend. The only difference lies in the expected benefit of waiting. As we have shown in the case of full uncertainty resolution, we expect that the benefit of waiting is higher without the pre-set trend: at least, the agency can "pretend" that a trend exists and act accordingly, in which case the benefit of waiting is the same as that under the pre-set trend. That is, we expect that $dv_w(\theta) \geq dv_1^p(\theta)$ and $dv_w(\theta) \geq dv_1^c(\theta)$. Then, as shown in Figure 4, $\tilde{\theta}^p(e) \leq \theta^p(e)$, and $\tilde{\theta}^c(e) \geq \theta^c(e)$.

Figure 4 is drawn for a particular level of e. It says that if the observed θ is lower than $\tilde{\theta}^p(e)$, that is, if the pollution damage is rather low, the emission standard should be increased by one unit. As in the case of pre-set trend, we expect $\tilde{\theta}^p(e)$ to be decreasing in e. Then as the standard is raised, the critical level $\tilde{\theta}^p$ decreases. The emission standard should be raised to such a level that the critical $\tilde{\theta}^p$ equals the current observed θ. Similarly, given e, if the observed pollution damage is sufficiently high so that $\theta > \tilde{\theta}^c$, the emission standard should be reduced, and consequently $\tilde{\theta}^c$ is raised, until $\tilde{\theta}^c(e) = \theta$. The current policy should not be changed if the θ value falls between $\tilde{\theta}^p(e)$ and $\tilde{\theta}^c(e)$. Note that the range of θ on which the current policy is not changed is larger than under a pre-set trend. The agency again is more reluctant to change the current policy if any change leads to a new trend that cannot be reversed.

5 Policy Implications and Discussion

Since the seminal work of Coase (1960), economists have understood that the presence of transaction costs affects the efficient emission levels. In this paper, we demonstrate that the consequences of such adjustment costs are more complex than static models depict. Specifically, an explicit dynamic formulation indicates that current *and future* transaction costs associated with changing a policy can augment or mitigate the static effects of transaction costs alone. There are a number of plausible cases in which considerations of future adjustment costs in a dynamic setting lead to more policy persistence than that a static treatment of adjustment costs generates.

At the beginning of this paper, we noted that political pressures rather than economic efficiency criteria are often credited with determining environmental standards. This belief is due, in part, to the rarity with which emission standards are changed, despite the fact that new information concerning damages and costs are regularly generated. In this paper, we show that policy persistence can be an efficient response to the costs associated with changing policies. That is, policy persistence may be a rational reaction by forward-looking policy makers to future transaction costs (which may be due to political pressures), rather than simply a passive outcome of the current political process.

The results of this paper hold an important message for those interested in influencing emission levels such as environmental or industry lobbyists. If a lobbyist would like to see the regulatory authority set a tough standard (low emission levels), he should work hard to convince the authority that it will *not* be difficult to relax the policy in the future if new information becomes available suggesting that a change is in order.

Our results also yield several insights for policy makers. First, policy makers should recognize the importance of transaction costs in determining the efficient emission standards. Since different transaction costs can yield quite different sets of standards (in both level and time path), it is important that the form of adjustment costs be understood and explicitly considered in policy setting. Second, to whatever extent possible, the authority should structure its decision making and policy formation to reduce future adjustment costs associated with changing standards. Third, these results may have important implications for instrument choice as they suggest that the existence of transaction costs associated with a particular policy are even more important than previously understood in choosing among instruments.

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