

**STATE ENFORCEMENT OF FEDERAL STANDARDS:
IMPLICATIONS FOR INTERSTATE POLLUTION**

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ABSTRACT

This paper explores the relationship between interstate air pollution and the division of power between federal and state agencies in setting and enforcing standards. In the context of the US Clean Air Act we argue that the EPA is able to monitor the adoption of technology-based standards more closely than it can monitor state-level enforcement, and that this causes an effective division of control between federal and state agencies. Our analysis offers three main insights into the interstate pollution problem in this setting. First, states have an incentive to enforce standards less stringently on firms located close to downwind borders, and this leads to excessive interstate pollution in equilibrium. Second, there can arise an inherent substitutability in the regulatory problem between strict standards and compliance effort, and this creates a strategic linkage between the federal policy on standards and state policies on enforcement. In particular, a tighter federal standard can induce less selective enforcement but can also lead to less enforcement overall. Third, states will attempt to neutralize the impact of location-based federal standards (that specifically target interstate pollution) in a way that actually exacerbates the underlying enforcement problem.

1. INTRODUCTION

Interstate pollution is an important issue in the US and in many other federations around the world. Rising concern over transboundary pollution flows within the US led to the passage of new legislation in March 2005 which the Environmental Protection Agency (EPA) claimed would “result in the largest pollution reductions and health benefits of any air rule in more than a decade”. [EPA News Release, 10 March 2005]. The intent of this new legislation – the Clean Air Interstate Rule (CAIR) – is to impose tighter restrictions on polluting facilities whose emissions tend to flow across state borders. The legislation focuses on 28 eastern states, where interstate air pollution is deemed to be a particular problem. CAIR “will require all 28 states to be good neighbors, helping states downwind by controlling airborne emissions at their source”. [*ibid.*].

This new legislation will support and supplement existing provisions of the Clean Air Act (CAA) designed to limit the flow of transboundary pollution. The CAA delegates much of the implementation of the Act to the states, but each state must submit a state implementation plan for approval by the EPA. This gives the EPA ultimate control over the standards imposed on polluting facilities (which are primarily technology-based and relatively easy for the EPA to monitor).¹ Moreover, section 110 of the CAA specifically requires state implementation plans to contain provisions that prohibit “any source ... within the state from emitting any air pollutant in amounts which will contribute significantly to non-attainment” of national air quality standards in another state. This requirement effectively prevents a state from imposing lax standards on facilities located close to state borders.

These federal legislative measures with respect to standards are effective in controlling interstate pollution only to the extent that on-going compliance is actually achieved. Responsibility for enforcement under the CAA is for the most part delegated to the states. The EPA is responsible for over-seeing state-level enforcement but this oversight is limited by the nature of enforcement activity in practice. Enforcement actions used by state agencies range from simple oral warnings to fully fledged judicial proceedings – with a series of escalating actions in between – but only “formal”

¹ See Revesz (1996) and Hutchinson and Kennedy (2006) for more detail on emission standards under the CAA, and federal versus state roles in setting those standards.

enforcement actions (those actions backed by some degree of legal force) are typically reported to EPA.² Yet *informal* enforcement actions are far more important on a day-today basis. According to the Environmental Council of the States, about 90% of all state administrative enforcement actions (across all federal environmental programs) are informal in nature.³ These informal actions are not tracked by EPA, due to the information processing burden involved. This lack of federal oversight means that states can in practice exercise considerable discretion with respect to enforcement. In particular, states may be able to weaken the impact of federal measures against interstate air pollution by enforcing standards less stringently on facilities located closer to downwind state borders.

To what extent does this selective enforcement occur in practice? In Hutchinson and Kennedy (2006) we examine violation rates among facilities regulated under the CAA for the period January 2000 to April 2003 and find a significant eastern-border effect: *ceteris paribus*, violation rates are higher for facilities located closer to eastern state borders. Since prevailing winds in the US tend to blow from west to east, this finding suggests that states are indeed more lenient on facilities whose emissions flow into a downwind neighboring state. The magnitude of this eastern border effect is large enough to be of practical concern to policy makers. Other empirical studies (discussed in section 2.3 below) have found near-border effects on pollution discharges, which may be at least partly attributable to selective enforcement behavior.

In this paper we examine how the federal regulator should manage the interstate pollution problem when states have effective control over enforcement. We construct a simple spatial model of a federation with prevailing west to east winds and an associated transboundary pollution problem. We show that equilibrium enforcement policy in this setting will favor facilities located close to a downwind state border, and that interstate pollution will therefore be excessive for any given federal standard. We then show that the optimal policy for the federal regulator is to set a stricter-than-first-best standard, even though this induces an equilibrium enforcement policy that is *more lenient* overall –

² See section 2.1 for further discussion on enforcement actions in practice.

³ For example, in 1999 states undertook 82,156 administrative enforcement actions. Of these, 73,968 were “informal” in nature and not tracked by EPA. These figures do not include judicial proceedings but these constitute a small fraction of state enforcement actions. See Brown and Green (2001), Table 7.

and induces less compliance overall – than when the first-best standard is applied. This paradoxical result arises because the federal regulator faces a tradeoff between inducing more enforcement close to state borders and inducing *less* enforcement further away from state borders. On balance, there is more lenient enforcement overall, but aggregate emissions and interstate pollution flows are both lower, and closer to their first-best levels.

We then examine whether the federal regulator can obtain a better outcome by imposing a policy of location-based standards, under which facilities located close to a state border face a stricter emission standard. We show that location-based standards can actually *exacerbate* the selectivity of state enforcement policy, and at the same time introduce an additional distortion into the regulatory problem: they drive a wedge between marginal abatement costs across polluting facilities. In the context of our model, we show that location-based standards are not an optimal federal policy.

The rest of the paper is organized as follows. Section 2 situates our work in the existing literature. Section 3 presents our basic model. Section 4 derives the first-best solution as a benchmark, and section 5 derives the optimal (second-best) federal policy. Section 6 concludes. An Appendix contains all proofs.

2. RELATED LITERATURE

Our paper sits at the interface of four distinct but related literatures: enforcement action choice; optimal policy under imperfect compliance; transboundary pollution and enforcement policy; and regulation in a hierarchical federal setting. In the discussion that follows we situate our paper in each of these areas of the literature. Our purpose is to sketch some key linkages among these areas by highlighting how they intersect in the context of our analysis of the interstate pollution problem.

2.1 Enforcement Action Choice

The key insight from Becker (1968) that compliance incentives are determined jointly by the penalty for non-compliance and the probability of detection has spawned a large literature on the design of optimal enforcement policy when monitoring is costly and

finances are finite.⁴ One aspect of that literature relates to the portfolio of actions used by enforcement agencies. To our knowledge the most comprehensive analysis of enforcement actions in the US is provided by Brown and Green (2001). They describe the full range of formal and informal enforcement actions used by state agencies, and provide an assessment of how effective these actions are in practice (as reported by the state agencies themselves).⁵ The two findings from that study that are most relevant to our work are (i) that informal state actions are far more common than formal actions (around 90% of all administrative enforcement actions are informal); and (ii) that these informal actions are surprisingly effective. For example, about three-quarters of the time, a simple oral warning is sufficient to bring a violating facility back into compliance. When this first line of action fails to achieve a return to compliance, increasingly formal actions are undertaken. Brown and Green note that state agencies use this escalating approach to enforcement for the simple reason that informal actions are far less costly than full-blown legal proceedings.

Other empirical work on enforcement has also found that informal actions are used widely by regulatory agencies as part of their enforcement mix. For example, Hamilton (1994 & 1996) examines EPA enforcement policy and finds that informal rule-making – such as a clarifying memo – is often preferred to more formal approaches which require administrative review. He argues that this revealed preference is motivated by political and budgetary considerations. Helland (1998) looks at the choice of inspection type by state environmental agencies in the enforcement of the US Clean Water Act (CWA). An inspection can take the form of a cursory check of a plant's paperwork or a more formal independent sampling of water quality. He finds that extensive use is made of the former, and concludes that budgetary considerations and political factors, such as the health of the local economy, are important determinants of the inspection type choice.⁶

⁴ See Heyes (2000) for a recent survey and Russell (2003) for a collection of key papers in the area.

⁵ Informal actions include oral warnings, warning letters, notices of violation, and consent orders. Formal actions – those with some degree of legal force – include non-judicial unilateral orders, emergency orders and judicial proceedings. All but the last of these actions are termed “administrative” actions.

⁶ Scholz and Wei (1986) and Olson (1996) draw similar conclusions with respect to the choice of enforcement actions by the OSHA and the FDA respectively. Magat et. al. (1986) provide a broad perspective on regulatory agency behavior, including a discussion of EPA enforcement actions.

2.2 Optimal Policy under Imperfect Compliance

The optimal enforcement literature usually assumes that the policy goal is to maximize compliance with an exogenously specified standard. However, one branch of the literature looks at the problem from a different perspective: how should regulatory instruments be chosen and set when enforcement – and hence compliance – is imperfect?⁷ A central message from that research is that a stricter standard (or higher tax or permit price) makes the regulated firm less willing to comply – because compliance is costly for the firm – and so greater enforcement stringency is needed to ensure compliance. Since monitoring is costly, there therefore arises a trade-off between the strictness of the standard and compliance with that standard.

The model from this literature closest to our own is that by Amacher and Malik (1996 & 1998) and its reinterpretation by Harford (2000), henceforth referred to as the AMH model. The AMH model examines a regulatory setting in which pollution abatement is produced using a fixed input and a variable input (“abatement capital” and “labor” respectively in the terminology of Harford). These inputs are substitutes in the production of abatement, and the first-best mix of inputs is that which minimizes total social cost (damage plus abatement cost).⁸ Our model is similar in structure (though the focus of our analysis – on transboundary pollution – is quite different). Firms install abatement equipment (a fixed input), which reduces their emissions to some baseline level. Ongoing maintenance of the equipment (a variable input) reduces the likelihood of an equipment failure and consequent discharge of emissions in excess of the baseline. Abatement equipment and maintenance effort are therefore substitutes in the production of *expected* abatement.

In the AMH model the regulator sets two standards: an abatement capital standard; and an ongoing emission standard. Compliance with the emission standard requires ongoing use of labor in combination with abatement capital. It is costly for the

⁷ Among the contributions to this research are Viscusi and Zeckhauser (1979), Jones (1989), Malik (1992), Amacher and Malik (1996 & 1998), Harford (2000), Neilson and Kim (2001) and Gottinger (2001).

⁸ Harford does not use the term “first-best” to describe this solution. He uses the term “first-best” to describe the optimal regulatory policy when enforcement is costly and the regulator can commit to an enforcement regime, as a benchmark against which to assess equilibria when commitment is not possible. In contrast, we use the term “first-best” to describe the solution to a central planning problem in which abatement inputs are chosen to minimize the sum of damage and abatement cost. We have imposed our own terminology on our discussion of the AMH model to ensure consistency throughout our paper.

regulator to monitor compliance with the emission standard, but the capital standard can be enforced without cost (because the installation of abatement capital is an easily observed one-time event). This asymmetry between monitoring costs drives a central result in the AMH papers: the optimal regulatory policy induces a mix of abatement inputs that is skewed towards capital (relative to the first-best mix), and the overall level of emissions is higher than first-best.

In our model we abstract from costly monitoring in any explicit sense; our state enforcement agencies do not face enforcement costs. However, recall that the underlying premise of our paper is that the federal agency is able to monitor the adoption of abatement equipment but cannot fully monitor the enforcement activity of states. This asymmetry gives the federal agency effective control over a technology-based emission standard but gives states effective control over the enforcement of ongoing compliance. We show that the optimal federal policy in this setting, in the presence of interstate pollution, is to set a technology-based standard that is stricter than first-best. This result is akin to the “capital bias” result in AMH. While our regulatory setting is quite different from that in AMH, the same basic forces are at play in both models: substitutability of abatement inputs; and asymmetry in the observability of those inputs.

2.3 Transboundary Pollution and Enforcement Policy

The theoretical literature on transboundary pollution has focused primarily on two main issues: how equilibrium policy choices are distorted by the presence of a transboundary externality between jurisdictions; and how cooperative agreements might be reached to overcome this distortion.⁹ Our paper is situated in the first of these two areas. States in our model do not account for the impact of their pollution on downwind neighboring states and therefore adopt enforcement policies that are too lenient – from a national perspective – on firms located near downwind state borders.

We are not aware of any existing theoretical work relating enforcement behavior to transboundary pollution but there is an incipient empirical literature on this issue. Gray and Shadbegian (2004) analyze emissions (both airborne and waterborne) from US pulp and paper plants and find evidence that plants located within 50 miles of a state border

⁹ See Folmer and Musu (1992) and Missfeldt (1999) for surveys of this literature.

discharge more pollution, on average, than other plants. They also test specifically for a near-border effect on the number of enforcement actions against plants, but find no evidence of this effect. This null-result could reflect our hypothesis that distortions are most likely to arise at the level of informal enforcement actions, which do not show up in official enforcement statistics. In Hutchinson and Kennedy (2006) we circumvent this potential measurement problem by focusing on violation rates. As noted earlier, we find strong evidence of an eastern border effect on violations for facilities regulated under the CAA.

A number of other papers find evidence of near-border effects on measured pollution discharges, but without necessarily linking that effect to enforcement behavior. For example, Sigman (2005) uncovers evidence of a transboundary distortion in state-level implementation of the CWA. She finds that a state's control of its CWA program – as determined by its “authorization” status – is associated with lower water quality in downstream states. While her data do not allow her to distinguish between weaker standards and less stringent enforcement as possible causes, she points out that authorized states have considerable discretion over both. Sigman (2002) also finds evidence of a near-border effect on pollution in international rivers. Helland and Whitford (2003) – in a study of data from the US toxics release inventory – find that toxic pollutant releases are higher in counties which border other states than in those that do not.¹⁰

2.4 Environmental Policy in a Hierarchical Federal Setting

There is a large literature on federalism and its connection to environmental policy.¹¹ The paper most closely related to our own is Silva and Caplan (1997). They examine a regulatory setting with one federal government and two subordinate regional governments. There are two policy instruments: a pollution tax – controlled by the federal government; and *ex post* pollution abatement – controlled by the regions. Pollution is a

¹⁰ Other empirical work has examined selective enforcement behavior that is unrelated to transboundary pollution considerations. For example, Deily and Gray (1991) find that regulators direct fewer inspections towards US steel mills that are on the verge of closing. Dion et.al. (1998) find evidence that enforcement in the Quebec pulp and paper industry is most stringent in instances where environmental damage from non-compliance is likely to be highest. Helland (1998 & 2001) examines the role of political and budgetary pressures in the determination of EPA enforcement practices.

¹¹ A sense of some of the main issues can be gleaned from Baron (1985), Oates and Schwab (1988), Jones and Schotchmer (1990) and Oates (2002). Revesz (1996) provides a perspective in the context of the CAA.

pure public bad for the federation as a whole. They consider two regulatory regimes: a centralized regime in which the federal government acts as Stackelberg leader (which they argue mirrors the US regulatory system); and a decentralized regime in which the regional governments move first (mirroring the EU system). They derive a number of interesting results but the one most relevant to our paper is a policy neutrality result. They show that the equilibrium to the game under a centralized (US-like) regime involves too little abatement by the regions – because of the transboundary externality – and that the federal government is powerless to correct that inefficiency because any attempt to ratchet up the pollution tax beyond its first-best level is completely neutralized by the regional governments through offsetting reductions in abatement.¹²

The neutrality result in our model is similar in spirit. Like Silva and Caplan, we cast the federal government as a Stackelberg leader whose efforts to address interstate pollution can be partially undone by state agencies, in our case through offsetting adjustments to their enforcement policies. In contrast to Silva and Caplan, we do not obtain *complete* neutrality because interstate pollution is not a pure public bad. In our model, emissions exposure declines with distance from the polluting plant. This implies an imperfect substitutability between federal and state instruments, which in turn gives the federal government some leverage with respect to the impact of the standard. Thus, in our setting, the optimal federal standard *is* stricter than the first-best standard.

3. THE MODEL

A federation of identical states is distributed around a latitudinal circle.¹³ Each state occupies an arc of length one. A continuum of identical polluting firms is distributed uniformly along the length of each state, and the mass of firms in each state is normalized to one.¹⁴ Prevailing winds blow from west to east, giving rise to an asymmetric

¹² Readers familiar with the literature on the private provision of public goods will notice the link between this neutrality result and the classic neutrality theorems of Warr (1983) and Bergstrom et. al. (1986). In particular, Bergstrom et. al. demonstrate how government supplementation of a continuous public good is offset in equilibrium by a neutralizing reduction in private contributions to the public good.

¹³ A model with states distributed along a line – in which case the two end states have only one neighbor – yields results similar to those based on the circle model but is somewhat more complicated. The circle model delivers the same key insights but in a simpler way.

¹⁴ Our assumption of a continuum of firms is not critical. A model with just two firms in each state – one closer to the border than the other – would yield similar results. In that setting the penalty function would be a step function, with two parameters. However, the problem becomes more complicated when there are

distribution of emissions exposure around each firm, and a potential interstate pollution problem.

The downwind transfer coefficient for emissions is given by

$$(1) \quad f(y) = \frac{2(r-y)}{r^2}$$

where $f(y)$ is the concentration of emissions at a point y miles downwind of a polluting firm that discharges one unit of emissions, and $r \in (0,1]$ is the maximum range of pollutant transportation.¹⁵ Let x denote the distance between a firm and the downwind border of its home state. A firm for whom $x \geq r$ is called an “inside firm”, while a firm for whom $x < r$ is called a “transboundary firm”. The fraction of a transboundary firm’s emissions that remain within-state is given by

$$(2) \quad \theta(x) = \int_0^x f(y)dy = \frac{x(2r-x)}{r^2}$$

The residual $1 - \theta(x)$ creates a transboundary exposure for the downwind neighboring state. This triangular exposure pattern is illustrated in Figure 1 for emissions discharged from an inside firm and a transboundary firm, labeled “ I ” and “ T ” respectively.

Environmental damage to a state is a function of the aggregate emissions to which it is exposed. Specifically, damage to state j is given by

$$(3) \quad D(E_j) = \delta E_j^2$$

where E_j is the emissions to which state j is exposed and $\delta > 0$ is a damage parameter. Note that this damage function is strictly convex in aggregate exposure. While the assumption of strict convexity is a common one – and a sensible one in our context – it should be noted that this assumption is important for many of our most interesting results. The key role of this assumption – and the sensitivity of our results to it – will become clear as we proceed.

three or more discrete firms, in which case the step-wise penalty function must have as many parameters as there are firms. The advantage of that approach is that the *optimal* penalty structure can in principle be solved for directly, but in practice, solving the optimization problem analytically with three or more parameters is not straightforward.

¹⁵ Note that $f(y)$ integrates to one. We restrict attention to $r \leq 1$ to avoid the analytical complications arising from allowing emissions discharged in one state to have an impact on states beyond its immediate downwind neighbor. The assumption has no bearing on our qualitative results.

The regulatory structure is a hierarchical one: the federal regulator sets an emissions standard, and states are responsible for enforcement of that standard. This complete division of control between federal and state agencies clearly overstates the true extent of that division under the CAA. Our purpose here is to capture the notion that the federal regulator has much greater control over standards than it does over enforcement because it is able to monitor the adoption of technology-based standards much more closely than it can monitor state-level enforcement. A model with a stark division of powers is the simplest and most tractable way to achieve that.

The federal standard s specifies the allowed level of emissions as a fraction of some baseline, which we normalize to one. Thus, $s \leq 1$. Firms adopt a technology consistent with the standard, and must undertake maintenance of that technology to ensure ongoing compliance with the standard. The cost of adopting the technology required to meet the standard is

$$(4) \quad a(s) = \sigma(1 - s)^2$$

where $\sigma > 0$ is a parameter. The cost of maintaining the technology is

$$(5) \quad c(m) = \mu m^2$$

where $m \in [0,1]$ is maintenance effort (henceforth referred to as compliance effort) and $\mu > 0$ is a parameter. Non-compliance is a stochastic event associated with the failure of abatement equipment, where the probability of failure is equal to $1 - m$. Equipment failure results in a discharge of emissions in excess of the standard by some amount $k > 0$.¹⁶ Thus, the expected volume of emissions discharged by a firm which undertakes compliance effort m is

$$(6) \quad g(s, m) = s + (1 - m)k$$

where we use g to denote expected emissions *discharged* to avoid confusion with emissions exposure.

States are responsible for enforcement of the federally specified standard. State-legislated actions against non-compliance are the same for all firms within a state

¹⁶ If equipment failure causes emissions to revert to the baseline level then $k = 1 - s$. In most settings, less-than-complete failure is a more likely scenario, though one can envisage a situation where catastrophic failure could lead to emissions even greater than the baseline. In any case, we have deliberately left the degree of failure unrestricted by leaving k unspecified.

(something easily monitored by the EPA in the case of the CAA) but the state enforcement agency can exercise discretion with respect to how *vigorously* it pursues enforcement. In particular, states may choose to pursue a less stringent enforcement policy for firms located close to the downwind state border relative to firms located in the interior of the state. This discrimination across firms based on location could take many forms. For example, near-border firms may be given more time to return to compliance after an equipment failure, or they may be allowed a greater number of repeated violations before more formal enforcement action is taken by the agency. We capture these various possibilities by allowing the state agency to levy a lower effective penalty (or a less onerous sanction) against transboundary firms relative to inside firms. In particular, we assume the following specification for the effective penalty a firm faces for non-compliance:

$$(7) \quad P = F - \phi(r - x) \text{ if } x < r \text{ and } P = F \text{ otherwise}$$

where F is a base level fine or sanction and ϕ is a discretionary policy parameter reflecting the extent to which enforcement is pursued less stringently against near-border firms.¹⁷ We assume that firms self-report non-compliance.¹⁸ The model as a whole is summarized in Figure 2.

4. EFFICIENT INTERSTATE POLLUTION

In this section we derive the first-best outcome as the solution to a central planning problem in which s and m are chosen to minimize total social cost in a representative state. It will later prove useful to split that planning problem into two stages. In the first stage m is chosen for a given value of s ; in the second stage s is chosen. We consider each stage in turn.

¹⁷ We have chosen to work with a linear penalty function because it is tractable, intuitive, and captures the essential feature of interest, namely, that P is increasing in x for $x < r$. Moreover, the main insights from our analysis are not dependent on this particular specification of the penalty function.

¹⁸ We envisage a truth-telling mechanism in the background, in which firms are motivated to self-report non-compliance by the threat of a severe penalty for failing to do so. This accords with common enforcement practice. We do not model this mechanism explicitly because it is not the focus of interest here. See Livernois and McKenna (1999) for a good treatment of incentive-compatible self-reporting schemes.

4.1 First-Best Compliance

The first stage planning problem is to set compliance effort to minimize total social cost in a representative state:

$$(8) \quad \min_m \delta \left(\int_0^1 [s + (1-m)k] dx \right)^2 + \int_0^1 \mu m^2 dx$$

where the first term measures damage, and the second term measures maintenance costs. Note that our assumption of identical states distributed around a circle means that emissions flowing into a state are equal in magnitude to emissions flowing out of that state. Thus, emissions exposure for a given state – the term inside the damage function in (8) – is simply equal to the quantity of emissions discharged within that state. Note too that technology adoption costs are irrelevant at this stage and are therefore omitted from the social cost expression in (8). Let $m^*(s)$ denote the solution to this first-stage planning problem. This solution is described in Proposition 1.

Proposition 1

- (a) If $\mu \leq \delta ks$ then $m^*(s) = 1$.
- (b) If $\mu > \delta ks$ then $m^*(s) \in (0,1)$ and $m^*(s)$ is increasing in s .

This solution has two key properties. The first is that fail-safe maintenance ($m = 1$) is optimal if and only if maintenance costs (reflected in μ) are sufficiently low relative to the impact of equipment failure (reflected in k); otherwise, less-than-perfect compliance is optimal. The second property is that compliance effort and strict standards are *substitutes*.

The substitutability between compliance effort and strict standards is crucial to the main results that follow, and so it is important to understand why it arises and the extent to which it generalizes beyond the specific functional forms we assume in the model. To that end, consider a more general setting in which the planning problem in (8) becomes

$$(9) \quad \min_m D \left(\int_0^1 g(s, m) dx \right) + \int_0^1 \mu m^2 dx$$

and the solution m^* solves

$$(10) \quad -D'(E) \frac{\partial g(s, m)}{\partial m} = 2\mu$$

A global minimum is assured if $g(s, m)$ is strictly concave in m and $D'(E) \geq 0$, or if $g(s, m)$ is weakly concave in m and $D'(E) > 0$. Now consider how m^* varies with s . Total differentiation of (10) yields

$$(11) \quad \frac{dm^*}{ds} = \frac{-D'(E) \frac{\partial^2 g(s, m)}{\partial m \partial s} - D''(E) \frac{\partial g(s, m)}{\partial m} \frac{\partial g(s, m)}{\partial s}}{D'(E) \frac{\partial^2 g(s, m)}{\partial s \partial s} + D''(E) \left(\frac{\partial g(s, m)}{\partial m} \right)^2}$$

The denominator of (11) is positive by the second order conditions for the minimization problem, so the key terms of interest are in the numerator. If damage is linear (that is, if $D''(E) = 0$) then $dm^*/ds > 0$ – as stated in Proposition 1(b) – if and only if $\partial^2 g(s, m)/\partial m \partial s < 0$; otherwise $dm^*/ds < 0$. This condition on $g(s, m)$ implies that standards and compliance effort are *technological substitutes*; that is, the marginal productivity of compliance effort – in terms of its effect on reducing expected emissions – is lower at a more stringent standard (a lower value of s). Such a situation might arise for example when a stringent standard can be met only by fuel-switching or the adoption of a new production technology which requires little ongoing maintenance once it is installed.

While technological substitutability will apply in many settings, in other cases it may be more plausible that standards and maintenance are *technological complements*; that is, the marginal productivity of compliance effort is *higher* at a more stringent standard ($\partial^2 g(s, m)/\partial m \partial s > 0$). This would apply for example when meeting a stringent standard requires extensive and maintenance-intensive end-of-pipe abatement measures retrofitted to an aging production technology. Most of our results will *not* hold in this setting if damage is linear.

Conversely, if damage is strictly convex (that is, if $D''(E) > 0$) then our results will hold under a much wider set of conditions on $g(s, m)$. In particular, in that case $dm^*/ds > 0$ if and only if

$$(12) \quad \frac{D''(E)}{D'(E)} > - \frac{\frac{\partial^2 g(s,m)}{\partial m \partial s}}{\frac{\partial g(s,m)}{\partial m} \frac{\partial g(s,m)}{\partial s}}$$

This condition holds unambiguously when standards and compliance effort are technological substitutes, and will also hold in the case of technological complements if the damage function exhibits a sufficiently high degree of convex curvature.

The central message of these observations is that our results do not generalize without qualification but are nonetheless likely to be widely applicable. The specific functional forms we assume imply that $D''(E) > 0$ and $\partial^2 g(s,m) / \partial m \partial s = 0$. Thus, our results would be reinforced in the case where $\partial^2 g(s,m) / \partial m \partial s < 0$ but weakened in the case where $\partial^2 g(s,m) / \partial m \partial s > 0$, and nullified if $\partial^2 g(s,m) / \partial m \partial s \geq 0$ and $D''(E) = 0$.

4.2 Decentralized Implementation

Having identified the socially optimal level of maintenance effort for any given standard, let us now consider the penalty function required to induce first-best compliance in a decentralized setting. Suppose the state regulator uses the enforcement policy described in (7) above. Faced with this penalty function, each (risk-neutral) firm solves the following problem:

$$(13) \quad \min_m \mu m^2 + (1-m)[F - \phi(r-x)i]$$

where $i = 1$ if the firm is transboundary and $i = 0$ otherwise. The choice of m by a firm of type i is therefore given by

$$(14) \quad m_i(F, \phi) = \frac{F - \phi(r-x)i}{2\mu}$$

Let $\{F^*(s), \phi^*(s)\}$ denote the policy parameters required to implement the first-best compliance effort. It is straightforward to show that $\phi^*(s) = 0 \quad \forall s$, and

$$(15) \quad F^*(s) = \frac{2\mu\delta k(s+k)}{\mu + \delta k^2}$$

if $m^*(s) < 1$, and $F^*(s) = 2\mu$ if $m^*(s) = 1$. The key feature of this solution is that enforcement stringency should *not* vary with distance to the downwind border. This

reflects the fact that emissions discharged by a particular firm cause the same damage whether or not the firm's home state suffers the exposure to those emissions. Thus, optimal compliance effort should not vary with distance to the border, and nor should enforcement stringency.

Next consider the level of interstate pollution that arises in the first-best solution. The aggregate emissions to which a representative state is exposed is given by

$$(16) \quad E^*(s) = \int_0^1 [s + (1 - m^*(s))k] dx = \frac{\mu(s+k)}{\mu + \delta k^2}$$

and the amount of that exposure due to emissions discharged by its upwind neighbor is

$$(17) \quad E_T^*(s) = \int_0^r [1 - \theta(x)][s + (1 - m^*(s))k] dx = \frac{\mu(s+k)r}{3(\mu + \delta k^2)}$$

Taking the ratio $E_T^*(s)/E^*(s)$, we see that a fraction $r/3$ of the emissions to which a state is exposed are interstate emissions. This result is clearly not a general one; it relies directly on our assumption that firms are distributed uniformly across the state. However, two general points do emerge from this result. First, interstate pollution *per se* is not a bad thing. While each individual state would prefer not to suffer a transboundary emissions exposure, some interstate pollution is efficient for the federation as a whole. This simple point is sometimes over-looked in the policy debate. Second, even in a first-best world, a tighter emission standard will not necessarily reduce the *fraction* of a state's emissions exposure caused by interstate pollution. In the context of our model, for example, $E_T^*(s)/E^*(s)$ is entirely independent of s .

4.3 The First-Best Standard

The first-best standard is given by

$$(18) \quad s^* = \arg \min_s \left(\delta \left(\int_0^1 [s + (1 - m^*(s))k] dx \right)^2 + \int_0^1 [\mu m^*(s)^2 + \sigma(1-s)^2] dx \right)$$

where the first term in the objective function measures damage, and the second term measures the sum of maintenance costs and technology adoption costs. The

corresponding first-best compliance effort is given by $m^* = m^*(s^*)$. The complete solution is described in Proposition 2.¹⁹

Proposition 2

- (a) Suppose $\sigma \geq \delta k$. Then the first-best solution is an interior one, with $s^* \in (0,1)$ and $m^* \in (0,1)$, if and only if $\mu > \sigma \delta k / [\sigma + \delta]$, and a partial corner, with $s^* \in (0,1)$ and $m^* = 1$, otherwise.
- (b) Suppose $\sigma < \delta k$. Then the first-best solution is
- (i) a partial corner, with $s^* \in (0,1)$ and $m^* = 1$, if and only if $\mu \leq \sigma \delta k / [\sigma + \delta]$;
 - (ii) an interior one, with $s^* \in (0,1)$ and $m^* \in (0,1)$, if and only if $\mu > \sigma \delta k / [\sigma + \delta]$ and $\mu < \sigma \delta k^2 / [\delta k - \sigma]$; and
 - (iii) a partial corner, with $s^* = 0$ and $m^* \in (0,1)$, if and only if $\mu \geq \sigma \delta k^2 / [\delta k - \sigma]$.

This solution is illustrated in Figure 3 where $\{\sigma, \mu\}$ space is partitioned into three critical regions. If maintenance costs (as reflected in μ) are very low relative to the cost of tighter standards (as reflected in σ) – the lower right region in Figure 3 – then it is optimal to have fail-safe maintenance ($m = 1$) but a positive level of emissions under the standard ($s^* > 0$). Conversely, if σ is very low relative to μ – the upper left region in Figure 3 – then the first-best standard involves zero emissions but optimal maintenance is less than perfect. For intermediate cases – the shaded region in Figure 3 – the solution is an interior one with $s^* \in (0,1)$ and $m^* \in (0,1)$. This balancing of standard strictness and compliance effort according to the relative cost of each reflects their inherent substitutability in the minimization of total social cost (as discussed earlier in the context of Proposition 1).

¹⁹ Note that the first-best standard is uniform across firms because all firms in our model are identical except for their location. Any heterogeneity along a different margin – such as technology adoption costs – would of course mean that standards should differ across firms, but *not* on the basis of location.

5. EQUILIBRIUM ENFORCEMENT AND OPTIMAL FEDERAL POLICY

In this section we first characterize the non-cooperative equilibrium enforcement policy among states for any given federal standard, and show that states will enforce that standard less stringently for firms located near their downwind borders. We then derive the optimal federal standard in response to the equilibrium behaviour of states, and compare that standard to the first-best solution. Finally, we ask whether the federal regulator can obtain a better outcome by imposing location-based standards, whereby facilities located close to a downwind state border face a stricter emission standard.

5.1 Equilibrium Enforcement

The enforcement problem for each state is to choose a penalty function (parameterized by F and ϕ) to minimize within-state costs, taking as given the federally mandated standard s . That is, the representative state solves

$$(19) \quad \min_{F, \phi} \delta \left(\int_0^r \theta(x) g_1(s, F, \phi) dx + \int_r^1 g_0(s, F, \phi) dx + E_T \right)^2 \\ + \int_0^r \mu m_1(F, \phi)^2 dx + \int_r^1 \mu m_0(F, \phi)^2 dx$$

where $g_i(s, F, \phi) = s + [1 - m_i(F, \phi)]k$ is expected emissions discharged by a firm of type i , where $i = 1$ if the firm is transboundary and $i = 0$ otherwise. The first term in (19) represents damage to the state; the second and third terms represent maintenance costs for transboundary and inside firms respectively. (Technology adoption costs are not relevant to this problem since they are determined only by the emission standard, which is set by the federal agency). The emissions to which the state is exposed has three parts, corresponding to the three terms inside the damage function in (19). The first term measures exposure to emissions discharged by the state's own transboundary firms. The second term measures exposure to emissions from the state's own inside firms. The third term (E_T) measures emissions from out-of-state to which the state is exposed but over which it has no control.

The solution to (19) yields best response functions of the form $F(E_T)$ and $\phi(E_T)$ for a representative state. From these best response functions we can derive the

(symmetric) equilibrium value of E_T and the corresponding equilibrium solutions for F and ϕ . (See the proof of Proposition 3 in the Appendix for details). This equilibrium is unique but can take any one of three possible forms, depending on parameter values: a corner solution in which the equilibrium enforcement policy induces all firms to choose $m = 1$; a partial corner solution in which some firms choose $m = 1$ and other firms choose $m < 1$; and an interior solution in which all firms choose $m < 1$. For the remainder of the paper we focus exclusively on the interior equilibrium; analysis of the corner solutions yields no additional insights of interest.²⁰ The key properties of the interior equilibrium are described in Proposition 3.

Proposition 3

Let $\{\hat{F}(s), \hat{\phi}(s)\}$ denote the equilibrium enforcement policy for any given value of s , and suppose it is interior. Then

- (a) $\hat{\phi}(s) > 0$;
- (b) $\hat{F}(s) > F^*(s)$;
- (c) $\hat{F}(s) - \phi(s)(r - x) < F^*(s)$ for $x \in [0, \bar{x})$, where $\bar{x} \in (0, r)$; and
- (d) $\hat{F}(s) - \phi(s)(r - x) > F^*(s)$ for $x \in [\bar{x}, r)$.

These results are illustrated in Figure 4. First consider results (a) and (c). These results stem directly from the transboundary externality in this economy. Transboundary firms located closer to the downwind border impose a lower cost on their home state – relative to firms located further from the downwind border – because a fraction of their emissions flow into the neighboring state. Each state therefore sets an expected penalty for transboundary firms that rises with distance from the downwind border. Thus, $\hat{\phi}(s) > 0$. In contrast, the first-best penalty on transboundary firms – expression (15) in section 4.1 – is set to reflect the full social cost of non-compliance, which includes the

²⁰ In the Appendix we derive a necessary and sufficient condition for the equilibrium to be interior, and relate that condition to the region of the parameter space in which the first-best solution is interior. We show that if the first-best solution is interior then the equilibrium at the first-best standard will also be interior but the converse is not true. The reason for that lack of congruence will soon become clear.

cost imposed on the downwind neighboring state. Thus, for firms located *closest* to the downwind border – those transboundary firms for whom $x \in [0, \bar{x})$ – the equilibrium expected penalty is lower than first-best; that is, $\hat{F}(s) - \phi(s)(r - x) < F^*(s)$. This is result (c).

Why doesn't this lower penalty apply to *all* transboundary firms, including those for whom $x \in [\bar{x}, r)$? The answer lies in the fact that the externality in this economy is symmetric. The selective enforcement policy adopted by any given state is also adopted by its *upwind* neighboring state. This means that in equilibrium there will be a higher-than-first-best *inflow* of emissions discharged by firms in the upwind neighboring state who are located closest to the border. To compensate for this excessive inflow, each state must induce a *higher* level of compliance from its inside firms; thus, these firms face a higher-than-first-best penalty. This explains result (b). Continuity of the penalty function then means that the same compensating-enforcement adjustment must also be true for those transboundary firms located furthest from the downwind border – those for whom $x \in [\bar{x}, r)$. This explains result (d).²¹

The enforcement policy described in Proposition 3 will induce variation across firms in terms of compliance behavior. In particular, firms located closest to the downwind state border will undertake less compliance effort than firms located further from the border. Moreover, compliance effort will be too low for firms located closest to the downwind border – relative to the first-best compliance effort corresponding to the given standard – and compliance effort will be too high for firms located further away from the downwind border. We state these results more precisely in the following corollary to Proposition 3.

Corollary

Let $\hat{m}_0(s) \equiv m_0(\hat{F}(s), \hat{\phi}(s))$ and $\hat{m}_1(s, x) \equiv m_1(\hat{F}(s), \hat{\phi}(s))$ denote the equilibrium compliance effort by an inside firm and transboundary firm respectively. Then

²¹ Note from Figure 4 that the equilibrium penalty function does not pass through the origin even though there is no benefit to the state from eliciting positive compliance from the firm located exactly on the downwind border (at $x = 0$). This reflects the fact that a *linear* penalty function is not optimal in this setting. However, as noted earlier, this is not important for our main results.

- (a) $\hat{m}_1(s, x) < \hat{m}_0(s)$ and $\hat{m}'_1(x) > 0$, for $x < r$; and
- (b) $\hat{m}_1(s, x) < m^*(s)$ for $x \in [0, \bar{x})$, $\hat{m}_1(s, x) > m^*(s)$ for $x \in (\bar{x}, r)$, and $\hat{m}_0(s) > m^*(s)$.

This distortion of compliance effort in equilibrium has two impacts on social cost. First, marginal maintenance costs are not equated across firms, and so total compliance cost is not minimized, given the overall level of emissions discharged. Second, aggregate emissions are higher than is first-best – given the standard – and so too is the flow of emissions across state borders. Moreover, interstate emissions constitute a higher fraction of the emissions to which any state is exposed, relative to the first-best. These results on equilibrium emissions are summarized in Proposition 4.

Proposition 4

Suppose the equilibrium is interior. Let $\hat{E}(s)$ denote equilibrium aggregate emissions exposure in a given state, and let $\hat{E}_T(s)$ denote the equilibrium interstate emissions to which that state is exposed. Then

- (a) $\hat{E}(s) > E^*(s)$;
- (b) $\hat{E}_T(s) > E_T^*(s)$; and
- (c) $[\hat{E}_T(s) / \hat{E}(s)] > [E_T^*(s) / E^*(s)]$.

These results point to an interstate pollution problem. The problem is not the existence of interstate pollution *per se*, but rather that interstate pollution flows are too high given the standard and that consequently, emissions exposure overall is too high. In the sections that follow we ask what – if anything – the federal regulator can do to ameliorate this interstate pollution problem through its policy on standards.²²

²² While we have argued that enforcement behavior is difficult to monitor, one could argue that the federal regulator should be able to *infer* enforcement behavior from observable compliance rates, and that direct federal intervention in state enforcement policy should therefore be possible. Legal difficulties associated with proof by statistical inference are likely to prevent this in practice. In any case, we abstract from that possibility here and focus on the policy instrument over which the federal regulator has more direct control.

5.2 The Second-Best Emission Standard

The problem for the federal regulator is to minimize total social cost in a representative state, taking as given the equilibrium enforcement policy described in Proposition 3.

Thus, the regulatory problem is

$$(20) \quad \min_s \delta \left(\int_0^r g_1(s, \hat{F}(s), \hat{\phi}(s)) dx + \int_r^1 g_0(s, \hat{F}(s), \hat{\phi}(s)) dx \right)^2 \\ + \int_0^r \mu m_1(\hat{F}(s), \hat{\phi}(s))^2 dx + \int_r^1 \mu m_0(\hat{F}(s), \hat{\phi}(s))^2 dx + \int_0^1 \sigma(1-s)^2 dx$$

Note that each state is exposed to a fraction $\theta(x)$ of the emissions discharged by its own transboundary firms but is also exposed to a fraction $1 - \theta(x)$ of the emissions from transboundary firms located in its upwind neighboring state. The first term inside the damage function in (20) represents the *sum* of these two emissions in the symmetric equilibrium. The second term inside the damage function represents emissions from inside firms. The remaining terms in (20) measure maintenance and technology adoption costs respectively.

The key distinction between this problem and the central planning problem in (18) is the strategic interaction between the federal regulator and the states. The nature of that interaction is described in Lemma 1.

Lemma 1

$\hat{\phi}'(s) > 0$, $\hat{F}'(s) > 0$ and $\hat{P}'(s) > 0$, where $\hat{P} = \hat{F} - \hat{\phi}(r-x)$.

Lemma 1 states that a stricter standard (a *smaller* value of s) induces states to adopt a *flatter and lower* penalty function; that is, there is less enforcement discrimination across firms with respect to distance to the downwind border, but there is also less stringent enforcement overall. These two effects on equilibrium enforcement relate to our earlier discussion on the substitutability between more compliance effort and stricter standards. The results can be explained as follows. A tighter standard reduces the incremental damage from an equipment failure, and because damage is strictly convex in emissions, this reduces the marginal benefit of compliance effort for all firms. The state

therefore induces a lower level of compliance effort by setting a *lower* penalty for all firms. However, the impact of a stricter standard on the marginal benefit of compliance effort – from the perspective of the state – is smaller for transboundary firms because only a fraction of their emissions actually damage the home state. Thus, the reduction in the penalty for non-compliance – in response to a stricter standard – is more moderate for transboundary firms. The closer a firm is to the downwind border, the smaller is the reduction in penalty when a stricter standard is imposed. Thus, a stricter federal standard induces a *flatter* penalty function. These two effects on the equilibrium penalty function are illustrated in Figure 5, where the penalty function is drawn for two different arbitrary values of the standard, s and $s' < s$.

The relationship between the federal standard and the equilibrium enforcement policy described in Lemma 1 poses a dilemma for the federal regulator in addressing the interstate pollution problem: a stricter standard will reduce state enforcement discrimination based on nearness to the downwind border but this amelioration of enforcement discrimination comes at the cost of lower compliance overall. Can the federal regulator necessarily produce a better outcome overall by setting a standard stricter than the first-best standard?

The answer to this question can be gleaned from results (b) and (d) in Proposition 3. Recall from these results that the equilibrium penalty for inside firms, and for transboundary firms located furthest from the downwind border, is higher than the first-best penalty, for *any* given value of the standard – including the first-best standard. Thus, equilibrium compliance by these firms will be excessive – relative to m^* – if the federal regulator sets the standard at its first-best level. This gives the federal regulator some room to tighten the standard to address enforcement discrimination even though this action induces lower compliance overall. The second-best standard is therefore stricter than the first-best standard. This result is summarized in Proposition 5.

Proposition 5

Let \tilde{s} denote the optimal (second-best) federal standard. Then $\tilde{s} < s^*$.

The second-best policy described in Proposition 5 ameliorates the problem of excessive interstate pollution but does not eliminate it. Some enforcement discrimination persists – recall that Proposition 3(a) holds for any s – and the flow of interstate pollution is still higher than is first-best (since Proposition 4 also holds for any s). This raises a natural question: can the federal regulator achieve a better outcome by setting location-based standards tailored specifically to counteract lenient enforcement close to downwind state borders? We explore this question next.

5.3 Location-Based Standards

Suppose the federal regulator uses a standard-setting rule of the following form:

$$(21) \quad s = s_1 + \rho\lambda(x) \text{ if } x < r \text{ and } s = s_0 \text{ otherwise}$$

where ρ is an unrestricted parameter and $\lambda(x) > 0$ is any continuous function for which $\lambda'(x) > 0$. This policy rule allows a stricter standard – a lower value of s – to be applied to transboundary firms located closer to the downwind border. We will refer to s_0 and s_1 as “base standards” for inside and transboundary firms respectively, and to ρ as the “accentuation parameter”; a higher value of ρ accentuates the location-based variation built into $\lambda(x)$. Note that the standard-setting rule in (21) could be rewritten without ρ – by simply redefining $\lambda(x)$ – but this accentuation parameter will prove useful in the derivation and interpretation of results. We begin by describing the properties of the equilibrium enforcement policy induced by this standard-setting rule.

Lemma 2

- (a) $\hat{\phi}'(s_0) > 0$, $\hat{F}'(s_0) > 0$ and $\hat{P}'(s_0) > 0$, where $\hat{P} = \hat{F} - \hat{\phi}(r - x)$;
- (b) $\hat{\phi}'(s_1) > 0$, $\hat{F}'(s_1) > 0$ and $\hat{P}'(s_1) > 0$; and
- (c) $\hat{\phi}'(\rho) > 0$, $\hat{F}'(\rho) > 0$ and $\hat{P}'(\rho) > 0$.

Results (a) and (b) in Lemma 2 are analogous to Lemma 1 and reflect exactly the same factors discussed in the explanation of that result. Result (c) in Lemma 2 pertains more specifically to location-based standards. This result states that an accentuation of

the location-based variation in standards assigned to transboundary firms – an increase in ρ – induces a *steeper and higher* equilibrium penalty function. That is, there is more discrimination across firms with respect to enforcement stringency, and firms further from the downwind border face a higher penalty, than under a federal policy in which standards are not location-based. Thus, the imposition of location-based standards exacerbates the distortion in equilibrium enforcement. This effect arises because states try to *neutralize* the impact of location-based standards by adopting a more discriminatory enforcement policy.

This neutralization of the federal policy is not complete, because compliance effort and strict standards are not perfect substitutes. Discriminatory enforcement is costly for states because some of the emissions discharged by transboundary firms do affect the home state, and these emissions rise when compliance falls among these firms. Thus, an increase in ρ does reduce equilibrium interstate emissions to some extent, for given values of s_0 , s_1 and $f(x)$. However, the partial neutralization of the federal policy seriously limits the efficacy of location-based standards as an instrument for reducing interstate pollution flows.

This shortcoming of location-based standards is compounded by an additional distortion that this policy introduces into the regulatory outcome: marginal technology adoption costs are not equated across firms. This means that aggregate technology adoption costs are excessively high for the overall level of aggregate emissions actually achieved when the federal regulator uses location-based standards. This inflation of costs is in addition to that associated with the distortion of compliance efforts across firms. A simpler policy of setting the same standard for all firms – regardless of location – does not have this drawback. Moreover, such a policy ameliorates rather than exacerbates the enforcement distortion. It follows that location-based standards are *not* an optimal policy for the federal regulator. Proposition 6 states this result more formally.

Proposition 6

Let $\{\tilde{s}_0, \tilde{s}_1, \tilde{\rho}\}$ denote the optimal (second-best) policy when the federal regulator uses the standard-setting rule in (18). Then $\tilde{s}_0 = \tilde{s}_1 = \tilde{s}$ and $\tilde{\rho} = 0$ for *any* function $\lambda(x) > 0$ for

which $\lambda'(x) > 0$. That is, the optimal federal policy is a common standard for all firms regardless of location.

6. CONCLUSION

This paper has explored the relationship between interstate air pollution and the division of control between federal and state agencies in setting and enforcing standards. In the context of the CAA, we have argued that the EPA is able to monitor the adoption of technology-based standards more closely than it can monitor state-level enforcement, and that this causes an effective division of control between the two levels of government.

Our model is based on particular assumptions and specific functional forms that facilitate tractability in an otherwise complicated setting, and as noted in section 4.1, many of our specific results do not generalize to every plausible setting. However, our analysis offers three insights into the interstate pollution problem that we believe are of significant policy interest. First, states have an incentive to enforce standards less stringently on firms located close to downwind borders, and this leads to excessive interstate pollution in equilibrium. Second, substitutability between strict standards and compliance effort in the regulatory problem – most likely when damage is strictly convex in emissions – creates a strategic linkage between the federal policy on standards and state policies on enforcement. In particular, a stricter standard can induce less selective enforcement but can also lead to less enforcement overall. A stricter-than-first-best standard can therefore only go part way to addressing the enforcement distortion and the associated interstate pollution problem. Third, states will attempt to neutralize the impact of location-based federal standards (that specifically target interstate pollution) in a way that can actually exacerbates the underlying selective enforcement problem. Thus, location-based standards are not an optimal federal policy.

APPENDIX

Proof of Proposition 1

The first-order condition for (8) yields

$$(A1) \quad m^*(s) = \frac{\delta(s+k)k}{\delta k^2 + \mu}$$

The solution in (A1) is less than one if and only if $\mu > \delta k s$. To obtain the second part of (b), differentiate (A1) with respect to s to obtain

$$(A2) \quad m^{*'}(s) = \frac{\delta k}{\delta k^2 + \mu} > 0.$$

Proof of Proposition 2

The first-order condition for (18) yields

$$(A3) \quad s^* = \frac{\sigma \delta k^2 + \mu(\sigma - \delta k)}{\sigma \delta k^2 + \mu(\sigma + \delta)}$$

Substituting (A3) into (A1) then yields

$$(A4) \quad m^* = \frac{\sigma \delta k(1+k)}{\sigma \delta k^2 + \mu(\sigma + \delta)}$$

The solution boundaries reported in Proposition 2 then follow directly from these expressions.

Proof of Proposition 3

Differentiating (19) with respect to F and ϕ yields best response functions given by

$$(A5) \quad F(s, E_T) = \alpha_F [(3-r)(s+k) + 3E_T]$$

where

$$(A6) \quad \alpha_F = \frac{4\mu\delta k(24-17r)}{\delta k^2(52r^2-177r+144)+12(12-9r)} > 0 \quad \text{since } r \leq 1, \text{ and}$$

$$(A7) \quad \phi(s, E_T) = \alpha_\phi [(3-r)(s+k) + 3E_T]$$

where

$$(A8) \quad \alpha_\phi = \frac{24\mu\delta k(3-2r)}{r[\delta k^2(52r^2-177r+144)+12(12-9r)]} > 0 \quad \text{since } r \leq 1.$$

Substituting (A5) and (A7) into (14) for $i=0$ and $i=1$ yields

$$(A9) \quad m_0(s, E_T) = \frac{F(s, E_T)}{2\mu} \quad \text{and}$$

$$(A10) \quad m_1(s, E_T, x) = \frac{F(s, E_T) - \phi(s, E_T)(r-x)}{2\mu}$$

respectively. The expected emissions discharged by an inside firm and a transboundary firm are then given by (A11) and (A12) respectively:

$$(A11) \quad g_0(s, E_T) = s + [1 - m_0(s, E_T)]k$$

$$(A12) \quad g_1(s, E_T, x) = s + [1 - m_1(s, E_T, x)]k$$

Using (A12) we can derive the total emissions discharged by transboundary firms (in a representative state) that flow across the downwind state border:

$$(A13) \quad G_T(s, E_T) = \int_0^r [1 - \theta(x)]g_1(s, E_T, x)dx$$

In the symmetric Nash equilibrium, $G_T(s, E_T) = E_T$. Making this substitution in (A13) and solving for E_T yields the interior equilibrium value of interstate emissions:

$$(A14) \quad \hat{E}_T = \frac{r(s+k)[\delta k^2(3-2r)^2 + 4\mu(4-3r)]}{4(4-3r)[\delta k^2(3-r) + 3\mu]}$$

Substituting (A14) into (A7) then yields

$$(A15) \quad \hat{\phi}(s) = \frac{6\mu\delta k(s+k)(3-2r)}{r(4-3r)[\delta k^2(3-r) + 3\mu]}$$

from which it follows that $\hat{\phi}(s) > 0$ since $r \leq 1$. This proves part (a). Substituting (A14) into (A5) yields

$$(A16) \quad \hat{F}(s) = \frac{\mu\delta k(s+k)(24-17r)}{(4-3r)[\delta k^2(3-r) + 3\mu]}$$

Using (14) we then have

$$(A17) \quad \hat{F}(s) - F^*(s) = \frac{r\mu\delta k(s+k)[\delta k^2(9-6r) + \mu]}{(4-3r)(\delta k^2 + \mu)[\delta k^2(3-r) + 3\mu]}$$

which is positive since $r \leq 1$. This proves part (b). Evaluating $\hat{F}(s) - \phi(s)[r-x] - F^*(s)$ at $x=0$ yields

$$(A18) \quad -\frac{\mu\delta k(s+k)[3\delta k^2(9-6r)(2-r) + \mu(18-13r)]}{(4-3r)(\delta k^2 + \mu)[\delta k^2(3-r) + 3\mu]} < 0$$

Since $\hat{F}(s) - \phi(s)[r-x] - F^*(s) > 0$ at $x = r$, results (c) and (d) follow by continuity.

Conditions for an Interior Equilibrium

Substituting (A14) into (A9) and (A10) yields the equilibrium compliance effort by an inside firm and transboundary firm respectively:

$$(A19) \quad \hat{m}_0(s) = \frac{\delta k(s+k)(24-17r)}{2(4-3r)[\delta k^2(3-r) + 3\mu]}$$

$$(A20) \quad \hat{m}_1(s, x) = \frac{\delta k(s+k)[(6-5r) + 6x(3-2r)]}{2r(4-3r)[\delta k^2(3-r) + 3\mu]}$$

It is straightforward to show that $\hat{m}_0 > \hat{m}_1$ for $x < r$. Thus, if $\hat{m}_0 < 1$ then $\hat{m}_1 < 1$.

Moreover, $\hat{m}_1 > 0 \quad \forall x \geq 0$. It follows that a necessary and sufficient condition for an interior equilibrium is $\hat{m}_0 < 1$. Using (A19), that condition is

$$(A21) \quad \mu > \frac{\delta k[s(24-17r) + 3kr(3-2r)]}{6(4-3r)}$$

To interpret this condition it is helpful to evaluate s at its first-best level, s^* . This will tell us the conditions under which the equilibrium will be interior if the federal regulator were to set the standard at s^* . If $s^* = 0$ then (A21) becomes

$$(A22) \quad \mu > \frac{r\delta k^2(3-2r)}{2(4-3r)}$$

Conversely, if $s^* \in (0,1)$ then setting $s = s^*$ from (A3) in (A21) yields a condition of the form

$$(A23) \quad \mu > h(\sigma, r)$$

where $h(\sigma, r)$ is too cumbersome to report here but has the following properties:

$$(A24) \quad h'(\sigma) > 0 \text{ and } h'(r) > 0$$

$$(A25) \quad h(\sigma, r) = \sigma\delta k / [\sigma + \delta] \text{ at } r = 0 \text{ and } h(\sigma, r) > \sigma\delta k / [\sigma + \delta] \text{ for all } r > 0$$

$$(A26) \quad h(\sigma, r) = \sigma\delta k^2 / [\delta k - \sigma] \text{ at } \sigma = 0, h(\sigma, r) > \sigma\delta k^2 / [\delta k - \sigma] \text{ for } 0 < \sigma < \bar{\sigma},$$

$$h(\sigma, r) = \sigma\delta k^2 / [\delta k - \sigma] = r\delta k^2(3-2r) / [2(4-3r)] \text{ at } \sigma = \bar{\sigma}, \text{ and}$$

$$h(\sigma, r) < \sigma\delta k^2 / [\delta k - \sigma] \text{ for } \sigma > \bar{\sigma}, \text{ where } \bar{\sigma} \equiv r\delta k(3-2r) / (8-3r-2r^2)$$

Conditions (A22) and (A23) are illustrated in Figure A1. The lighter shaded area in Figure A1 depicts the region in which the equilibrium is interior when $s = s^*$. Note by comparing Figure A1 with Figure 3 that the equilibrium is interior only if the first-best compliance effort is also interior; that is, if $m^* \in (0,1)$. However, the converse is not true; the darker shaded area in Figure A1 depicts the region in which $m^* \in (0,1)$ but the equilibrium is *not* interior when $s = s^*$. This region vanishes as r falls towards zero; the $\mu = h(\sigma, r)$ boundary pivots down and condition (A22) becomes less restrictive (so the critical value on the vertical axis falls towards zero). This is as expected; the first-best solution and the equilibrium coincide when $r = 0$ because there is no transboundary externality in that case.

Proof of Proposition 4

Aggregate emissions discharged within a state in equilibrium is given by

$$(A27) \quad \hat{G}(s) = \int_0^r \hat{g}_1(s, x) dx + \int_r^1 \hat{g}_0(s) dx = \frac{3(s+k)\mu}{\delta k^2(3-r) + 3\mu}$$

where $\hat{g}_1(s, x) = s + [1 - \hat{m}_1(s, x)]k$ and $\hat{g}_0(s) = s + [1 - \hat{m}_0(s)]k$. In symmetric equilibrium, $\hat{E}(s) = \hat{G}(s)$. Aggregate emissions discharged within a state when $m = m^*$ for all firms is given by

$$(A28) \quad G^*(s) = \int_0^1 g^*(s) dx = \frac{\mu(s+k)}{\delta k^2 + \mu}$$

where $g^*(s) = s + [1 - m^*(s)]k$ and $m^*(s)$ is given by (A1), noting that if the equilibrium is interior then so too is the first-best solution. Given state symmetry, $E^*(s) = G^*(s)$. It then follows from (A27) and (A28) that

$$(A29) \quad \hat{E}(s) - E^*(s) = \frac{r\mu\delta k^2(s+k)}{(\delta k^2 + \mu)[\delta k^2(3-r) + 3\mu]}$$

which is strictly positive since $r \leq 1$. This proves part (a).

Emissions discharged within a state that cross the downwind border in equilibrium is given by

$$(A30) \quad \hat{G}_T(s) = \int_0^r [1 - \theta(x)] \hat{g}_1(s, x) dx = \frac{r(s+k)[\delta k^2(3-2r)^2 + 4\mu(4-3r)]}{4(4-3r)[\delta k^2(3-r) + 3\mu]}$$

In symmetric equilibrium, $\hat{E}_T(s) = \hat{G}_T(s)$. Emissions discharged within a state that cross the downwind border when $m = m^*$ for all firms is given by

$$(A31) \quad G_T^*(s) = \int_0^r [1 - \theta(x)] g^*(s) dx = \frac{r(s+k)\mu}{3(\delta k^2 + \mu)}$$

Given state symmetry, $E_T^*(s) = G_T^*(s)$. It then follows from (A30) and (A31) that

$$(A32) \quad \hat{E}_T(s) = E_T^*(s) = \frac{r\delta k^2(s+k)[3\delta k^2(3-2r)^2 + \mu(27-20r)]}{12(4-3r)(\delta k^2 + \mu)[\delta k^2(3-r) + 3\mu]}$$

which is strictly positive since $r \leq 1$. This proves part (b).

From (A31) and (A28) we have

$$(A33) \quad E_T^*(s) / E^*(s) = \frac{r}{3}$$

From (A30) and (A27) we have

$$(A34) \quad \hat{E}_T(s) / \hat{E}(s) = \frac{r}{3} + \frac{r\delta k^2(3-2r)^2}{12\mu(4-3r)}$$

which is greater than $r/3$. This proves part (c).

Proof of Lemma 1

From (A15),

$$(A35) \quad \hat{\phi}'(s) = \frac{6\mu\delta k(3-2r)}{r(4-3r)[\delta k^2(3-r) + 3\mu]} > 0 \text{ since } r \leq 1$$

and from (A16),

$$(A36) \quad \hat{F}'(s) = \frac{\mu\delta k(24-17r)}{(4-3r)[\delta k^2(3-r) + 3\mu]} > 0 \text{ since } r \leq 1$$

Then using (A35) and (A36) we have

$$(A37) \quad \hat{P}'(s) = \frac{\mu\delta k[r(6-5r) + 6x(3-2r)]}{r(4-3r)[\delta k^2(3-r) + 3\mu]} > 0 \text{ since } r \leq 1$$

Proof of Proposition 5

Let $C(s)$ denote the objective function in (20). Differentiate $C(s)$ with respect to s and evaluate at $s = s^*$ from (A3) to yield

$$(A38) \quad C'(s^*) = \frac{r\sigma\mu\delta^2k^2(k+1)[3\delta k^2(3-2r)^2 + \mu(27-20r)]}{2(4-3r)[\delta k^2(3-r) + 3\mu]^2[\sigma\delta k^2 + \mu(\sigma + \delta)]}$$

which is strictly positive. Since $C(s)$ is strictly convex in s , and since $C'(\tilde{s}) = 0$, it follows that $\tilde{s} < s^*$.

Proof of Lemma 2

The enforcement problem for a representative state when facing standards of the form in (21) is

$$(A39) \quad \min_{F, \phi} \delta \left(\int_0^r \theta(x) g_1(s_0, s_1, \rho, F, \phi) dx + \int_r^1 g_0(s_0, s_1, \rho, F, \phi) dx + E_T \right)^2 + \int_0^r \mu m_1(F, \phi)^2 dx + \int_r^1 \mu m_0(F, \phi)^2 dx$$

where $g_i(s_0, s_1, \rho, F, \phi) = s_i + \rho\lambda(x)i + [1 - m_i(F, \phi)]k$. The solution to (A39) yields best response functions of the form

$$(A40) \quad F(s_0, s_1, \rho, E_T) = \beta_{F0} + \beta_{F1}s_0 + \beta_{F2}s_1 + \beta_{F3}E_T + \beta_{F4} \int_0^r \rho(2r-x)x\lambda(x)dx$$

where $\beta_{F0} = (3-r)k\gamma_F > 0$, $\beta_{F1} = 3(1-r)\gamma_F > 0$, $\beta_{F2} = 2r\gamma_F > 0$, $\beta_{F3} = 3\gamma_F > 0$, $\beta_{F4} = 3\gamma_F / r^2 > 0$ and

$$(A41) \quad \gamma_F = \frac{4\mu\delta k(24-17r)}{\delta k^2(5r^2-177r+144) + 36\mu(4-3r)} > 0, \text{ and}$$

$$(A42) \quad \phi(s_0, s_1, \rho, E_T) = \beta_{\phi0} + \beta_{\phi1}s_0 + \beta_{\phi2}s_1 + \beta_{\phi3}E_T + \beta_{\phi4} \int_0^r \rho(2r-x)x\lambda(x)dx$$

where $\beta_{\phi0} = 3(3-r)k\gamma_\phi / r > 0$, $\beta_{\phi1} = 3(1-r)\gamma_\phi / r > 0$, $\beta_{\phi2} = 2\gamma_\phi > 0$, $\beta_{\phi3} = 3\gamma_\phi / r > 0$, $\beta_{\phi4} = 3\gamma_\phi / r^3 > 0$ and

$$(A43) \quad \gamma_\phi = \frac{24\mu\delta k(3-2r)}{\delta k^2(5r^2-177r+144) + 36\mu(4-3r)} > 0$$

Following the same procedure as described in the proof of Proposition 3, (A40) and (A42) can be used to solve for the equilibrium enforcement policy:

$$(A44) \quad \hat{\phi}(s_0, s_1, \rho) = \omega_\phi [(1-r)s_0 + rs_1 + k + \rho \int_0^r \lambda(x) dx] \quad \text{where}$$

$$(A45) \quad \omega_\phi = \frac{6\mu\delta k(3-2r)}{r(4-3r)[(3-r)\delta k^2 + 3\mu]} > 0, \quad \text{and}$$

$$(A46) \quad \hat{F}(s_0, s_1, \rho) = \omega_F [(1-r)s_0 + rs_1 + k + \rho \int_0^r \lambda(x) dx] \quad \text{where}$$

$$(A47) \quad \omega_F = \frac{\mu\delta k(24-17r)}{(4-3r)[(3-r)\delta k^2 + 3\mu]} > 0$$

Note that

$$(A48) \quad \omega_F - \omega_\phi(r-x) = \frac{\mu\delta k[r(6-5r) + 6x(3-2r)]}{r(4-3r)[\delta k^2(3-r) + 3\mu]} > 0$$

Parts (a) – (c) of Lemma 2 follow directly from (A44), (A46) and (A48).²³

Sketch Proof of Proposition 6

Compliance effort levels under the equilibrium enforcement policy are given by

$$(A49) \quad \hat{m}_0(s_0, s_1, \rho) = \frac{\hat{F}(s_0, s_1, \rho)}{2\mu} \quad \text{and}$$

$$(A50) \quad \hat{m}_1(s_0, s_1, \rho, x) = \frac{\hat{F}(s_0, s_1, \rho) - \hat{\phi}(s_0, s_1, \rho)(r-x)}{2\mu}$$

for inside firms and transboundary firms respectively. The corresponding emission levels are

$$(A51) \quad \hat{g}_0(s_0, s_1, \rho) = s_0 + [1 - \hat{m}_0(s_0, s_1, \rho)]k \quad \text{and}$$

$$(A52) \quad \hat{g}_1(s_0, s_1, \rho, x) = s_1 + \rho f(x) + [1 - \hat{m}_1(s_0, s_1, \rho, x)]k$$

Now suppose $\lambda(x)$ is given. Then the policy problem for the federal regulator is

$$(A53) \quad \min_{s_0, s_1, \rho} \delta \left(\int_0^r \hat{g}_1(s_0, s_1, \rho, x) dx + \int_r^1 \hat{g}_0(s_0, s_1, \rho) dx \right)^2$$

²³ Note that if $s_0 = s_1$ and $\rho = 0$ – that is, if standards are uniform – then (A44) and (A46) reduce to (A15) and (A16) respectively.

$$\begin{aligned}
& + \int_0^r \mu \hat{m}_1(s_0, s_1, \rho, x)^2 dx + \int_r^1 \mu \hat{m}_0(s_0, s_1, \rho)^2 dx \\
& + \int_0^r \sigma [1 - s_1 - \rho \lambda(x)]^2 dx + \int_r^1 \sigma (1 - s_0)^2 dx
\end{aligned}$$

The first-order conditions for this problem are long and complicated. We used *Maple 10* to find the solution. (The programming code is available from the authors). The solution is $\tilde{s}_0 = \tilde{s}_1 = \tilde{s}$ and $\tilde{\rho} = 0$ for *any* function $\lambda(x)$ for which $\lambda(x) > 0$ and $\lambda'(x) > 0$.

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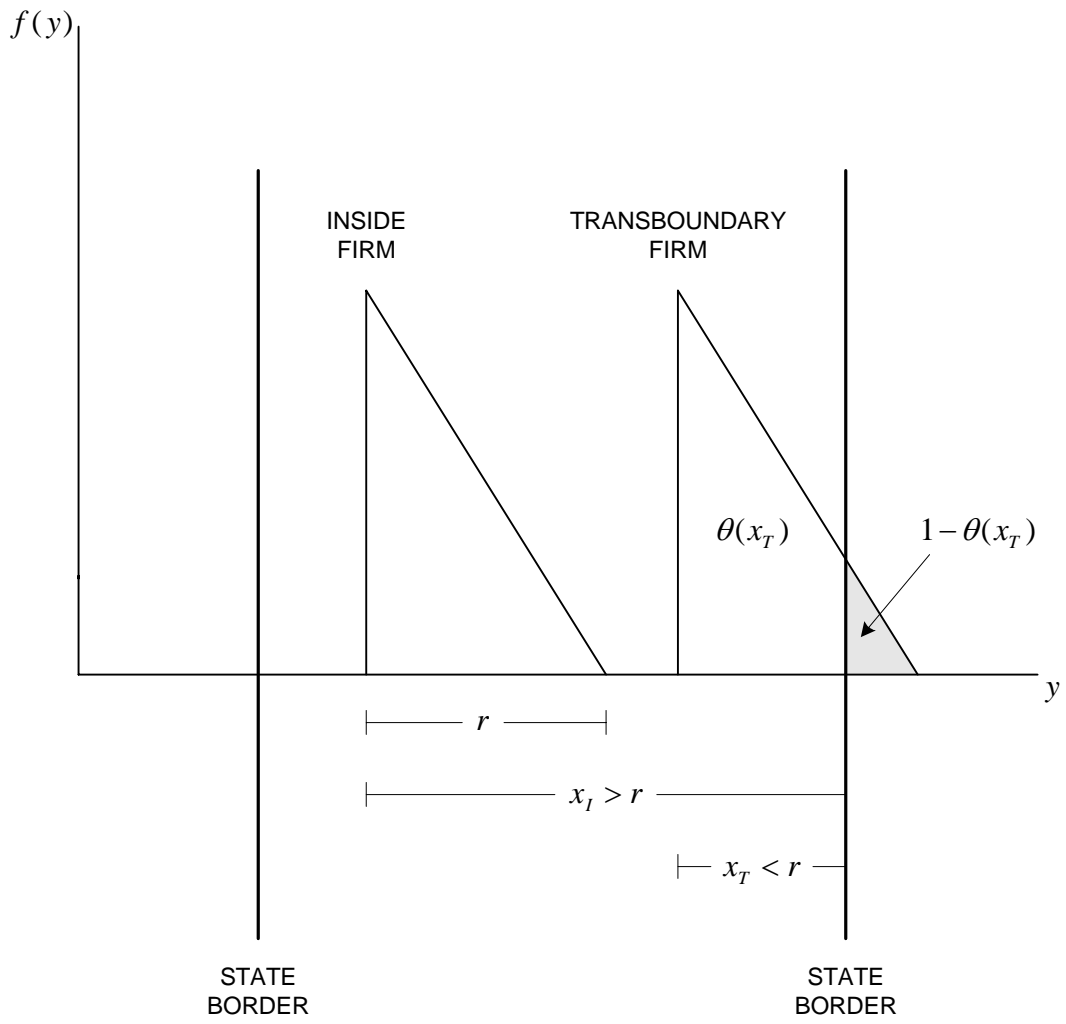


FIGURE 1

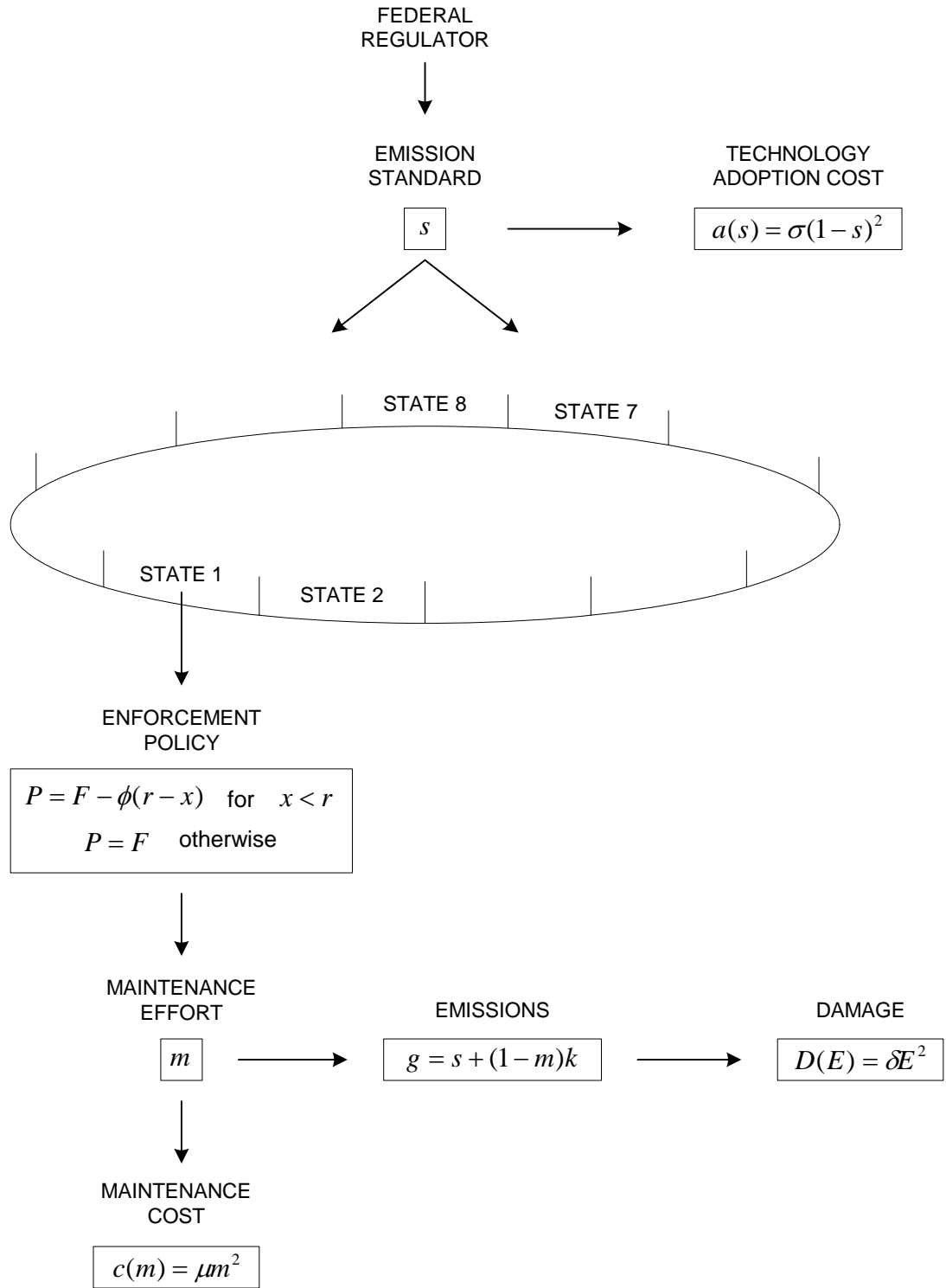


FIGURE 2

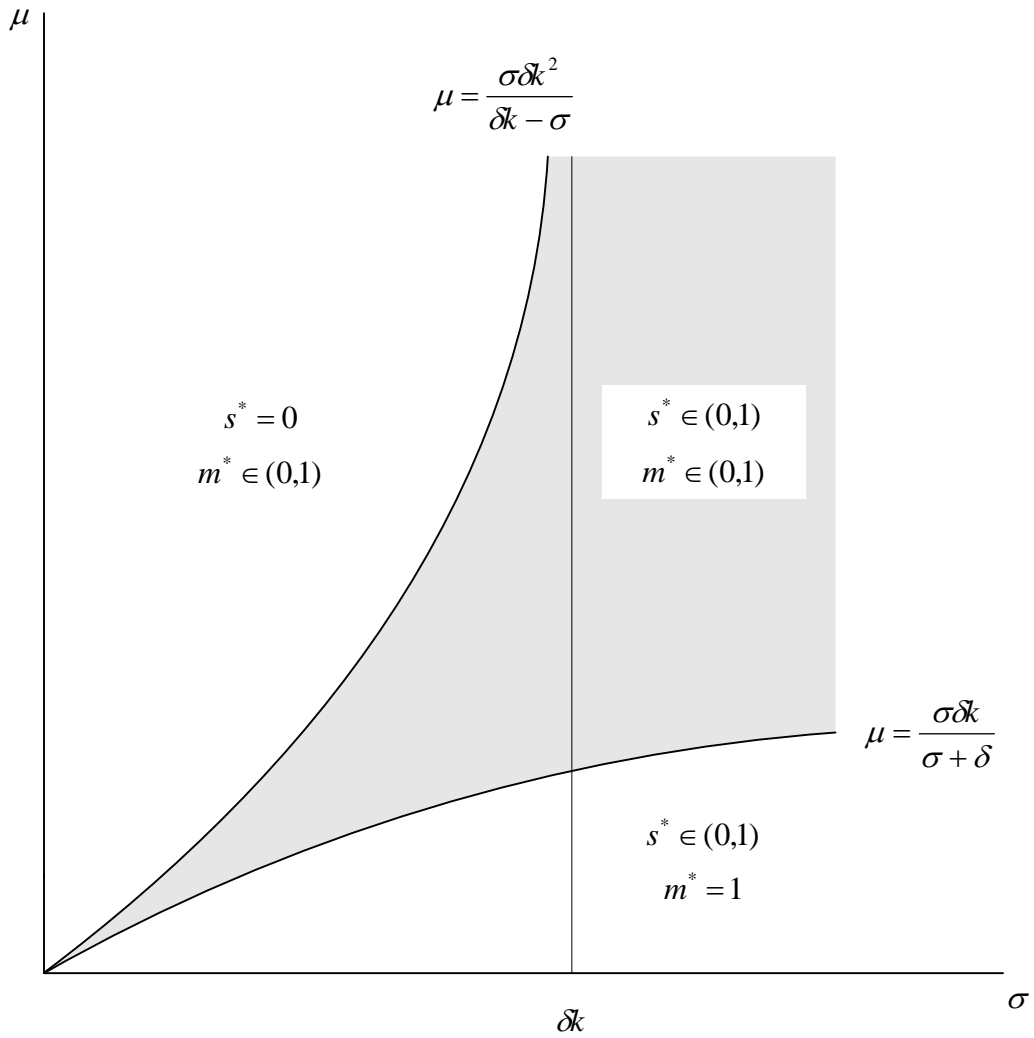


FIGURE 3

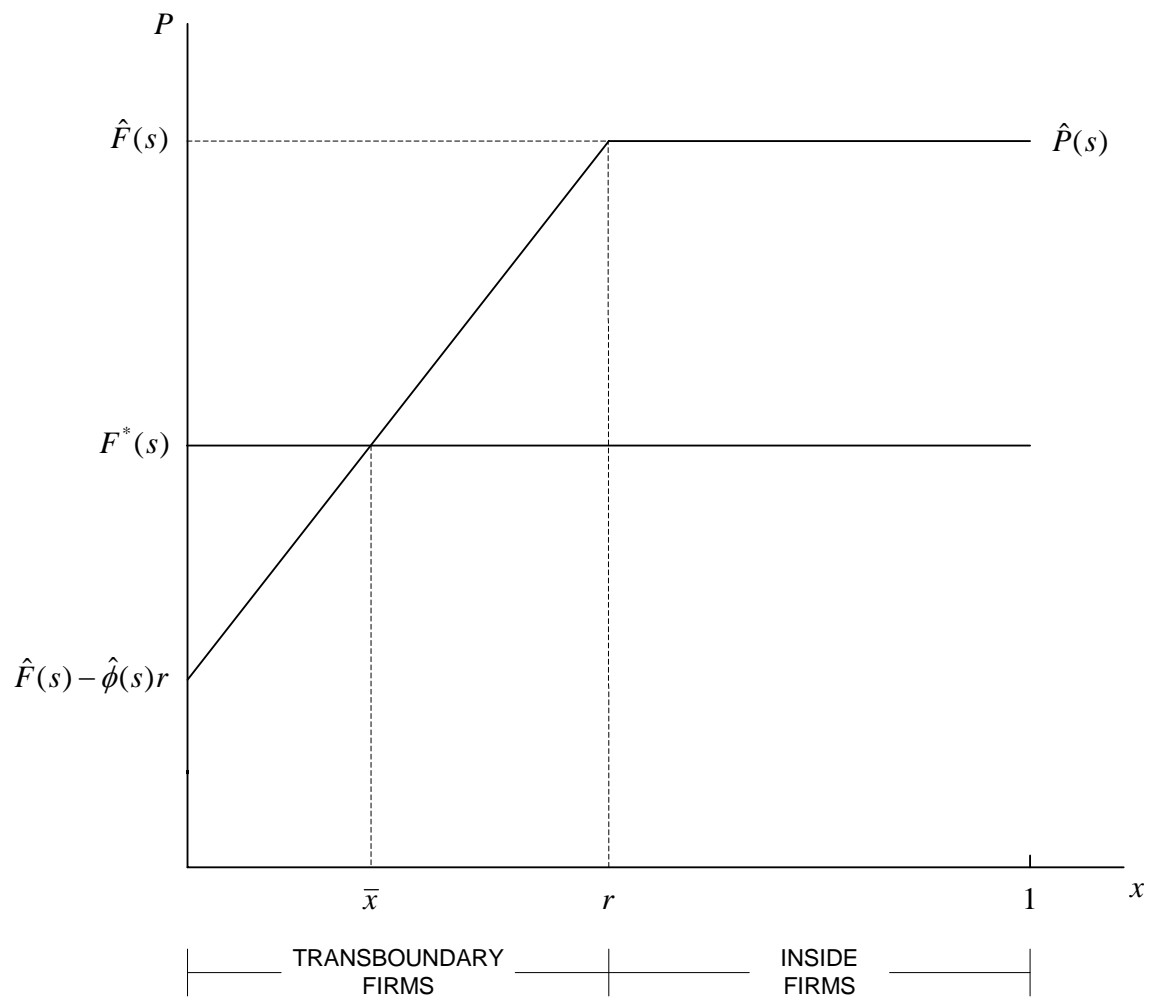


FIGURE 4

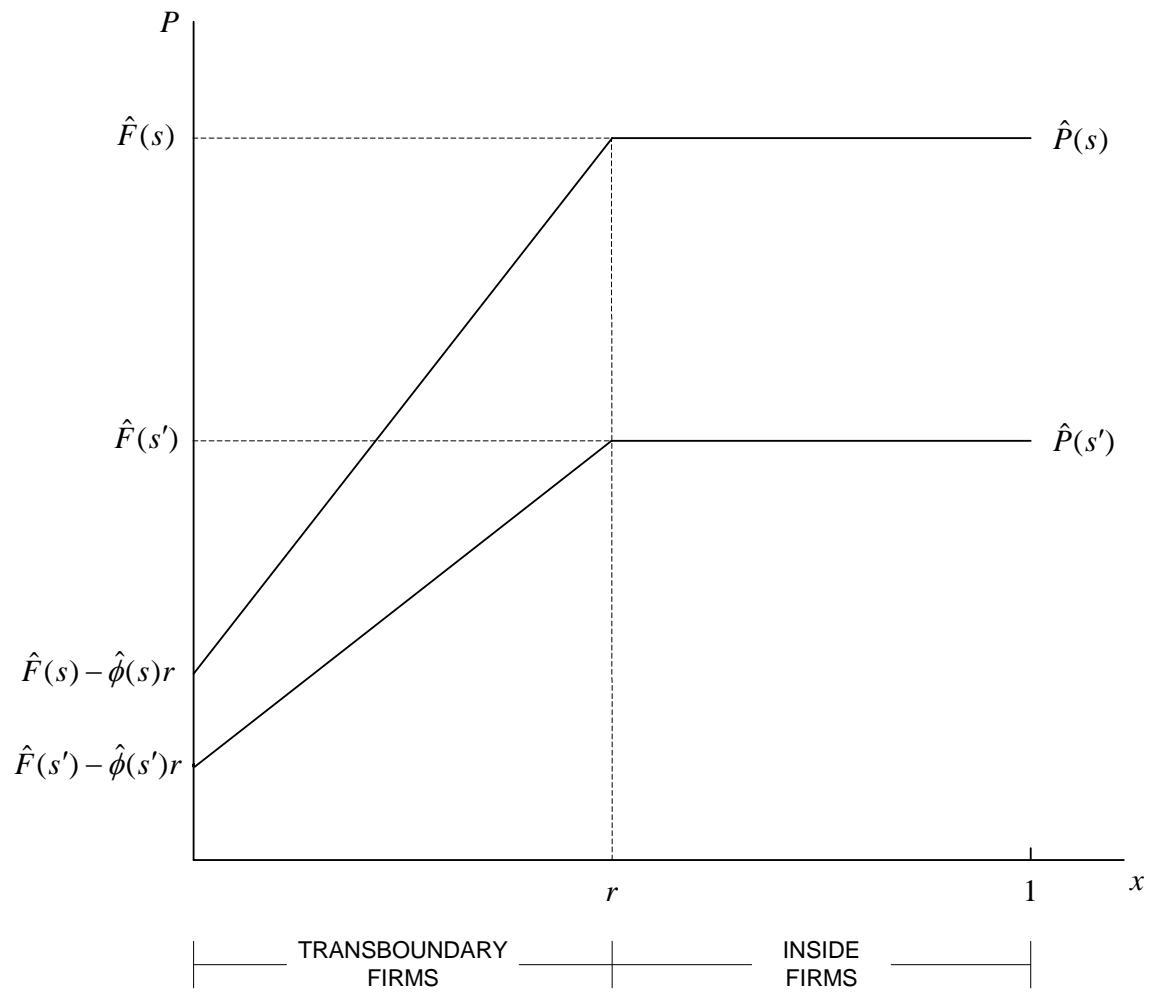


FIGURE 5

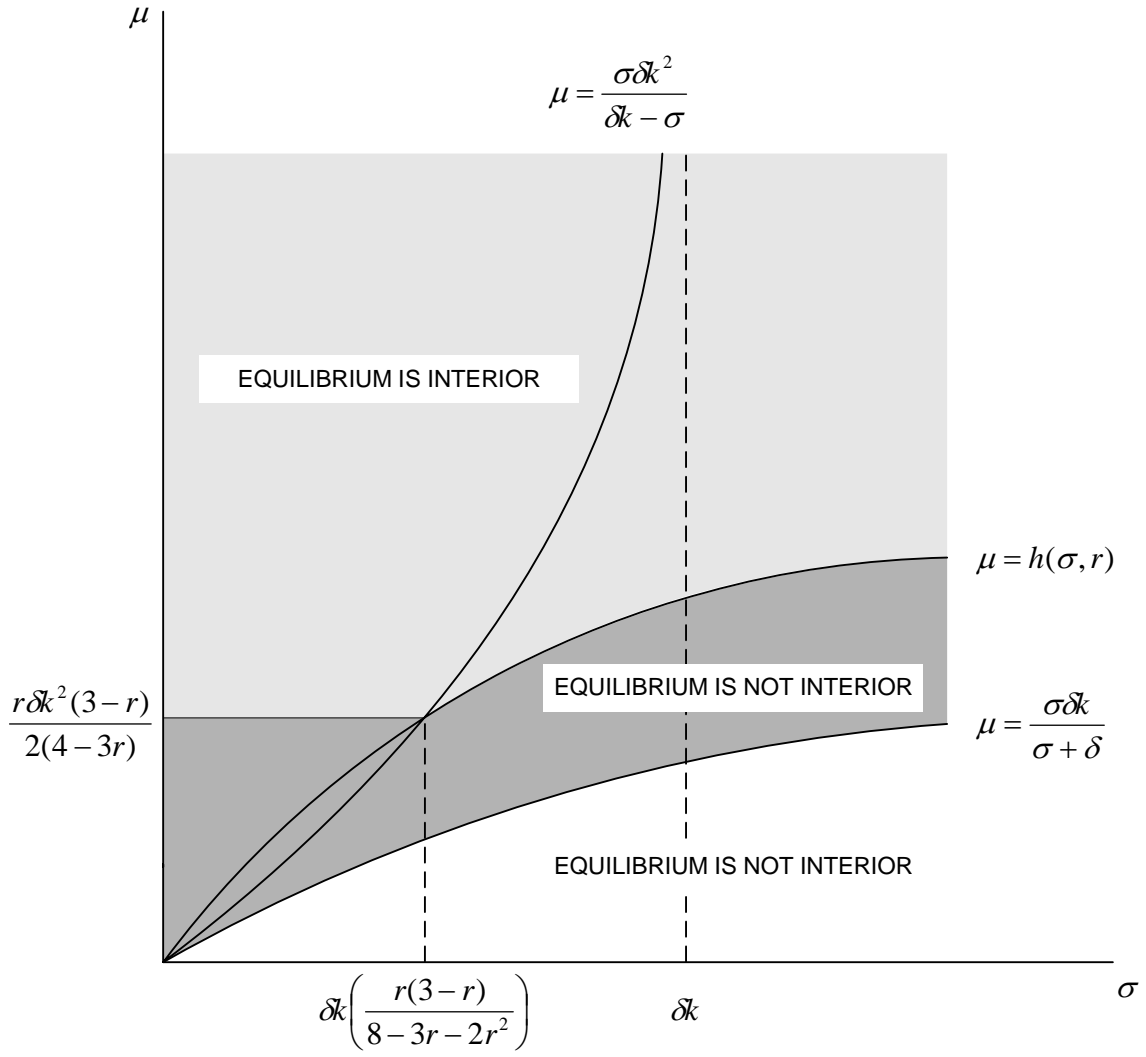


FIGURE A1