Emissions Standards and Ambient Environmental Quality Standards in Stochastic Receiving Media

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Abstract

Many important environmental policies involve some combination of emission controls and ambient environmental quality standards, for instance SO_2 emissions are capped under Title IV of the U.S. Clean Air Act Amendments while ambient SO_2 concentrations are limited under National Ambient Air Quality Standards (NAAQS). This paper examines the relative performance of emissions standards and ambient standards in stochastic environmental media. For environmental media characterized by greater dispersion in receiving ability, the optimal emissions policy becomes more stringent, while the optimal ambient policy often becomes more lax. In terms of economic performance, emissions policies are superior to ambient policies for relatively non-toxic pollutants when damage functions are not highly convex, whereas ambient standards welfare dominate emissions standards for sufficiently toxic pollutants. In the case of combined policies that jointly implement emissions standards and ambient standards, we show that the optimal level of each standard relaxes relative to its counterpart in a unilateral policy, allowing for greater emissions levels and higher pollution concentrations in the environmental medium.

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1 Introduction

Most industrial countries adopt environmental policies that involve some combination of emissions controls and ambient environmental quality standards. Ambient standards, which set limits on allowable pollution concentrations in the receiving environmental media, have been implemented in the United States since at least the U.S. Rivers and Harbors Act of 1899, and currently serve as the backbone of U.S. environmental policy through limits on allowable pollution concentrations codified in the National Ambient Air Quality Standards (NAAQS) of the Clean Air Act and Water Quality Standards (WQS) of the Clean Water Act.[1] At the same time, the trend in environmental policy over the last several decades has been towards the use of market-based emissions controls, typically through cap and trade systems on pollution. This recent gravitation of environmental policy towards emission controls has led in many cases to overlapping policies that combine ambient standards with emissions standards on common pollutants. For example, the U.S. cap and trade programs for sulfur dioxide (SO_2) and for nitrogen oxides (NO_x) currently operate in conjunction with ambient standards on SO_2 and NO_x concentrations under NAAQS.[2]

The joint use of ambient standards and emissions standards for pollution control problems has emerged as an important policy issue under the EPA's new

[1] The NAAQS set allowable pollution concentrations for six so-called "criteria pollutants" –Carbon Monoxide (CO), Nitrogen oxides (NO_x), Ozone (O_3), Lead (Pb), Sulfur Dioxide (SO_2), and Particulate matter (PM_{10} and $PM_{2.5}$)– and specify both an acceptable annual mean concentration and a maximum concentration in a given interval of time, generally the second highest 24-hour period each year. For more details on the requirements of the U.S. Clean Air Act, see Lester Lave and Gilbert Omenn (1981) and Richard Liroff (1986).

[2] On June 2, 2010, the U.S. EPA replaced the NAAQS primary standard for SO_2 from an annual average ambient concentration limit of 30 parts per billion (ppb) and 24-hour average concentration limit of 140 ppb with a more stringent 1-hour standard of 75 ppb on ambient SO_2 concentrations. The cap and trade system for SO_2 currently limits annual emissions among electric utilities to 8.95 million tons under Title IV of the Clean Air Act Amendments of 1990.

order, the so-called ‘Transport Rule’. The Transport Rule, proposed by EPA on June 2, 2010 to address ambient air quality in 31 eastern states and the District of Columbia, curtails one of the greatest advantages of market-based emissions policies –trading– by removing earlier provisions in the Clean Air Interstate Rule (CAIR) that permitted emissions sources to trade SO_2 and NO_x allowances across state lines. Given the long-standing prevalence of ambient standards in over a century of U.S. environmental policy, it is surprising to note that the economic performance of ambient standards and the optimal design of policies that jointly implement ambient standards and emissions standards are subjects that have received little attention to date.

In this paper we consider environmental policy design in settings where both emissions and ambient policy instruments are available. Our observations are framed around a point source of pollution, say a firm, that releases emissions into a stochastic environmental medium characterized by a continuum of receiving conditions, for example a river with variable streamflow. Social damages depend on pollution concentrations in the environmental medium, where pollution concentrations are the product of the firm’s emissions level and the stochastic environmental input. The socially optimal resource allocation in this setting involves an adaptive policy that aligns the marginal value of emissions with state-contingent marginal damages. Because adaptive policies of this form are not commonly observed, and indeed may be impractical to levy in receiving media that revise continuously, we examine the class of emissions standards and ambient standards that do not vary (spatially or temporally) across environmental realizations. Our policy comparison thus encompasses ambient standards of the form underlying NAAQS and WQS that stipulate uniform pollution concentration limits across all airsheds and water bodies in the U.S., as well as emissions standards of the form underlying U.S. cap-and-trade programs for SO_2 and NO_x of the Clean Air Act and pollution discharge permits of the Clean Water Act.

Our central insights on environmental policy design arise from the fact that ambient standards and emissions standards have substantially different properties when applied to a distribution of environmental outcomes. Emissions policies exploit the central tendency of the damage distribution by calibrating the marginal value of emissions with expected marginal damage, whereas ambient policies allow firms to pollute freely beneath the ambient threshold while constraining pollution releases at the upper tail of the damage distribution, thereby facilitating better matches between pollution loads and receiving conditions in the environmental medium.[3]

We organize the paper by first comparing the relative performance of unilateral ambient standards and emissions standards in stochastic environmental media, and then defining the optimal combined policy that jointly implements both forms of instruments. For environmental media characterized by greater dispersion in receiving ability, we find the optimal emissions standard always becomes more stringent (permits a lower emissions level), whereas the optimal ambient policy in many cases becomes more lax (allows higher pollution concentrations). The reason is that greater dispersion in the ability of the environmental medium to receive pollution leads to increased variability in pollution concentrations, and this raises expected damages on the margin. At the same time, greater dispersion in receiving conditions allows for superior customization of the ambient standard to control pollution in high-damage states, for instance

[3]Indeed, there is evidence that firms do vary emissions with environmental conditions under ambient standards. Vernon Henderson (1996) argues that firms in high ozone areas met NAAQS ozone requirements in part by staggering economic activity with the daily cycle of ozone production, which led to a dampening of daily ozone peaks in the 1980's.

during periods of thermal inversion. In terms of economic performance, we demonstrate that emissions standards are superior to ambient standards for relatively non-toxic pollutants with damage functions that are not highly convex in pollution concentrations, whereas ambient policies welfare dominate emission policies for sufficiently harmful pollutants.

For policies that jointly implement ambient standards and emissions standards, we demonstrate that the optimal combined policy relaxes each standard relative to that which would emerge under a unilateral environmental policy of either type. Specifically, when an emissions standard is introduced in a market with a prevailing ambient standard, the optimal emissions standard allows for greater pollution levels than would occur under unilateral emissions policy and the optimal ambient standard relaxes to allow for higher pollution concentrations in the receiving medium.

There is a large and growing empirical literature on the effectiveness of ambient standards as a pollution control approach. Matthew Kahn (1994) finds that the growth rate of manufacturing employment is slower in particulate non-attainment counties relative to counties in attainment with the NAAQS criteria standard for particulates (PM10 and PM2.5), which suggests a shifting of pollution flows to regions that are better able to assimilate it. Vernon Henderson (1996) and Randy Becker and Vernon Henderson (2000) find that the number of VOC-emitting firms in a given region declines significantly in response to a switch in that region from ozone attainment to non-attainment status. Meredith Fowlie (2010) shows that the EPA's recent NO_x SIP Call, which instituted a market-based cap and trade program for nitrogen oxides in the eastern U.S., created differential responses among electric utilities in states with deregulated and regulated energy markets, indicating that government interventions in consumer markets facilitate inefficient pollution trading outcomes across jurisdictions. These empirical studies highlight the importance of theoretical work that characterizes the efficiency properties of ambient standards.

The remainder of the paper is structured as follows. In the next section we construct a simple model framed around a polluting firm that releases emissions into a stochastic environmental medium. We characterize the socially optimal resource allocation in Section 3 and consider the relative performance of unilateral ambient standards and emissions standards in Section 4. In Section 5, we examine combined policies that jointly implement ambient standards and emissions standards on firms. We demonstrate our central outcomes numerically in Section 6, and then conclude the paper with a brief discussion of policy implications for pollution control in settings that are characterized in principle by both spatial and temporal variation in receiving conditions.

2 The Model

Consider a polluting entity, which may be a firm, a community waste-disposal facility, or a collection of firms and facilities that deposits pollution into an environmental medium. The polluting entity (hereafter "firm") faces opportunity costs for reducing emissions, E, below an unregulated emissions level, $E_{\max}$, and we represent these costs by a smoothly increasing and convex abatement cost function $-C(E)$, where $C_E < 0$ and $C_{EE} > 0$ for $E < E_{\max}$.

Emissions create social damage among agents who derive services from the environmental medium, for instance individuals utilizing water downstream from a pollution source. The social damage from emissions depends on *ambient* environmental quality in the receiving medium, as would be the case when the health of downstream agents who consume water depends on pollution concentrations. In practice, ambient environmental quality levels are determined by the interaction between pollution emissions and a potentially large number of stochastic environmental variables; however, for analytic convenience we confine attention to circumstances in which it is possible to characterize the prevailing state of the environmental medium with a single stochastic variable drawn from a known distribution, for example receiving water that varies in volume according to a rainfall input. For expedience, we refer to the distribution of receiving conditions in the environmental medium as a stochastic "receiving distribution". The receiving distribution may be interpreted as capturing temporal variation in pollution assimilative capacity at a single location or a spatial variation in pollution receptivity across regionally distinct emissions locations at a single point in time.

We represent the distribution of outcomes in the environmental medium by the random parameter φ and relate the ambient pollution concentration to the level of emissions as $A = \varphi E$. Thus, pollution concentrations are higher (and social damages are greater) for a given level of pollution when the environmental medium is characterized by larger values of φ in the receiving distribution. We assume that φ is distributed according to a density function f with compact support $[\varphi_l, \varphi_h]$, where $\varphi_l \geq 0$.[4]

We consider environmental damages to be given by the function $D(A, \delta)$, which depends on the ambient pollution concentration, A, and a damage parameter $\delta > 0$ that represents the toxicity of the pollutant. We assume social damages are increasing and convex in the ambient pollution level, $D_A(A, \delta) > 0$ and $D_{AA}(A, \delta) \geq 0$, and that an increase in the damage parameter increases

[4] Our analysis of continuous states of nature applies to the case of river pollution, where the environmental damage from a unit of pollution with a given biochemical oxygen demand varies continuously with streamflow in the receiving water, and to the case of urban air pollutants, where ambient pollution concentrations are a decreasing function of the atmospheric lapse rate.

both the damage and the marginal damage from an increment in pollution concentrations, $D_\delta(A, \delta) > 0$ and $D_{A\delta}(A, \delta) > 0$.

To clarify the outcomes of the model, we assume the third derivatives of the functions $C(.)$ and $D(.)$ are sufficiently small so as to not overturn our results. For expositional convenience, we set $C_{EEE}(E) = D_{AAA}(A, \delta) = 0$.

We consider the choice of abatement technology to be exogenous to firms.[5] This case accords with environmental polices that combine ambient standards with separate policy controls in the form of technological requirements on polluters, for instance the U.S. Clean Water Act requires polluters to install the "best available technology" as a minimum regulatory requirement for a pollution discharge permit. In practice, investment levels are often fixed at the time short-run abatement decisions are made, as would be the case when polluters make infrequent investments in abatement equipment and emit pollution into continuously varying environmental media.

3 The Social Optimum

The social objective is to minimize social cost, SC, which we take to be the sum of abatement cost and environmental damage. Given a particular state of the environmental medium, φ, social cost can be written in terms of the emissions level,

$$SC(E, \varphi, \delta) = C(E) + D(\varphi E, \delta), \tag{1}$$

or equivalently in terms of the ambient pollution level,

$$SC(A, \varphi, \delta) = C(A/\varphi) + D(A, \delta). \tag{2}$$

At the socially optimal resource allocation, firms would observe the state of

[5] In a companion paper, we consider endogenous investment in abatement equipment. Policy implications for this case do not differ materially from the outcomes described below.

nature φ and then adjust their abatement effort to correspond with prevailing environmental conditions in a manner to minimize social cost in equation (1), or equivalently equation (2). Minimizing social cost with respect to the emissions level gives the first-order necessary condition

$$-C_E(E) = \varphi D_A(\varphi E, \delta). \tag{3}$$

Condition (3) sets marginal abatement cost equal to state-contingent marginal damages, which involves firms making continuous adjustments in emission levels to align the benefits and costs of pollution on the margin. Let $E^*(\varphi, \delta)$ denote the solution to equation (3). Making use of the implicit function theorem, it is straightforward to verify that $E^*(\varphi, \delta)$ is decreasing in both φ and δ. The optimal level of emissions decreases in environmental states associated with higher social damages and, for given receiving conditions, declines with the toxicity of the pollutant.

The optimal ambient pollution level, $A^*(\varphi, \delta) = \varphi E^*(\varphi, \delta)$, also varies continuously with φ and is decreasing in δ; however, the optimal ambient pollution concentration can either increase or decrease in φ, depending on the elasticity of the marginal abatement cost function. Let $\varepsilon_c = -C_{EE}(E)E/C_E(E) > 0$ denote the elasticity of the marginal abatement cost function.

Proposition 1. $A^*(\varphi, \delta)$ is decreasing (increasing) in φ when $\varepsilon_c \leq (>)1$.

The optimal ambient environment can either become "cleaner" or "dirtier" when receiving conditions in the environment facilitate higher damages from a given input of pollution. Under environmental conditions associated with high damages (φ "large"), for instance during periods of low streamflow in the receiving water, the optimal ambient pollution concentration standard "relaxes" (A^* increases) whenever the marginal abatement cost function is elastic ($1 < \varepsilon_c$).

The reason is that pollution concentrations rise at a unit rate in emissions, while marginal abatement cost rises at more than a unit rate in emissions with elastic marginal abatement cost. Only under circumstances in which the marginal abatement cost function is unit elastic ($\varepsilon_c = 1$) is the optimal ambient standard independent of receiving conditions in the environmental medium.

To better understand this outcome, suppose conditions in the environmental medium cycle smoothly between the upper and lower boundaries of φ. If the marginal abatement cost function is unit elastic ($1 = \varepsilon_c$), the optimal ambient standard on pollution concentrations is constant irrespective of the state of nature, which implies that the optimal emissions level varies countercyclically with environmental states with an amplitude that exactly mirrors the cycle of environmental realizations. Now suppose the marginal abatement cost function is elastic ($1 < \varepsilon_c$), so that marginal abatement costs rise by more than one percent for a one percent reduction in emissions. In this case, the optimal emissions pattern remains countercyclical with receiving conditions, but with a reduced amplitude to account for the magnification of emissions adjustments into greater than proportional changes in marginal abatement cost. Conversely, if the marginal abatement cost function is inelastic ($\varepsilon_c < 1$), then the optimal emissions pattern varies countercyclically with receiving conditions with a larger amplitude to capitalize on the firm's ability to reduce emissions with less than proportional changes in marginal abatement cost.

Under circumstances in which firms do not internalize social damages, the first-best allocation can be decentralized by a state-contingent emissions policy. To see this, suppose the regulator can select a tax schedule on emissions, $\tau(\varphi)$, that varies according to realized states of nature φ. Under this regulation, the compliance cost of the firm in the abatement stage is given by

$$TC(E, \tau(\varphi)) = C(E) + \tau(\varphi)E,$$

which is minimized at an emission level that solves

$$-C_E(E) = \tau(\varphi). \quad (4)$$

By inspection of (3) and (4), this policy results in the optimal state-contingent ambient environmental quality level whenever the tax in each state of nature is set equal to the realized marginal damage; that is, when $\tau(\varphi) = \varphi D_A(\varphi E, \delta)$.[6]

Suppose the environmental medium varies continuously in its ability to assimilate pollution. In this case, a continuously variable tax (or emissions cap) is likely to be impractical. Instead, as is typically done in practice, the regulator might consider some combination of two policy forms: (*i*) an ambient standard that sets the maximum allowable pollution concentration in the receiving medium at $A = A_s$; and (*ii*) an emissions policy that sets a maximum allowable emissions level at $E = E_s$ irrespective of prevailing receiving conditions.

4 Ambient vs. Emissions Policies

In this section we consider ambient standards of the form implemented by NAAQS of the Clean Air Act and WQS of the Clean Water Act that limit allowable pollution concentrations at a uniform level across all U.S. airsheds and waterways. We then compare the performance of uniform ambient policies to uniform emissions policies that levy a non-varying cap on emissions.

[6] Alternatively, the regulator could issue state-contingent tradable allowances in the amount $L(\varphi) = E^*(\varphi, \delta)$, which would imply a competitive permit price of $\sigma(\varphi) = \varphi D_A(\varphi E, \delta)$ in state of nature φ.

4.1 Ambient Standards

For a given level of an ambient standard, $A = A_s$, one of three outcomes must occur. For sufficiently large values of A_s, the standard never binds, and the firm remains free to pollute at the unregulated level, $E = E_{\max}$, in all states of nature. For smaller values of A_s that limit pollution levels under at least some receiving conditions, it is possible that the ambient standard binds on emissions levels in states of nature with high pollution damages, but does not bind on emissions levels in states of nature with low pollution damages. In this case there exists a $\hat{\varphi} = \hat{\varphi}(A_s) \in [\varphi_l, \varphi_h]$ such that for $\varphi \geq \hat{\varphi}$ the firm must choose an emissions level that complies with the ambient standard, $E = A_s/\varphi$, while for $\varphi < \hat{\varphi}$, the firm remains free to emit pollution at the unregulated level, $E = E_{\max}$. Finally, it is possible that A_s is sufficiently stringent that it binds on the desired emissions level for all $\varphi \in [\varphi_l, \varphi_h]$. For notational convenience we define $\hat{\varphi} = \varphi_l$ for this case, which implies that $\hat{\varphi}'(A_s) = 1/E_{\max} > 0$ (since by definition $\hat{\varphi}(A_s)E_{\max} = A_s$).

Consider the problem of a regulator who seeks to minimize social cost through the selection of an ambient standard. The regulator's objective function is to minimize expected social cost, which is given by

$$\begin{aligned} SC^A(A_s, \delta) &= \int_{\hat{\varphi}(A_s)}^{\varphi_h} C\left(\frac{A_s}{\varphi}\right) dF(\varphi) + D(A_s, \delta)[1 - F(\hat{\varphi}(A_s))] \\ &\quad + \int_{\varphi_l}^{\hat{\varphi}(A_s)} D(\varphi E_{\max}, \delta) dF(\varphi). \end{aligned} \tag{5}$$

The objective function has three terms. The first two terms represent abatement cost and social damages in the binding region ($\varphi \geq \hat{\varphi}$) in which the firm selects the emission level $E = A_s/\varphi$ to meet the ambient standard of A_s. The third term represents social damages from pollution in the non-binding region in which the polluter selects $E = E_{\max}$. The interval over which these damages are expressed collapses to zero as $\hat{\varphi}(A_s) \to \varphi_l$.

The regulator's first-order condition is given by

$$-\int_{\hat{\varphi}(A_s)}^{\varphi_h} C_E\left(\frac{A_s}{\varphi}\right)\frac{1}{\varphi}dF(\varphi) = D_A(A_s,\delta)[1-F(\hat{\varphi}(A_s))].^7 \qquad (6)$$

The optimal uniform ambient standard defined by condition (6) equates expected marginal abatement cost with marginal damage in the regulated tail of the receiving distribution. For states of nature in which the ambient standard binds, $1-F(\hat{\varphi}(A_s))$, marginal social damage is constant at the level of the ambient standard, $D_A(A_s,\delta)$, so that marginal social damage in the regulated portion of the receiving distribution is $D_A(A_s,\delta)[1-F(\hat{\varphi}(A_s))]$. Marginal abatement cost varies with environmental realizations in the upper tail of the receiving distribution as the firm expends greater resources to comply with the ambient standard for larger draws of φ. Accordingly, the optimal ambient standard is selected to equate marginal social damage with expected marginal abatement cost over states of nature in which the ambient standard binds. Pollution levels remain unregulated at $E = E_{\max}$ for all other environmental realizations.

Let A_s^* denote the solution to equation (6). Given that $E = E_{\max}$ at the boundary of the regulated region, the solution A_s^* defines the truncation point in the environmental medium where the regulation goes into effect, $\hat{\varphi}^* = \hat{\varphi}(A_s^*) = \frac{A_s^*}{E_{\max}}$. The optimal outcome under a uniform ambient standard that solves equation (6) differs from the first-best outcome in expression (3) in that a single regulated pollution concentration is chosen to equate marginal social damage with expected marginal abatement cost under a uniform ambient pollution standard, whereas the socially optimal resource allocation selects a different ambient pollution concentration in each state of nature to align state-contingent benefits and costs on the margin. Let $SC^A(A_s^*,\delta)$ denote expected social cost under the

[7] For the remainder of the paper we assume the second-order condition is satisfied.

optimal uniform ambient standard.

The optimal ambient standard, A_s^*, in (6) depends critically on the toxicity of the pollutant, δ. Making use of the implicit function theorem on (6) and the second-order condition for the regulator's problem, it is straightforward to show that the optimal ambient policy satisfies $\partial A_s^*/\partial\delta < 0$. For more damaging pollutants, the optimal uniform ambient standard allows lower pollution concentrations in the environmental medium. Moreover, as δ rises, the optimal uniform ambient standard binds more frequently across states of nature, which implies that $\hat{\varphi}$ decreases towards φ_l. Thus, as the toxicity level of the pollutant rises, the ambient standard adjusts smoothly from a regime in which the ambient standard binds only in some states of nature to a regime in which the ambient standard is always binding.

The optimal ambient standard depends on characteristics of the receiving distribution, φ. Specifically, a change in the distribution of receiving conditions in the environmental medium alters the ambient standard as follows:

Proposition 2. *Let F and G be two distributions with supports $[\varphi_l(F), \varphi_h(F)]$ and $[\varphi_l(G), \varphi_h(G)]$, and let $A_s^*(F)$ and $A_s^*(G)$ denote the optimal ambient standards with respect to F and G, respectively. If*

$$\int_{\varphi_l(F)}^{\varphi_h(F)} -C_E\left(\frac{A_s}{\varphi}\right)\frac{1}{\varphi}dF(\varphi) < \int_{\varphi_l(G)}^{\varphi_h(G)} -C_E\left(\frac{A_s}{\varphi}\right)\frac{1}{\varphi}dG(\varphi) \qquad (7)$$

for all A, then $A_s^*(F) < A_s^*(G)$.

Proposition 2 states that the optimal ambient standard on pollution concentrations relaxes (A_s^* increases) for distributions of φ associated with higher expected marginal abatement cost. In the event that the function $-C_E\left(\frac{A_s}{\varphi}\right)\frac{1}{\varphi}$ is convex, which holds whenever $\varepsilon_c \geq \frac{1}{2}$, the interpretation of (7) in the case of distributions of F and G with identical means is that G second-order stochastically dominates F. Put differently, a mean-preserving increase in the dispersion of φ increases expected marginal abatement costs when $\varepsilon_c \geq \frac{1}{2}$, and this induces the regulator to relax the ambient standard by raising the allowable pollution concentration A_s^*.

A greater dispersion of outcomes in the receiving distribution relaxes the optimal ambient standard when the marginal abatement cost function is sufficiently elastic. The economic motivation for relaxing the ambient standard in this case is similar to the intuition underlying Proposition 1. The more elastic the marginal abatement cost function, the less able the firm to make emissions cuts on the margin without large commensurate increases in cost. The critical value of the elasticity of marginal abatement cost for which the ambient standard relaxes in response to an increased dispersion of receiving conditions is twice as high in the social optimum than under a uniform ambient policy, because the socially optimal resource allocation simultaneously controls pollution concentrations in both tails of the receiving distribution.

4.2 Emissions Standards

Now suppose the regulator sets a uniform emissions standard, $E = E_s$. In the interesting case in which the emissions standard is set below the unregulated emissions level of the firm, the abatement decision involves selecting an emissions level that exactly meets the standard. The regulator's problem is

$$\min_{E_s} \{C(E_s) + \int_{\varphi_l}^{\varphi_h} D(\varphi E_s, \delta) dF(\varphi)\},$$

which has the first-order condition

$$-C_E(E_s) = \int_{\varphi_l}^{\varphi_h} \varphi D_A(\varphi E_s, \delta) dF(\varphi). \tag{8}$$

Condition (8) states that marginal abatement cost be set equal to the expected marginal damage that arises in the stochastic environmental medium under a uniform emissions standard of E_s units.

Notice that the difference between the outcome of the emissions cap in equation (8) and the first-best outcome for emissions in expression (3) is that, under a uniform emissions standard, the level of the standard depends on expected marginal damage in the environmental medium rather than on the actual marginal damage that arises under each realization of φ. Let E_s^* denote the solution to (8) and let $SC^E(E_s^*, \delta)$ denote expected social cost under the optimal uniform emissions standard.

Proposition 3. *Let F and G be two distributions with supports $[\varphi_l(F), \varphi_h(F)]$ and $[\varphi_l(G), \varphi_h(G)]$, and let $E_s^*(F)$ and $E_s^*(G)$ denote the optimal emissions standards with respect to F and G, respectively. If*

$$\int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_A(\varphi E_s, \delta) dF(\varphi) < \int_{\varphi_l(G)}^{\varphi_h(G)} \varphi D_A(\varphi E_s, \delta) dG(\varphi) \tag{9}$$

for all E, then $E_s^*(F) > E_s^*(G)$.

Proposition 3 states that if the expected marginal damage under F is smaller than the expected marginal damage under G, the optimal emissions standard allows a greater level of emissions under F than under G. It is straightforward to show that the function $\varphi D_A(\varphi E_s, \delta)$ is convex in φ. Hence, for equal means of the distributions F and G, condition (9) says that G second-order stochastically dominates F. Given that environmental damage is a convex function of pollution concentrations, greater dispersion in the distribution of φ increases the expected marginal damage of emissions, and the optimal emissions standard accordingly becomes more stringent. A greater dispersion of outcomes in the receiving distribution always leads to a lower emissions standard, and this is true even under circumstances in which the optimal ambient standard would allow greater pollution concentrations in the environmental medium.

4.3 Policy Comparison

Before turning to combined policies, it is useful to draw some general implications on the comparative performance of unilateral policies of each form levied in isolation. Ambient standards, which moderate damages at the upper tail of the distribution, have the advantage of better matching the regulation to prevailing conditions in the receiving medium. Emissions polices, which seek to control expected marginal damages, effectively target the mean of the damage distribution, but fail to exploit matches between emissions levels and prevailing environmental conditions. For relatively toxic pollutants (δ "large") and for pollutants with highly convex damage functions, ambient polices tend to outperform emissions policies. We can formally state this outcome as follows.

Proposition 4:

i) *For δ sufficiently large, $SC^A(A_s^*, \delta) < SC^E(E_s^*, \delta)$.*

ii) *With constant marginal damage, there exists an interval of damage parameters $[\underline{\delta}, \overline{\delta}]$ and an environmental support $[\varphi_l, \varphi_h]$ such that $SC^E(E_s^*, \delta) < SC^A(A_s^*, \delta)$ for $\delta \in [\underline{\delta}, \overline{\delta}]$.*

Proof See the appendix.

The intuition for this result is as follows. For a given support $[\varphi_l, \varphi_h]$, the variance of the damage distribution increases as δ rises, and this favors ambient standards that control damages in high-damage states. The variation in abatement cost for polluters, however, depends only on the particular outcome for φ, and is not related to the degree of toxicity of the pollutant. It follows that there must be some level of toxicity for which policies targeted to control damages outperform policies designed to stabilize emissions. In contrast, for sufficiently low values of δ, the marginal damage from increasing pollution concentrations in the environmental medium becomes negligible, and both optimal emissions standards and optimal ambient standards are accordingly lax. Because the abatement cost function is convex in φ, policies that limit the variability in abatement cost across states of nature by stabilizing emissions levels tend to perform better than policies that limit the variability in damages by stabilizing ambient pollution concentrations in the receiving medium.

5 Combined Policies

Given that most industrial countries implement some form of air and water quality standards, an important issue when regulators levy market-based emissions policies is the jointly optimal mix of ambient standards and emissions standards in a combined policy approach. Under an ambient standard, damages are controlled in the upper tail of the receiving distribution while polluters remain unregulated for other draws from the receiving distribution. Nevertheless, because pollution damages potentially exist at all points in the receiving distribution, the use of an ambient standard provides scope for emissions policies to address the external cost of pollution in portions of the receiving distribution left unregulated by the ambient standard.

We consider combined policies of the following form. For states of nature that lead to pollution concentrations below the ambient standard, $\varphi < \tilde{\varphi}$, pollution is regulated by emissions policy at some level, $E = E_c$, and the emissions policy remains in effect as long as pollution concentrations remain below the level of the ambient standard. As φ increases beneath $\tilde{\varphi}$, pollution concentrations rise in the environmental medium at the regulated emissions level E_c until the ambient standard eventually is met; thereafter, for further increases in φ, the ambient standard is binding and the firm must continually adjust emissions downward for $\varphi > \tilde{\varphi}$ to maintain the ambient standard.

We consider two cases of combined policy that differ according to the degree of observability of values in the receiving distribution. In the first case, the regulator can independently observe the prevailing draw from receiving distribution, φ, and design policies contingent on the realization. In the second case, the regulator cannot directly observe the value of φ, and is confined to implementing policies that switch between emissions standards and ambient standards contingent on observed pollution concentrations, A.

5.1 Observable φ

Consider the problem of a regulator who seeks to minimize social cost through the joint selection of an ambient standard and an emissions standard in a setting with observable values of φ. When the regulator can directly observe values of φ, it is possible to set environmental policy that instructs firms on which policy regime to follow contingent on prevailing conditions in the receiving distribution. Under these circumstances, the combined policy can stipulate

$$\begin{aligned} E &\leq E_c \quad if \quad \varphi_l < \varphi \leq \tilde{\varphi} \\ E &\leq \frac{A_c}{\varphi} \quad if \quad \tilde{\varphi} < \varphi \leq \varphi_h, \end{aligned}$$

where E_c and A_c denote the regulated emissions and ambient quality levels in the combined policy.

Notice that this policy defines state-contingent property rights for pollution. For environmental outcomes in the receiving distribution that satisfy $\varphi \leq \tilde{\varphi}$, emissions policy is in effect, and it is possible to provide clear property rights for emissions in a manner that supports the use of marketable allowances. For outcomes of the receiving distribution that satisfy $\varphi > \tilde{\varphi}$, the ambient standard overrides property rights for emissions, and the firm must make whatever adjustments are necessary to meet the ambient standard. Emissions allowances no longer grant property rights to pollution, and the value of $\tilde{\varphi}$ that divides the property rights regimes operates much like the strike price in an options contract. Put differently, the combined policy under observable φ is consistent with an American-style options market for pollution allowances in which firms can exercise the option to pollute at any time before the expiration date in the event that $\varphi \leq \tilde{\varphi}$.

In the case of observable φ, the regulator selects E_c, A_c, and the boundary value $\tilde{\varphi}$ to minimize

$$C(E_c)F(\tilde{\varphi})+\int_{\varphi_l}^{\tilde{\varphi}} D(\varphi E_c,\delta)dF(\varphi)+\int_{\tilde{\varphi}}^{\varphi_h} C\left(\frac{A_c}{\varphi}\right) dF(\varphi)+D(A_c,\delta)[1-F(\tilde{\varphi})]. \quad (10)$$

The first two terms of objective function (10) represent abatement cost and social damages in the region in which the emissions standard is binding ($\varphi \leq \tilde{\varphi}$). Emissions are constant at the regulated level for these environmental states, while pollution concentrations in the environmental medium (and consequently damages) vary according to the realization of φ. The third and fourth terms represent abatement cost and social damages in the region in which the ambient standard binds ($\tilde{\varphi} \leq \varphi$). As in the case of a unilateral ambient standard, the emissions level of the polluting entity decreases monotonically with φ to maintain pollution concentrations at a level that meets the ambient standard. Environmental quality is constant for these environmental states, while emissions vary according to the realization of φ.

The regulator's first-order necessary conditions for the selection of A_c, E_c, and $\tilde{\varphi}$, respectively, are

$$-C_E(E_c)F(\tilde{\varphi}) = \int_{\varphi_l}^{\tilde{\varphi}} \varphi D_A(\varphi E_c, \delta) dF(\varphi) \tag{11}$$

$$-\int_{\tilde{\varphi}}^{\varphi_h} C_E\left(\frac{A_c}{\varphi}\right)\frac{1}{\varphi} dF(\varphi) = D_A(A_c, \delta)[1 - F(\tilde{\varphi})] \tag{12}$$

$$C(E_c) + D(\tilde{\varphi}E_c, \delta) = C\left(\frac{A_c}{\tilde{\varphi}}\right) + D(A_c, \delta) \tag{13}$$

Conditions (11) and (12) represent the same essential trade-offs as in equations (6) and (8), but with expectations defined over the binding region for each policy. Condition (11) equates marginal abatement cost with expected marginal damage over states of nature bound by the emissions standard and condition (12) equates expected marginal abatement cost with marginal damage over states of nature bound by the ambient standard.

Notice by inspection of equation (11) that the emissions standard in a combined policy allows a greater level of emissions than a unilateral emissions policy. The reason is that the damage function is convex in pollution concentrations, so that the expected marginal damage of emissions is lower for values of the receiving distribution censored by the ambient standard than expected marginal damage defined over the entire support. Equation (12) similarly reveals that the ambient standard in a combined policy allows higher pollution concentrations in the environmental medium than in the case of a unilateral ambient standard. This is because firms engage in abatement activities beneath the ambient standard in a combined policy, and this raises expected marginal abatement cost for draws from the receiving distribution that require the firm to engage in further abatement activities.

Condition (13) determines the boundary that divides the policy regimes. The switching point that divides policy regimes in the receiving distribution equates social cost under the emissions standard with social cost under the ambient standard at the boundary state of nature $\tilde{\varphi}$. If the social cost did not align for each form of regulation at $\tilde{\varphi}$, then it would be possible to reduce social cost by shifting the boundary in a manner to capitalize on the regulation with lower social cost.

Let $(E_c^*, A_c^*, \tilde{\varphi}_c^*)$ denote the solution to (11)-(13). Notice that the transition from the emissions standard to the ambient standard need not be continuous; that is, it can be the case that $E_c^* \tilde{\varphi}_c^* \neq A_c^*$, so that the permissible level of emissions "jumps" at the boundary that divides the two regimes.

5.2 Unobservable φ

Now suppose that φ cannot be observed directly by the regulator, but that the prevailing ambient pollution concentration, A, can be observed. In this case, the policy is set such that

$$E \leq \min\{E_c, \frac{A_c}{\varphi}\} \quad for \quad all \quad \varphi_l < \varphi \leq \varphi_h.$$

The regulator's problem is to select E_c and A_c to minimize

$$C(E_c)F(\tilde{\varphi}) + \int_{\varphi_l}^{\tilde{\varphi}} D(\varphi E_c) dF(\varphi) + \int_{\tilde{\varphi}}^{\varphi_h} C\left(\frac{A_c}{\varphi}\right) dF(\varphi) + D(A_c)[1 - F(\tilde{\varphi})],$$

subject to the condition that $E_c \tilde{\varphi} = A_c$.

The regulator's first-order necessary conditions are:

$$C_E(E_c)F(\tilde{\varphi}) + \int_{\varphi_l}^{\tilde{\varphi}} \varphi D_A(\varphi E_c, \delta) dF(\varphi) + \lambda\tilde{\varphi} = 0 \qquad (14)$$

$$\int_{\tilde{\varphi}}^{\varphi_h} C_E\left(\frac{A_c}{\varphi}\right)\frac{1}{\varphi} dF(\varphi) + D_A(A_c, \delta)[1 - F(\tilde{\varphi})] - \lambda = 0 \qquad (15)$$

$$[C(E_c) + D(\tilde{\varphi}E_c, \delta) - C\left(\frac{A_c}{\tilde{\varphi}}\right) - D(A_c, \delta)]f(\tilde{\varphi}) + \lambda E_c = 0. \qquad (16)$$

Substitution of the constraint $E_c\tilde{\varphi} = A_c$ in (16) yields

$$[C(E_c) + D(\tilde{\varphi}E_c, \delta) - C(E_c) - D(\tilde{\varphi}E_c, \delta)]f(\tilde{\varphi}) + \lambda E_c = 0.$$

For non-degenerate combined policies, $E_c > 0$, it follows immediately that $\lambda = 0$. Thus, first-order conditions (14) and (15) reduce to

$$-C_E(E_c)F(\tilde{\varphi}) = \int_{\varphi_l}^{\tilde{\varphi}} \varphi D_A(\varphi E_c, \delta) dF(\varphi) \quad (17)$$

$$\int_{\tilde{\varphi}}^{\varphi_h} -C_E\left(\frac{A_c}{\varphi}\right)\frac{1}{\varphi} dF(\varphi) = D_A(A_c, \delta)[1 - F(\tilde{\varphi})] \quad (18)$$

Let $(E_c^u,\ A_c^u)$ denote the solution to conditions (17) and (18). Notice that the conditions that define E_c^u and A_c^u are identical to conditions (11) and (12), but that the unobservability of φ precludes the possibility of selecting a boundary condition on the environmental state that joins the two regions with anything other than a smooth transition in the policy variables. That is, the solution $(E_c^u,\ A_c^u)$ does not globally minimize cost in (E, A, φ)-space. Nevertheless, the superior efficiency of an environmental policy that is contingent on the realization of φ is potentially offset by a greater information requirement. Virtually all industrial countries measure pollution concentrations in major airsheds and waterways, which makes policies contingent on prevailing ambient air and water quality levels considerably simpler to implement.

5.3 Combined Policy Outcomes

Environmental policies that jointly implement both ambient standards and emissions standards can be characterized as follows. First, under both combined policy regimes, the optimal switching point of $\tilde{\varphi}$ that divides the binding region of each regulation relates to the equilibrium value of $\hat{\varphi}$ under a unilateral ambient standard according to:

Proposition 5. *The optimal switching point in a combined policy, $\tilde{\varphi}$, satisfies*

$\tilde{\varphi} \geq \hat{\varphi}$.

The intuition behind Proposition 5 is straightforward. Given that states of nature with relatively low pollution concentrations are regulated under an emissions standard in a combined policy approach, emissions levels are below $E_{\max}$ at the boundary point of the receiving distribution, and this results in an ambient standard that binds in fewer states of nature.

Proposition 6. *Relative to the outcome under a unilateral emissions or ambient policy, a combined policy:*

i) *levies an ambient standard that allows higher pollution concentrations;*

ii) *levies an emissions standard that allows a higher level of emissions; and*

iii) *results in lower social cost.*

In the next section we illustrate the performance of various forms of environmental policy for specific functional forms for the abatement cost and pollution damage functions. Our numerical analysis considers combined policies with unobservable φ, because we believe policies that depend on ambient pollution concentrations are considerably more practical to implement than policies that are contingent on receiving conditions in environmental media.

6 Numerical Analysis

In this Section we consider the policy outcomes in an example with a quadratic abatement cost function, $C(E) = \frac{(\alpha - \beta E)^2}{2\beta}$, a damage function that is linear in pollution concentrations, $D(E, \delta) = \delta\varphi E$, and a uniform receiving distribution, $f(\varphi) = \frac{1}{\varphi_h - \varphi_l}$.[8] The social optimal resource allocation is characterized by a state-contingent emissions pattern that equates marginal abatement cost, $-C_E(E) = \alpha - \beta E$, with marginal damage, $D_E(E, \delta) = \delta\varphi$, which yields $E^* = \frac{\alpha - \delta\varphi}{\beta}$.

Table 1 compares the outcomes for emissions policy and ambient policy with the social optimum in the case where $\alpha = 100$, $\beta = 1$, $\varphi_l = 0$, $\varphi_h = 1$ for variations in pollution toxicity in the range $\delta \in [20, 100]$. Under ambient policy, the optimal policy is always non-binding (because $\varphi_l = 0$ eliminates pollution damages at the lower boundary of environmental outcomes), and the critical value of the receiving distribution satisfies $\hat{\varphi}^* = \frac{A_s^*}{100}$. Notice that social cost is lower under emissions policy than under ambient policy for pollutants with low levels of toxicity, but that an ambient standard welfare dominates an emissions standard for relatively toxic pollutants. Under either policy, the optimal value of the standard decreases monotonically with the toxicity of the pollutant.

Table 2 shows the outcomes for combined policy with unobservable φ for an identical parameterization of the model. Notice by comparing the entries in Tables 1 and 2 that the combined policy leads to superior economic performance relative to the outcome under a unilateral ambient standard or unilateral emissions standard for each level of pollution toxicity. For low levels of pollution toxicity ($\delta < 33.7$), the combined policy reverts to a pure emissions standard, and the ambient standard is set at a level that guarantees pollution concentrations never exceed the ambient standard under E_c^*. For higher levels of pollution toxicity, the combined policy switches to a mix of policy instruments that increasingly emphasizes the use of ambient standards to curtail environmental damages.

[8] Numerical results based on a quadratic damage function with increasing marginal damage generates qualitatively similar outcomes.

Notice that the ambient standard in the combined policy approach decreases monotonically with pollution toxicity, as in the case of a unilateral ambient standard, whereas the emissions standard is non-monotonic in δ. The reason is that the optimal combined policy exploits the superior ability of emissions policy to control pollution for relatively non-toxic pollutants and the greater efficiency of ambient policy to control damages for more toxic pollutants. For low levels of pollution toxicity, the combined policy emphasizes emissions policy, and the emissions standard accordingly decreases with toxicity; however, for more toxic pollutants, the optimal combined policy emphasizes ambient policy, and emissions rise towards the unregulated level, $E_{\max}$, as the combined policy converges towards a unilateral ambient standard.

It is worthwhile to note that a combined policy based on observable φ does not differ substantially in terms of economic performance from a policy contingent on measured pollution concentrations in the receiving medium.[9] Indeed, the switching points $\tilde{\varphi}$ are closely matched for combined policies with observable and unobservable φ and similar trends emerge for social cost under each form of combined policy. Thus, our numerical results suggest that ambient policies indexed to readily available information on ambient air and water quality levels can closely approximate the performance of more elaborate policies that depend on direct observations of receiving conditions in the environmental medium.

Figure 1 depicts the outcome for expected abatement cost under various combinations of uniform environmental policy instruments and the social optimum for the parameter values described above. Notice that expected abatement cost is lower under an emissions standard relative to the social optimum, but higher under an ambient standard. The reason is that an emissions standard

[9] For the combined policy in the case of observable φ, both $\hat{\varphi}_c^* E_c^* > A_c^*$ and $\hat{\varphi}_c^* E_c^* < A_c^*$ can hold, depending on the toxicity of the pollutant.

does not provide flexibility in tailoring emissions levels to receiving conditions in the environmental medium, and this results in regulation that emphasizes the control of abatement costs.

Figure 2 displays expected environmental damages under an emissions standard, an ambient standard, a combined policy, and the social optimum. Notice that expected environmental damage under an emissions standard is higher than the socially optimal resource allocation, while the ambient standard involves a level of expected damage that is sometimes higher and sometimes lower than the socially optimum. The reason is that the uniform ambient standard truncates pollution concentrations in the receiving distribution at the level of the ambient standard, leaving firms unregulated in low-damage states, whereas the socially optimal resource allocation adjusts pollution in every state of nature. Under a uniform ambient standard, pollution concentrations are higher than optimal in the unregulated portion of the receiving distribution and lower than optimal in the regulated tail of the receiving distribution.

7 Policy Implications

On June 2, 2010 the U.S. EPA tightened the NAAQS primary standard for SO_2 from the original ambient standards set in 1971 and proposed dramatic restrictions in interstate trading of SO_2 and NO_x emissions in the Transport Rule. The increased stringency of the NAAQS SO_2 standard to a 1-hour concentration standard of 75 ppb closely follows a period of gradual tightening of emissions policy under Title IV of the Clean Air Act Amendments to a current emissions standard of 8.95 million tons. Our analysis suggests several policy implications in light of these recent rulings. First, it is clear that considerable efficiency gains may exist in developing combined environmental policies that take into account interactions between prevailing ambient standards and recently-introduced emissions standards in the joint selection of policy instruments. The optimal environmental policy that combines the two forms of regulation would respond to the introduction of emissions policy by relaxing the prevailing ambient standard to allow for greater pollution concentrations in the receiving environmental medium.

Second, the Transport Rule deeply erodes one of the greatest benefits of market-based emissions policies by virtually eliminating SO_2 and NO_x trading across state lines. While the curtailment of interstate trading responds to a shortcoming of cap and trade systems that stems from an inability to predict the exact location in which pollution will ultimately occur, it is clearly suboptimal to resolve the intersection between emissions standards and ambient air quality standards by introducing frictions in pollution exchange markets. Our analysis suggests a more efficient combination of emissions standards and ambient standards would be to introduce an American-style options markets for emissions allowances in which the option to exercise pollution rights is indexed either to receiving conditions in the environmental medium or to prevailing ambient air quality levels at regional monitoring sites.

Our findings also have implications for tailoring environmental policy to regionally distinct environmental media. There is often a spatial as well as temporal distribution of assimilative capacity in the environmental media that receive pollution. For example, air quality in Los Angeles and Bakersfield, California are similar in terms of annual average ozone concentrations, while Los Angeles is characterized by substantially greater variation in hourly ozone concentrations (due, in part, to more frequent periods of thermal inversion). An implication of the model is that the optimal emissions policy would maintain a lower emissions level in Los Angeles than in Bakersfield, while the optimal ambient standard would allow higher ozone concentrations in Los Angeles than in Bakersfield when the elasticity of marginal abatement cost for ozone-producing pollutants satisfies $\varepsilon_c \geq \frac{1}{2}$.

An essential distinction between emissions standards and ambient standards is that emissions policies are associated with lower abatement costs and higher environmental damages than ambient standards for a given level of social cost. Both ambient policies and combined policies shift a greater share of social costs into abatement markets, which results in a smaller share of social cost in the form of residual environmental damage. This difference in the distribution of social cost between abatement costs and environmental damages can have important consequences for the rate of technical innovation in abatement markets. Indeed, in a companion paper, we find that firms invest more heavily in abatement equipment under ambient standards relative to equilibrium investment levels that emerge under emissions standards.

An important area for future research is to develop models that address stock accumulation problems in environmental media. The accumulation of pollution concentrations in environmental media can occur both over time, as in the case of persistent greenhouse gases, and over space, as in the case of waste disposal in a drainage canal shared by multiple polluters. Stock pollutants introduce a cascading effect of pollution in the environmental medium, for instance pollution released in a drainage canal by an upstream firm increases pollution concentrations in the receiving medium for a downstream firm. Stock accumulation problems in correlated environmental media alters the policy implications outlined here by introducing a spatial (or temporal) policy gradient with higher taxes on upstream (or early period) polluters to account for the external cost of emissions on subsequent users of the resource.

Another potentially fruitful direction for future analysis is the design of ambient standards in markets with multiple polluters. In the case of a single point source for pollution, as considered here, the responsibility for complying with an ambient standard can be given to the firm. If there is more than one polluter, the regulator could implement an instrument involving collective punishment in the event that the ambient standard is not met. Indeed, mechanisms that rely on the use of ambient environmental quality levels to impose collective punishment on individual firms are at the heart of the literature on regulating non-point emissions sources, for instance the collective tax considered by Kathleen Segerson (1988) and the random punishment mechanism suggested by A.P. Xepapadeas (1991). An interesting direction for future analysis is to formally examine combined policies of the form considered here in a framework that accounts for compliance incentives among multiple pollution sources along the lines developed by Juan-Pablo Montero (2008).

8 Proofs

Proof of Proposition 1: Rewriting the first order condition (3) as

$$-C_E\left(\frac{A}{\varphi}\right) = \varphi D_A(A,\delta) \tag{19}$$

differentiating with respect to A and applying the implicit function theorem, we obtain:

$$\frac{dA}{d\varphi} = \frac{-D_A(A,\delta) + \frac{A}{\varphi^2}C_{EE}\left(\frac{A}{\varphi}\right)}{\varphi D_{AA}(A,\delta) + \frac{1}{\varphi}C_{EE}\left(\frac{A}{\varphi}\right)} = \frac{C_E\left(\frac{A}{\varphi}\right) + E\cdot C_{EE}\left(\frac{A}{\varphi}\right)}{\varphi^2 D_{AA}(A,\delta) + C_{EE}\left(\frac{A}{\varphi}\right)}$$

where we used (19) in the last equation. Recognizing that the denominator is positive by the second-order condition, we obtain the result.

Proof of Proposition 2: Recall that $A^*(F)$ satisfies $D_A(A^*(F),\delta) = \int_{\varphi_l(F)}^{\varphi_h(F)} -C\left(\frac{A^*(F)}{\varphi}\right)\frac{1}{\varphi}dF(\varphi)$. By (7), we obtain:

$$\begin{aligned} 0 &= D_A(A^*(F),\delta) + \int_{\varphi_l(F)}^{\varphi_h(F)} C_E\left(\frac{A^*(F)}{\varphi}\right)\frac{1}{\varphi}dF(\varphi) \\ &> \int_{\varphi_l(G)}^{\varphi_h(G)} C_E\left(\frac{A^*(F)}{\varphi}\right)\frac{1}{\varphi}dG(\varphi) + D_A(A^*(F),\delta) \end{aligned}$$

Thus $A^*(F)$ is not optimal with respect to G. Since under G the derivative of the expected marginal social cost is negative but increasing, social cost can be reduced by increasing A^*. Therefore $A^*(G) > A^*(F)$.

Proof of Proposition 3: Recall that $L^*(F)$ satisfies $-C_E(L^*(F)) = \int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_\varphi(\varphi L^*(F),\delta)dF(\varphi)$. By (9), we obtain:

$$\begin{aligned} 0 &= C_E(L^*(F)) + \int_{\varphi_l(F)}^{\varphi_h(F)} \varphi D_\varphi(\varphi L^*(F),\delta)dF(\varphi) \\ &< \int_{\varphi_l(G)}^{\varphi_h(G)} \varphi D_\varphi(\varphi L^*(F),\delta)dG(\varphi) + C_E(L^*(F)) \end{aligned}$$

Thus $L^*(F)$ is not optimal with respect to G. Since expected marginal damage under distribution G and standard $L^*(F)$ is larger than the marginal abatement cost, social cost can be reduced by decreasing L^*. Therefore $L^*(G) < L^*(F)$.

Proof of Proposition 4: For the proof we need the following Lemma:

Lemma 1 *Define* $\Gamma(\varphi, A) = C\left(\frac{A}{\varphi}\right)$*. Then for A sufficiently large,* $\Gamma_{\varphi\varphi} > 0$*.*

Proof of Lemma 1: Differentiating $\Gamma(\varphi, A)$ with respect to φ yields $\Gamma_\varphi = C'\left(\frac{A}{\varphi}\right) \cdot \left(-\frac{A}{\varphi^2}\right)$ and $\Gamma_{\varphi\varphi} = A\left[\frac{A}{\varphi}C''\left(\frac{A}{\varphi}\right) + 2C'\left(\frac{A}{\varphi}\right)\right]/\varphi^3$. Now if A is sufficiently large, in particular if it is close to $\varphi E_{\max}$, the term $C'\left(\frac{A}{\varphi}\right)$ gets arbitrarily close to zero. Since $C'' > 0$ by assumption, $\Gamma_{\varphi\varphi}$ will be positive.

Proof of Proposition 4 (continued): Ad i) First consider the case of a highly damaging pollutant with a large δ coefficient. Differentiating the equations (6) and (8) with respect to δ, it is straightforward to see that $\partial\overline{E}^*/\partial\delta < 0$, and $\partial A^*/\partial\delta < 0$. Thus a higher assessment of damage induces lower levels of emissions under both the emissions standard and the ambient standard. Since $\varphi_l > 0$, the ambient standard is always binding in all states of the world if δ is sufficiently high.

Now let $\overline{E}^* = \overline{E}^*(\delta)$ denote the optimal emissions standard for a given δ. Next let $\widetilde{A}$ be chosen such that the expected damage is the same under both the emissions standard $\overline{E}^*$ and the ambient standard $\widetilde{A}(\overline{E}^*(\delta))$; that is,

$$D(\widetilde{A}(\overline{E}^*(\delta)), \delta) = E_\varphi D(\varphi\overline{E}^*(\delta), \delta) \tag{20}$$

Now observe that by Jensen's inequality

$$E_\varphi D(\varphi\overline{E}, \delta) \geq D(\overline{\varphi}\overline{E}, \delta) \tag{21}$$

Let $D^{-1}(\cdot, \delta)$ be the inverse function to $D(\cdot, \delta)$. Since $D^{-1}(\cdot, \delta)$ is a positive monotonic function, applying this to (20) and using (21) yields

$$\widetilde{A}(\overline{E}^*(\delta)) = D^{-1}(E_\varphi D(\varphi\overline{E}, \delta), \delta) \geq D^{-1}(D(\overline{\varphi}\overline{E}, \delta), \delta) = \overline{\varphi}\overline{E}. \tag{22}$$

Since $C(\cdot)$ is decreasing in E we obtain

$$C\left(\frac{\widetilde{A}(\overline{E}(\delta))}{\overline{\varphi}}\right) \leq C\left(\frac{\overline{\varphi}\overline{E}(\delta)}{\overline{\varphi}}\right) = C(\overline{E}(\delta)) \tag{23}$$

Now choose δ sufficiently large such that $\Gamma(\varphi, \widetilde{A}(\overline{E}^*(\delta))) = C\left(\frac{\widetilde{A}(\overline{E}^*(\delta))}{\varphi}\right)$ is convex in φ. Next, consider the expected benefit of the standard $\widetilde{A}$ and apply Jensen's inequality to the function $\Gamma(\varphi, \widetilde{A}) = C\left(\frac{\widetilde{A}}{\varphi}\right)$, which is convex in φ for $\widetilde{A} = \widetilde{A}(\overline{E}^*(\delta))$. Doing so, and making use of (20) yields

$$\begin{aligned} E_\varphi C\left(\frac{\widetilde{A}}{\varphi}\right) + D(\widetilde{A}, \delta) &= E_\varphi \Gamma(\varphi, \widetilde{A}) + D(\widetilde{A}, \delta) \\ &< \Gamma(\overline{\varphi}, \widetilde{A}) = C\left(\frac{\widetilde{A}}{\overline{\varphi}}\right) + D(\widetilde{A}, \delta) \\ &\leq C\left(\overline{E}^*\right) + E_\varphi D(\varphi \overline{E}^*(\delta), \delta) \end{aligned}$$

where the last inequality follows from (20) and (23) and the definition of $\widetilde{A}$. Since $\widetilde{A}$ is not necessarily the optimal ambient standard with respect to δ, we obtain:

$$\begin{aligned} E_\varphi\{SC^A(A^*(\delta), \delta)\} &\leq E_\varphi\{SC^A(\widetilde{A}(\overline{E}^*(\delta)), \delta)\} \\ &< E_\varphi\{SC^{\overline{E}}(\overline{E}^*(\delta)), \delta)\} \end{aligned}$$

where $A^*(\delta)$ is the optimal ambient standard for δ.

Ad ii): A linear damage function is given by $D(A, \delta) = \delta A$. Now let $A^*(\delta)$ denote the optimal ambient standard for δ, and let $\tilde{E}(A^*(\delta))$ denote the emissions standard that leads to the same expected damage as $A^*(\delta)$, i.e. $D(A^*(\delta)) = E_\varphi\{D(\varphi \cdot \tilde{E}(A^*(\delta)))\}$. Moreover let $\overline{E}^*(\delta)$ be the optimal emissions standard for δ. By the linearity of the damage function we obtain $A^*(\delta)) = E_\varphi\{\varphi \cdot \tilde{E}(A^*(\delta))\}$. If δ is sufficiently small but bounded away from zero, we have $\tilde{E}(A^*(\delta)) < E_{\max}$ but close to $E_{\max}$. Therefore also $A^*(\delta)/\overline{\varphi} = \tilde{E}(A^*(\delta)) < E_{\max}$ and $A^*(\delta)/\varphi < E_{\max}$ for $\varphi < \overline{\varphi}$ but sufficiently close to $\overline{\varphi}$. Now we know from Lemma 1 that $C\left(A/\varphi\right)$ is convex in φ if A/φ is sufficiently close to $E_{\max}$.

Therefore Jensen's inequality yields

$$E_\varphi\{C\left(A/\varphi\right)\} > C\left(A/\overline{\varphi}\right) \tag{24}$$

This yields:

$$\begin{aligned}
E_\varphi\{SC^A(A^*(\delta),\delta)\} &= E_\varphi\{C\left(A^*(\delta)/\varphi\right)\} + \delta A^* > C\left(A^*(\delta)/\overline{\varphi}\right) + \delta A^*(\delta) \\
&= C(\tilde{E}(A^*(\delta)) + \delta E_\varphi\{\varphi\tilde{E}(A^*(\delta)) \\
&> C(E^*(\delta)) + \delta E_\varphi\{\varphi E^*(\delta)\} = E_\varphi\{SC^A(E^*(\delta),\delta)\}
\end{aligned}$$

for some δ from some interval $[\underline{\delta},\overline{\delta}]$ with $\underline{\delta} > 0$, and a suitable interval $[\varphi_l,\varphi_h]$.

Proof of Proposition 5: Assume that $\hat{\varphi} < \tilde{\varphi}$. Then we can rewrite (10) as

$$\min_{E,A,\hat{\varphi}}\{C(E)F(\hat{\varphi}) + \int_{\underline{\varphi}}^{\hat{\varphi}} D(\varphi E)dF(\varphi) + \int_{\hat{\varphi}}^{\tilde{\varphi}} D(\varphi E_{\max})dF(\varphi)$$
$$+ \int_{\hat{\varphi}}^{\bar{\varphi}} C\left(\frac{A}{\varphi}\right)dF(\varphi) + D(A)[1-F(\hat{\varphi})]\}$$

Note that in the interval $[\hat{\varphi} < \tilde{\varphi}]$ the abatement cost is zero since by definition of $\tilde{\varphi}$ we have $A/\varphi > E_{\max}$ for $\varphi < \tilde{\varphi}$. Now let $L^*(\hat{\varphi})$ be the optimal emissions standard referring to the interval $[\underline{\varphi} < \hat{\varphi}]$. Then

$$\begin{aligned}
& C(E^*(\hat{\varphi}))F(\hat{\varphi}) + \int_{\underline{\varphi}}^{\hat{\varphi}} D(\varphi E^*(\hat{\varphi}))dF(\varphi) + \int_{\hat{\varphi}}^{\tilde{\varphi}} D(\varphi E_{\max})dF(\varphi) \\
> \; & C(E^*(\hat{\varphi}))F(\hat{\varphi}) + \int_{\underline{\varphi}}^{\tilde{\varphi}} D(\varphi E^*(\hat{\varphi}))dF(\varphi) \\
> \; & C(E^*(\tilde{\varphi}))F(\hat{\varphi}) + \int_{\underline{\varphi}}^{\tilde{\varphi}} D(\varphi E^*(\tilde{\varphi}))dF(\varphi)
\end{aligned}$$

where $E^*(\tilde{\varphi})$ is the optimal standard referring to the interval $[\underline{\varphi} < \tilde{\varphi}]$. Therefore the original policy with $\hat{\varphi} < \tilde{\varphi}$ and $E^*(\hat{\varphi})$ cannot have been optimal.

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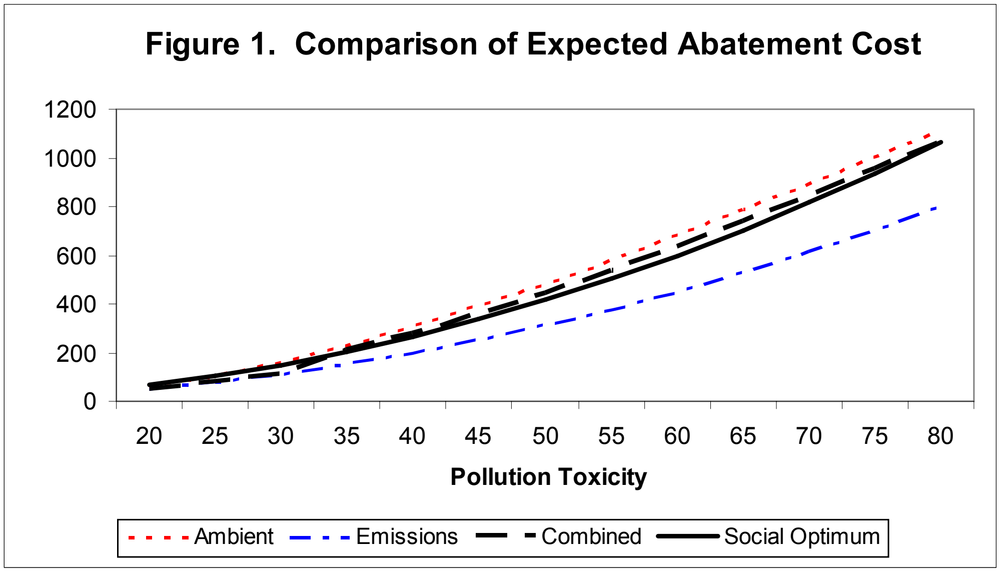
Figure 1. Comparison of Expected Abatement Cost
1200
1000
800
600
400
200
0
20 25 30 35 40 45 50 55 60 65 70 75 80
Pollution Toxicity
Ambient
Emissions
Combined
Social Optimum

Figure 1:

.

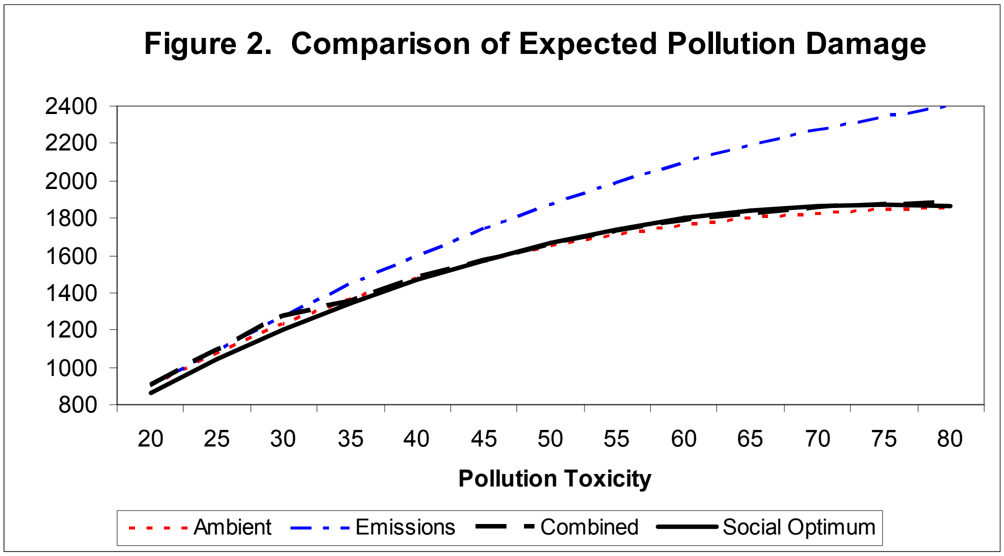
Figure 2. Comparison of Expected Pollution Damage
2400
2200
2000
1800
1600
1400
1200
1000
800
20
25
30
35
40
45
50
55
60
65
70
75
80
Pollution Toxicity
Ambient
Emissions
Combined
Social Optimum

Figure 2:

.

.

TABLE 1 – COMPARISON OF POLICY OUTCOMES: SINGLE POLICIES

($\alpha = 100.0$, $\beta = 1.0$, $\varphi_l = 0.0$, $\varphi_h = 1.0$)

	Policy Outcome				
Toxicity	Social Optimum	Emissions Policy		Ambient Policy	
δ	$SC(E^*)$	E_s^*	$SC(E_s^*)$	A_s^*	$SC(A_s^*)$
$\delta = 20$	933	90	950	68.6	963
$\delta = 30$	1,350	85	1,388	57.7	1,394
$\delta = 40$	1,733	80	1,800	48.9	1,784
$\delta = 50$	2,083	75	2,187	41.7	2,133
$\delta = 60$	2,400	70	2,550	35.8	2,445
$\delta = 70$	2,683	65	2,888	30.9	2,722
$\delta = 80$	2,933	60	3,200	26.8	2,969
$\delta = 90$	3,150	55	3,488	23.3	3,187
$\delta = 100$	3,333	50	3,750	20.3	3,381

TABLE 2 – COMBINED POLICY OUTCOMES

($\alpha = 100.0$, $\beta = 1.0$, $\varphi_l = 0.0$, $\varphi_h = 1.0$)

Toxicity	Policy Outcome Social Optimum	Combined Policy Outcomes			
δ	$SC(E^*)$	E_c^*	A_c^*	$\tilde{\varphi}_c^*$	$SC(A_c^*, E_c^*)$
$\delta = 20$	933	90.0	–	1.0	950
$\delta = 30$	1,350	85.0	–	1.0	1,388
$\delta = 40$	1,733	88.1	52.5	0.60	1,754
$\delta = 50$	2,083	87.2	44.6	0.51	2,104
$\delta = 60$	2,400	86.9	38.1	0.44	2,418
$\delta = 70$	2,683	86.9	32.6	0.38	2,699
$\delta = 80$	2,933	87.1	28.1	0.32	2,949
$\delta = 90$	3,150	87.5	24.3	0.28	3,171
$\delta = 100$	3,333	88.0	21.1	0.24	3,368