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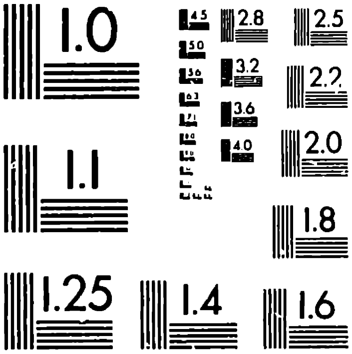

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STUDIES IN TRADE AND TRANSBOUNDARY EXTERNALITIES

by

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B.A., Honours Economics
University of British Columbia
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Submitted to the Department of Economics
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ABSTRACT

This dissertation focuses on issues of trade and transnational pollution in both a cooperative and non-cooperative setting. The first chapter examines the coordinated use of tariffs an domestic emissions taxes to deal with transboundary pollution and imperfect competition in the absence of international agreement. A two-country, open-economy model is developed involving strategic (Cournot) interaction between a domestic and foreign firm that produce a polluting good. Acting as a Stackelberg leader vis-a-vis the firms, the home government chooses instruments, which may include a domestic emissions tax, an output tax, and an import tariff on the polluting good, to maximize social welfare. In this model, I find that, when the home government can *subsidize* the domestic produce through a (negative) output tax, it can achieve a "first-best" solution using an import tariff and a (Pigouvian) emissions tax, at least in the absence of transboundary pollution. (This generalizes a closed-economy result of Buchanan (1969) to an open-economy setting.) In contrast with other studies, however, I find that in *either* the absence of an output tax *or* the presence of transboundary pollution, the optimal emissions tax is no longer "Pigouvian." At the same time, the optimal tariff, in addition to being influenced by the price elasticity of imports, becomes a kind of environmental "countervailing" tax.

In the second chapter, I discuss one way in which gains may be achieved through a coordinated program of policies between nations in the context of transboundary pollution and trade by studying a specific example. A major barrier to any U.S.-Canadian agreement for the control of acid rain appears to be a widespread (but undocumented) belief that the costs to the United States of any joint abatement program would be prohibitive. In this chapter I report estimates of the costs of the United States and Canada of achieving a 15 percent reduction in acid rain concentrations under a joint tradeable permit system for sulfur dioxide emissions. I use point-source data for the 200 largest sulfur dioxide emitters in each of Canada and the United States, transfer coefficients that relate emissions in different regions to acid rain concentrations in specified "sensitive receptor" regions, and fitted cost functions for each point source, to estimate the costs facing each country under different acid rain abatement programs. The simulations show (1) that an autarkic program of abatement in each country induces significant benefits in the other, and (2) that a joint program of abatement would lead to substantial cost savings for *both* the United States and Canada. The results also document, however, large differentials in the gains that would accrue to each country, suggesting that there may be serious obstacles, in the form of difficulties in arriving at a division of the gains from trade, to achieving agreement on a joint program of abatement.

Thesis Supervisor: Professor Peter Diamond

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INTRODUCTION

Many of the concerns peculiar to "environmental" economics involve studies in applied microeconomic theory that have been solved in the setting of a closed economy. The problems of public goods, of externalities, and the use of Pigouvian taxes and market-based incentives as solutions to those problems, have been well understood for years. Many of these insights are now even finding expression in the actions of elected officials, policy makers and administrators.

Many real environmental problems, on the other hand, are not naturally closed-economy problems. Differential environmental standards in neighboring countries may influence the effectiveness of domestic environmental programs. There currently exist rather widespread apprehensions that differential environmental standards may influence flows among trading partners, calling into question the wisdom of free trade. Here, too, there exists a substantial literature that has deployed neo-classical trade models to obtain insights about the trade implications of environmental concerns.

In general, however, the study of environmental issues in an open economy has not been given the attention it deserves. New techniques, especially game-theoretic techniques, elsewhere now so widely employed, have been little used in the study of environmental issues. Equally little attention has been devoted to open economy implications of applied solutions (using market-based incentives) to domestic environmental problems.

This dissertation takes steps in the direction of filling those gaps. It studies the nature of the solutions to domestic environmental problems in the framework of an open economy in both non-cooperative and cooperative settings. Essay 1 is devoted to the former. I use applied game-theory to study the nature of both optimal emissions taxes and optimal tariffs in a bilateral setting involving trade in a good the production of which in either country gives rise to domestic environmental harm. I assume there exists no bilateral agreement for control of the externality. Assuming that firms engage in Cournot competition, and assuming also that the domestic government acts as a Stackelberg "leader," I study its optimal formulation of emissions and trade taxes. In general, I find that these taxes take "standard" forms -- a Pigouvian emissions tax and a tariff that reflects the price elasticity of imports -- *only* when the domestic government can supplement the implementation of domestic environmental policy (captured in its emissions tax) by subsidizing domestic production. When it cannot, I find that the forms of *both* the emissions tax and the import tariff change in a way that reflects the presence of the externality. Of particular interest is the finding that the import tax incorporates environmental concerns, after the fashion of an environmental "countervailing" tax.

Essay 2 studies the effect of bilateral trade in the setting of a market-based system for the abatement of an externality, specifically a system of tradable licenses to pollute. In particular I study the gains to be realized through bilateral trade in the *licenses* themselves. This issue is explored using simulation techniques, based on actual data drawn from an extensive inventory of the sources of precursors to North American acid rain. Contrary to prior beliefs that are widely credited with having stalled U.S.-Canadian efforts to arrive at a bilateral agreement for the control of acid rain, my findings strongly suggest that, in pollution licenses as in goods, there are gains to be realized from trade.

CHAPTER ONE:

The Nature of Optimal Tariffs and Emissions Taxes in the Presence of Imperfect Competition, Transboundary Pollution and Trade

I. Introduction

Increasingly stringent environmental standards in the United States, such as those enacted with the 1990 Amendments to the Clean Air Act and the proposed changes to the Resource Conservation and Recovery Act, have heightened awareness of the relationship between trade and environmental policies. With non-uniformity of environmental standards across countries and the apparently accelerating trend towards free-trade agreements, there is increasing concern about the implications of trade with countries that have less stringent environmental controls than the United States. This has stimulated pressure to expand the role of "countervailing taxes," imposed to counteract the "unfair" trade practices claimed to be associated with differential environmental standards. On the other hand, environmentalists have long been concerned about the impact of trade policies on the domestic environment. Those that favor high pollution industries, for example, can worsen environmental damage by increasing domestic emissions. All such problems may be complicated by flows of pollutants across national borders (so-called "transboundary" pollution).

In a closed economy, one of the classic correctives for production externalities is the "Pigouvian" tax. By setting the tax rate equal to the marginal damage from the externality (and rebating the proceeds in lump sums to consumers), a first-best outcome can be achieved. The

Pigouvian tax seems, moreover, to be robust to alterations of context. For example, several studies (principally Markusen (1975) and Krutilla (1991)), have found that, with the introduction of international trade (and, in a very limited way, transboundary pollution), the Pigouvian tax remains an optimal remedy for the consequences of environmental damage. By the same token, Buchanan (1969) shows that, in the presence of imperfect competition in a closed economy, the Pigouvian tax continues to be optimal, at least as long as the planner also has access to a (negative) output tax.

To date, however, very little work has been done on the nature of optimal emissions taxes in the presence of transboundary pollution, and equally little attention has been paid to the nature of optimal trade and emissions taxes in a setting in which environmental and trade policies are jointly determined. In this paper I develop a two-country model that I use to study the optimal structure of both emissions and import taxes in the presence of imperfect competition, transboundary externalities and trade. One innovation in this study is that I allow for the *joint* determination of trade, environmental, and industrial policies; a second is that I allow for the possibility of transboundary environmental damage; finally, in contrast with other work, I allow for differences across countries in the relationship between production and pollution.

In the setting of this model, I find that optimal determination of governmental instruments frequently produces emissions taxes that differ from the Pigouvian tax. I do find that, in the presence of imperfect competition and trade (but in the absence of transboundary pollution), a planner with a complete set of instruments (including an output tax) at its disposal can deal optimally with pollution through a Pigouvian tax. I find, on the other hand, that in the presence of incoming transboundary pollution this result disappears: the optimal emissions tax ceases to be Pigouvian; and the optimal tariff takes on the flavor of a "countervailing" environmental tax. I also study instances in which the planner has less than a complete set of instruments at its disposal. My findings generally suggest that, in the presence of imperfect competition, the availability of an output subsidy is an important (if not indispensable) adjunct to the optimal prescription of a Pigouvian emissions tax (a conclusion that may be of practical significance given the tendency of trade agreements to curtail subsidies to production); and that, in the presence of inflows of transboundary pollution, the Pigouvian tax generally is not the optimal emissions tax.

The paper is divided into five sections. In Section II, I formulate a Cournot model of bilateral imperfect competition, in which I assume that the private firms take governmental policy choices, expressed as parameters of the firms' objective functions, as given. In that section I characterize the response of the firms' solutions as we vary those policy choices. In Section III, I turn to the problem of the home government's maximization of domestic welfare, acting first as a central planner, and than as a leader vis-á-vis the firms. Special cases, involving particular assumptions about the production of pollution or more limited availability of instruments, are investigated in Section IV. Section V summarizes the study and offers some concluding observations on the policy implications of our model.

II. The Influence of Policy on The Firms' Problem

In this and the next section, I formulate a two-country model that will be used to explore the optimal formulation of trade and environmental policies and their impact on domestic and foreign firm behavior. We study the problem in a setting in which the polluting industry has a duopolistic market structure, and in which there (may) exist transboundary flows of pollution. The governmental actors are the "domestic" country (denoted "Country D") and the "foreign" country ("Country F"). Two goods are assumed to be produced in each country, consisting of (1) a homogenous good whose production generates pollution (denoted "G"), and (2) a competitively produced composite (numeraire) good (denoted "M") that may be produced in either

D or F. I assume that any single industry in either country is small compared to the entire economy, and, therefore, cannot affect factor prices.

One firm in each country produces the polluting good (G). The domestic firm produces only for home consumption. In the interests of simplicity, I assume the foreign firm produces solely for export to Country D.[1] Competition between the foreign and domestic firms in Country D is assumed to be Cournot (quantity) competition.

This section is devoted to the impact on the equilibrium behavior of both firms (in producing G) of policies implemented by Country D, which is assumed to have three instruments at its disposal. These consist of (1) an emissions tax (t), (2) an import tariff (β), and (3) an output tax (α), each assumed to be an excise tax in \$ per unit of emissions, and \$ per unit of output or import, as the case may be. Country D is further assumed to act as a Stackelberg leader vis-à-vis both the domestic and foreign firms in fixing t, β, and α. In other words, it is assumed that Country D can credibly pre-commit to some level of import tax, output tax (or subsidy) and domestic emissions tax that will not be altered after the firms choose their outputs. Accordingly, the firms take all taxes as given. In general, all policy parameters of Country F are assumed to have been chosen in advance; it takes no retaliatory action against Country D.

II.a Assumptions on Firm Behavior

I make the following assumptions about firm behavior.

PRODUCTION OF G. The domestic firm produces q units of the polluting good for domestic consumption. The foreign firm produces Q units of the polluting good, all of which

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[1] Thus, while we assume no domestic consumption of G in country F, this simplifying assumption does not affect the core results of the model.

it exports to Country D. Aggregate production is given by $G = q + Q$. Cournot competition is taken to prevail between the domestic and foreign firm in Country D.

PRODUCTION OF POLLUTION. I assume pollution to be a function of both the output levels and the amount of abatement technology that are chosen by each firm. For the domestic firm, emissions (denoted by e) are therefore given by:

$$e = h(q, a), \tag{1}$$

where a is the amount of abatement technology chosen by the domestic firm.

I make the following assumptions about the derivatives of the emissions function (using primes to denote derivatives, and subscripts to denote partial derivatives):

$$\begin{gathered} h(q, a) \geq 0 \\ h(0, a) = 0 \\ h_1 \geq 0 \ , \ h_{11} \geq 0 \\ h_2 \leq 0 \ , \ h_{22} \geq 0 \\ h_{12} = h_{21} \leq 0. \end{gathered} \tag{2}$$

These assumptions imply (1) that pollution is increasing at an *increasing* rate with output levels, and (2) that pollution is decreasing at a *decreasing* rate with abatement technology. Thus, the emissions function is assumed to be convex in each of its arguments. The force of the assumed non-positive sign on the cross partial derivative (h_{12}) is that marginal emissions from increasing output decrease with increased levels of abatement.

Except as specifically noted, uppercase letters will be used to denote corresponding functions and magnitudes for the foreign firm. Thus, the emissions function of the foreign firm is given by:

(3) $$E = H(Q, A).$$

Assumptions similar to those made about the derivatives of the emissions function of the domestic firm are made for the foreign firm.

COSTS. The firms' costs are assumed to consist of production costs (denoted, respectively, $c(q)$ and $C(Q)$), and the costs of adopting pollution abatement technology (denoted $f(a)$ and $F(A)$). I assume these cost functions to be increasing in their arguments and convex.[2]

DOMESTIC DEMAND. I assume that the inverse demand curve for G in Country D, denoted by

(4) $$p = p(G) = p(q+Q),$$

is twice continuously differentiable. I also make several technical assumptions about $p(\ )$. Specifically, I assume there is some output level, $G^0 > 0$ such that $p(G) > 0$ for $G < G^0$ and $p(G) = 0$ for $G > G^0$. I assume also that $p'(G) < 0$ for $G < G^0$, and that $p'(G) + Gp''(G) < 0$ for all $0 \leq G \leq G^0$. The latter condition assures the existence of downward sloping reaction functions for both firms -- the goods are strategic substitutes -- and the existence of a unique Cournot equilibrium in pure strategies.[3]

II.b Firm Conduct

With the above assumptions, the domestic firm maximizes profits, taking as given the domestic emissions tax (t), output tax (α), and foreign output (Q), by selecting its output (q) and abatement level (a) to solve:

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[2] I assume also that $c(0) = C(0) = f(0) = F(0) = 0 = c'(0) = C'(0) = f'(0) = F'(0)$.

[3] *See* Gaudet and Salant (1991) for a proof of this proposition.

$$(5a) \qquad Max_{q,\,a}\ \pi = [q\{p(q + Q) - \alpha\} - c(q) - f(a) - th(q, a)].$$

Similarly, the foreign firm must choose how much to produce for export to Country D. In so doing, it is assumed to face a local emissions tax (denoted by *T*), as well as Country D's import tariff (β). Accordingly, it chooses (Q) and (A), taking T, β, and q as given, to solve:

$$(5b) \qquad Max_{Q,\,A}\ \Pi = [Q\{p(q + Q) - \beta\} - C(Q) - F(A) - T\,H(Q, A)].$$

Necessary first-order conditions for profit maximization by both firms engaged in Cournot competition are given by:

$$(6) \qquad \begin{aligned} &(a)\ \ \pi_q:\ \ p + qp' - c' - th_1 - \alpha = 0; \\ &(b)\ \ \pi_a:\ \ -f' - th_2 = 0; \\ &(c)\ \ \Pi_Q:\ \ p + Qp' - C' - TH_1 - \beta = 0; \\ &(d)\ \ \Pi_A:\ \ -F' - TH_2 = 0. \end{aligned}$$

Conditions (6a) and (6c) are generally familiar: each firm sets marginal revenue equal to marginal cost. For the foreign firm, however, Country D's import tariff also influences the optimal choice of Q. In (6b) and (6d), the firms' abatement technology is chosen to equate the marginal cost of abatement with the marginal savings, through reduced emissions taxes, from a marginal increase in a (or A). Hence, in equilibrium, the level of abatement chosen by each firm is determined by (1) local environmental policy (captured by t or T), (2) the cost associated with its choice of abatement, and (3) its pollution generating technology. Given our assumption that $f'(0) = F'(0) = 0$, when either D or F ignores the environment (by fixing its emissions tax at zero), its firm optimally sets its abatement technology to zero.

Second-order conditions sufficient for interior solutions to the equations given in (6) to yield a local maximum for each firm are given in Appendix A. Comparative statics, together with technical and other assumptions needed to sign the derivatives, are outlined in Appendix B. Table B-I summarizes the comparative static results.

II.c The Impact of Policy on Firm Conduct

In this section I develop some basic insights about the influence of the policy parameters, t, β and α, on the firms' equilibrium behavior, by rewriting the firms' problem in terms of their reaction (best response) functions in Q - q space. In this general formulation of the problem, of course, the quantities a and A enter the first-order conditions in a way that prevents us from writing the reaction functions in closed form in the usual way. If, however, we assume that the derivatives of their profit functions are locally invertible where necessary, we can solve for those reaction functions implicitly.[4]

We proceed by solving equation 6(b) implicitly for the optimal level of abatement, *given* q and t, which we write as:

$$a^{*} = a(q, t). \tag{7}$$

Using (7), we rewrite the first-order condition 6(a) as:

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[4] A complete derivation of the reaction functions is given in Appendix C.

(6a′)

$$p(G) + qp'(G) - c'(q) - th_1(q, a(q, t)) - \alpha$$

$$= p(G) + qp'(G) - j_q(q, t, \alpha) = 0,$$

where

$$j_q(q, t, \alpha) = c'(q) + th_1(q, a(q, t)) + \alpha,$$

and where we have isolated the policy parameters (t and α) in the term $j_q(\,)$. Solving the first order condition 6(a′) implicitly (and using the fact that $G = q + Q$), we obtain the domestic firm's reaction function:

(8)

$$q^* = q(Q, t, \alpha).$$

Similarly, we can rewrite the foreign firm's first order condition (6(c)) as:

(6c′)

$$p(G) + Qp'(G) - J_Q(Q, T, \beta) = 0,$$

where

$$J_Q(Q, T, \beta) = C'(Q) + TH_1(Q, A(Q, T)) + \beta.$$

By symmetry, we obtain the foreign firm's reaction function:

(9)

$$Q^* = Q(q, T, \beta).$$

Our assumptions about the domestic inverse demand curve assure that the reaction functions in (8) and (9) will be downward sloping, leading to a pure strategy Nash equilibrium. From the equations that implicitly define q^* (and Q^*), the policy parameters only enter the terms $j_q(\,)$ (and $J_Q(\,)$). Hence, the impact of the policy parameters on the equilibrium responses of the firms will turn on the derivatives of those terms. From those derivatives we obtain the following propositions.

PROPOSITION 1: AN INCREASE IN THE DOMESTIC EMISSIONS TAX (t) LEADS TO A DECREASE IN DOMESTIC OUTPUT (q) AND AN INCREASE IN IMPORTS (Q) IF t IS GREATER THAN THE "RELATIVE MARGINAL COST" OF DOMESTIC ABATEMENT.

The domestic emissions tax enters directly only into the domestic reaction function. Differentiating j_q with respect to t, we obtain (as more fully worked out in Appendix C):

(10)
$$\begin{aligned}\frac{\partial j_q}{\partial t}\Big|_q = j_{qt} &= h_1(q,\, a(q,\, t)) + t h_{12}\frac{\partial a}{\partial t}\\ &= h_1 - t h_{12}\frac{h_2}{f'' + t h_{22}}.\end{aligned}$$

The term j_q is increasing in t, causing the domestic firm's reaction function to shift *in*, if j_{qt} is positive, or if:

(11)
$$\frac{-h_1 f''}{h_1 h_{22} + h_2 h_{12}} \leq t.$$

From our assumptions about the derivatives of h and f, the left-hand side of (11) is negative. Hence, for all *positive* values of t, an increase in t will induce an inward shift of the domestic firm's reaction function, leading to a decrease in domestic output and an increase in imports. This relationship will also hold, moreover, for some levels of emissions *subsidies*.

It is easier to acquire a feel for the nature of the relationship defined by (11) by considering the special case in which $h_{12} = 0$. In that case, the condition in (11) simplifies to:

(12)
$$\frac{-f''}{h_{22}} \leq t.$$

The expression in (12) implies that, as long as the tax rate exceeds the *ratio* of (1) the rate at which the *marginal* cost of abatement is rising, to (2) the rate at which *marginal* abatement is slowing with additions of abatement technology -- which we might denote the "relative marginal cost of abatement" -- an increase in t will lead to a fall in domestic output. Note that the relationship given in (12) will always hold true, given the second order conditions for profit maximization.

PROPOSITION 2: AN INCREASE IN THE IMPORT TARIFF (β) INDUCES AN INCREASE IN DOMESTIC PRODUCTION (q) AND A FALL IN IMPORTS (Q).

In this instance we need only focus on J_Q. Clearly, J_Q is increasing in β, so that an increase in β will induce an inward shift in the foreign reaction function, leading to a fall in imports and a rise in domestic production.

PROPOSITION 3: $|H_{11}| \geq |H_{12}|$ IS A SUFFICIENT CONDITION FOR AN INCREASE IN THE DOMESTIC EMISSIONS TAX (t) TO INDUCE A RISE IN THE PRICE OF G.

Using the expressions for q_t and Q_t in Table B-I, the marginal change in equilibrium supply of G (with respect to t) is given by:

$$G_t = q_t + Q_t = \left(\frac{h_1 \pi_{aa} - h_2 \pi_{qa}}{Det\ S}\right)\left(\Pi_{QQ}\Pi_{AA} - \Pi_{AQ}^2 - \Pi_{AA}\Pi_{qQ}\right)$$

$$(13) \quad = \left(\frac{h_1 \pi_{aa} - h_2 \pi_{qa}}{Det\ S}\right)\left((C'' - p')(F'' + TH_{22}) + TF''H_{11} + T^2\,(H_{11}^2 - H_{12}^2)\right).$$

By assumption (see Appendix B) the numerator of the fraction in (13) is negative, whereas *Det S* is positive (see Table B-I). Thus, aggregate change in output will be negative, and the price of G will rise, if the second factor on the right hand side of (13) is positive. All terms in that second factor, *other than* $H_{11}^2 - H_{12}^2$, are positive. Hence, a sufficient (but, certainly, not a necessary) condition for this result is $|H_{11}| \geq |H_{12}|$.

The intuitive content of $|H_{11}| \geq |H_{12}|$ is [to be supplied.]

PROPOSITION 4: $|H_{11}| \geq |H_{12}|$ IS A SUFFICIENT CONDITION FOR AN INCREASE IN THE DOMESTIC OUTPUT TAX (α) TO INDUCE A RISE IN THE PRICE OF G.

An increase in the domestic output tax clearly induces an inward shift of the domestic firm's reaction function. This implies that domestic output decreases while foreign imports rise. From Table B-I, the aggregate change in equilibrium supply is given by:

$$(14) \qquad G_\alpha = q_\alpha + Q_\alpha = -\frac{\pi_{aa}(\Pi_{AQ}^2 - \Pi_{QQ}\Pi_{AA} + \Pi_{AA}\Pi_{qQ})}{DetS}.$$

Since $\pi_{aa} < 0$ by the second order conditions, the reasoning behind Proposition 3 tells us that a sufficient condition for equilibrium supply of G to decrease in α, producing an increase in the equilibrium price, is $|H_{11}| \geq |H_{12}|$.

III. The Determination of Optimal Policy

In this section, I turn to the decision making process of the domestic government in choosing trade, emissions, and output taxes to maximize domestic social welfare. I take a partial equilibrium approach to these matters so as to focus attention on the polluting industry.

I study the optimal choice of instruments by Country D in two somewhat different ways. First I characterize the solution to the Planner's problem, in which it is assumed that

Country D *itself* knows the foreign firm's reaction function, and directly chooses q and a, as well the import tariff (β), to maximize domestic social welfare. Having characterized the solution, I then decentralize the problem, allowing the domestic *firm* to choose q and a (as described in Section II), while the domestic *government* chooses t and α (as well as β) to maximize domestic welfare. I show, *first*, that when Country D has an output tax at its disposal, the solution to the Planner's problem may be replicated. In this instance, moreover, with trade *and* imperfect competition (but no incoming transboundary pollution), the optimal emissions tax is a Pigouvian tax, and the optimal tariff is (as is typically found in trade models) driven by the price elasticity of imports. (The emissions tax result generalizes to an open economy framework the closed economy result of Buchanan (1969).) *Second*, however, I show that, *even with* all three instruments at its disposal, the optimal emissions tax ceases to be Pigouvian in the presence of transboundary flows of pollution into Country D; and, moreover, that the optimal tariff becomes (at least in part) what might be described as an environmental "countervailing" tax.

The study of optimal choices by Country D is then extended by restricting the number of available instruments, thereby leading to second and third best alternatives. In particular, I no longer allow the government to impose an output tax. In that case, the domestic government maximizes welfare by choosing the optimal import and domestic emissions tax, but, again, the optimal emissions tax no longer is Pigouvian. Thereafter, I study instances of particular abatement technologies, and even more restricted availability of instruments.

III.a Consumer Utility and Domestic Welfare

Consumer Utility. Consumers in Country D are assumed to be identical and to have "quasi-linear" preferences over G and the composite good, M, such that all increases in income are spent on M.[5]

Consumers' utility is defined as:

$$U = \int_0^{q+Q} p(x)dx - L(B^D), \tag{15}$$

where L is the loss function associated with the environmental degradation due to the prevailing domestic ambient level of pollution, B^D, and $p(\,)$ is the inverse demand curve for G defined in Equation (4). The loss function is assumed to be increasing in the level of *ambient* pollution and convex.

Our assumption about transboundary pollution means that domestic ambient pollution depends upon both domestic and foreign production of G and the associated emissions. The relationship between foreign production and ambient domestic pollution is specified by a "source-receptor" coefficient, that describes the percentage of foreign pollution that enters Country D. (In applications, the source-receptor coefficient would be determined by air mass flows for atmospheric pollution, and by water flows for water pollution.) Similarly, the fraction of domestic pollution that remains in Country D is determined by its "own" source-receptor coefficient.

The total level of ambient pollution in Country D is therefore given by:

$$B^D = r_1 H(Q, A) + (1 - r_2)h(q, a), \tag{16}$$

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[5] See Tirole (1988), pg. 7.

where r_1 is the source-receptor coefficient on foreign pollution entering Country D, and (for subsequent convenience) $(1 - r_2)$ is Country D's own source-receptor coefficient.[6] Note that:

$$r_1,\ r_2 \in [0,\ 1] \tag{17}$$

I assume Consumers are unable to distinguish between units of G produced abroad and those produced at home, and so do not take into account how their own consumption of G contributes to domestic ambient pollution, through increases in either domestic production or imports. As a result, consumers incorrectly take B^D as given, and do not internalize the externality in their consumption of G.[7]

DOMESTIC WELFARE. Country D's objective is to maximize domestic social welfare. Because the price of the composite good, M, is normalized to one, the domestic welfare function may be specified as the sum of consumer utility (which includes consumers' evaluation of environmental damages from pollution, which the planner is assumed to know), domestic profits, and government revenue. Note that an additional dollar of profit or tax revenue is used to consume the composite good (M), which produces one extra unit of utility.

I assume that, in contrast with consumers, the domestic government *can* distinguish between goods produced domestically and those produced abroad.[8] Hence, the Planner's loss function from domestic ambient pollution is:

$$L = L\big(r_1(H(Q,A) + (1-r_2)h(q,a)\big). \tag{18}$$

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[6] I assume that both source-receptor coefficients are locally unchanged in the neighborhood of the equilibrium.

[7] See Diamond, P.; "Consumption Externalities and Imperfect Competitive Pricing;" *Bell Journal of Economics*; 4, 1973, pp. 526-538.

[8] This distinction might be justified by assuming, for example, that the government has access to statistics on output and imports, information not readily available to consumers.

With these assumptions, welfare in Country D is given by:

$$W = \int_0^{q+Q} p(x)\,dx - (q + Q)*p(q + Q) + \alpha q + \beta Q + th(q, a) \tag{19}$$

$$+ \pi - L\big(r_1 H(Q, A) + (1 - r_2)h(q, a)\big),$$

where total revenues from the output, import and emissions taxes, respectively, are given by αq, βQ and $th(q, a)$. In writing the welfare function in this fashion, I assume that all taxes collected are distributed as lump-sum rebates to consumers.[9]

III.b Optimal Taxes and Tariffs

The domestic government's objective is to maximize social welfare (as given in (19)). I first solve the Planner's problem, and then investigate the circumstances under which the solution to that problem may be decentralized.

III.b.1 The Planner's Problem

To solve the Planner's problem, I first re-write Equation (19) as

$$W = \int_0^{q+Q(q,\, \beta)} p(x)\,dx - Q(q, T, \beta)*p(q + Q(q, T, \beta))$$

$$- c(q) - f(a) + \beta Q(q, T, \beta) \tag{20}$$

$$- L\big(r_1 H(Q(q, T, \beta), A) + (1 - r_2)\, h(q, a)\big),$$

---

[9] I do not explicitly include a balance of trade equation in the model, to insure that the value of Country D's imports equals the value of its exports (and likewise for Country F). This condition is implicitly imposed. Country D buys pQ of imports and receives βQ in tariff revenues. Country F receives $Q(p - \beta)$ in revenues through its exports Country D. By assuming this to be spent solely on M, imported from Country D, a balance of trade implicitly exists.

using the domestic profit function (5a), and substituting the foreign firm's *reaction function* (9) into the domestic welfare function.

The Planner directly chooses domestic output and abatement, as well as an import tariff. The first-order conditions for an interior solution are given by:

(21a)
$$\frac{\partial W}{\partial q}: \quad p - L'*\left(r_1 H_1 \frac{\partial Q}{\partial q} + (1 - r_2)h_1\right) - c' - Qp*\left(1 + \frac{\partial Q}{\partial q}\right) + \beta \frac{\partial Q}{\partial q} = 0;$$

(21b)
$$\frac{\partial W}{\partial a}: -L'(1 - r_2)h_2 - f' = 0;$$

(21c)
$$\frac{\partial W}{\partial \beta}: \beta + \frac{Q}{\frac{\partial Q}{\partial \beta}} - Qp' - L'r_1 H_1 = 0.$$

Equations (21a)-(21c) are slight variations on otherwise familiar conditions. The optimal level of domestic output is found by equating marginal revenue (including revenue from tariffs) with marginal cost (including the "costs" of tariff revenues, and the loss from domestic ambient pollution); and optimal domestic abatement by equating the marginal reduction in loss from domestically produced pollution to the marginal cost of abatement. The optimal tariff is a function of the price elasticity of imports and the loss from increased foreign production through increased foreign emissions pollution. I denote the solutions to the first-order conditions (21), together with the foreign firm's optimal choice of output and abatement (written as a function of those solutions), by $\tilde{\beta}, \tilde{q}, \tilde{a}, \tilde{Q}(\tilde{q}, T, \tilde{\beta}), \tilde{A}(\tilde{q}, \tilde{\beta})$.

III.b.2 Decentralizing the Planner's Solution

To ascertain under what circumstances the Planner's solution may be decentralized, I begin with the case in which there is no transboundary pollution flowing into Country D (*i.e.*, $r_1 = 0$.) Denoting by α^* and t^* (and β^*) taxes optimally chosen by the planner, I rewrite the domestic firm's problem, taking α^* and t^* as given, as:

$$\text{(5a')} \qquad Max_{q,\,a}\ \pi = \left[q\left\{p(q + Q) - \alpha^*\right\} - c(q) - f(a) - t^* h(q, a)\right].$$

By equating the planner's first-order conditions ((21a) and (21c)) with the first-order conditions for a solution to (5a'), it can then easily be shown that, when the latter are evaluated at $q = \tilde{q},\ a = \tilde{a},$ *both* sets of first-order conditions are satisfied if:

$$\text{(22)} \qquad \begin{aligned} &(a) \quad t^* = L'\big((1 - r_2)\, h(\tilde{q}, \tilde{a})\big)\,(1 - r_2), \\ &(b) \quad \alpha^* = \tilde{q}\,\tilde{p}' + \tilde{Q}\,\tilde{p} + \tilde{Q}\frac{\partial \tilde{Q}}{\partial q}\left(\tilde{p}' + \tilde{p} - \frac{1}{\dfrac{\partial \tilde{Q}}{\partial \beta}}\right), \textit{ and} \\ &(c) \quad \beta^* = \tilde{Q}\,\tilde{p}' - \frac{\tilde{Q}}{\dfrac{\partial \tilde{Q}}{\partial \beta}} \end{aligned}$$

In other words, when Country D chooses the taxes given by (22), and the domestic firm maximizes profits by choosing q and a, the firm optimally chooses $q^* = \tilde{q}$ *and* $a^* = \tilde{a}$. Thus, the taxes given by (22) induce the domestic firm to replicate the Planner's solution.

The noteworthy feature of (22) is that, when there is no incoming pollution and the Planner can choose α (as well as t and β), the optimal emissions tax -- $L'(1 - r_2)$ -- is set equal to the marginal (domestic) damage from that fraction of domestic emissions that is not "exported" to Country F. That is, it is simply the Pigouvian tax. Thus, in an open economy framework, our finding corroborates the closed economy finding of Buchanan (1969) that, even in the presence of imperfect competition, the Pigouvian tax remains appropriate as long as the government can also fix an output tax. Consistent with his findings, α^* in (22b) is (generally)[10] negative. Intuitively, the Planner can rectify the consequences of the imperfect competition by subsidizing domestic output, leaving itself free to deal with the environment through a Pigouvian tax.[11]

Next, I relax the assumption of no incoming pollution, setting $r_1 > 0$. Once again, I find that the planner can induce the domestic firm to choose $q^* = \tilde{q}$ *and* $a^* = \tilde{a}$, in this instance by setting:

$$
(23)\quad
\begin{aligned}
&(a)\quad t^* = L'\big(r_1 H(\tilde{Q}, \tilde{A}) + (1 - r_2) h(\tilde{q}, \tilde{a})\big) * (1 - r_2),\\
&(b)\quad \alpha^* = \tilde{q}\tilde{p}' + \tilde{Q}\tilde{p} + \tilde{Q}\frac{\partial \tilde{Q}}{\partial q}\left(\tilde{p}' + \tilde{p} - \frac{1}{\frac{\partial \tilde{Q}}{\partial \beta}}\right), \textit{ and}\\
&(c)\quad \beta^* = \tilde{Q}\tilde{p}' - \frac{\tilde{Q}}{\frac{\partial \tilde{Q}}{\partial \beta}} + L'(r_1 H(\tilde{Q}, \tilde{A}) + (1 - r_2) h(\tilde{q}, \tilde{a})) * r_1 H_1(\tilde{Q}, \tilde{A}).
\end{aligned}
$$

The first striking feature here is that, *even with* an output tax, the optimal emissions tax is *no longer* a "true" Pigouvian tax. It now equals the product of the domestic marginal damage from *all* ambient pollution and the (unexported) *domestically produced* pollution. (Since L is increasing and convex, the tax in (23a) is higher than the Pigouvian tax.) Equally interesting, however, is the fact that the optimal tariff now has also changed: *it* now takes into account the

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[10] A sufficient condition for α^* to be negative is for β^* to be greater than zero. (To see this, one can differentiate the best response function of the foreign firm and use the domestic firm's second order conditions for profit maximization to sign the tax.)

[11] Although tangential to our discussion, it can also easily be shown that the expression for the optimal import tax (β) in (22c) is, like the optimal import tax found in trade models that are not preoccupied with the environment, a function of the price elasticity of imports. See, for example, Brander and Spencer (1984).

loss (in the form of damage from incoming foreign emissions) associated with foreign production. Taxes on *domestic* activity (t and α) are now inadequate to deal with environmental damage. The optimal tariff is required to serve environmental objectives, too. (In part it has become, at least in an environmental sense, a "countervailing" tax.) In other words, it now requires *both* an emissions *and* an import tax to rectify the consequences of the externality normally achieved through a Pigouvian emissions tax alone. Through that combination of instruments, however, the Planner's solution still may be achieved.

In sum: with a complete set of instruments (including an output tax) at its disposal, Country D can decentralize the solution to the Planner's problem. In the absence of incoming transboundary pollution, the emissions tax is the Pigouvian tax. If, however, there exist transboundary flows of pollution into Country D, the decentralized requires *both* an output tax and an import tariff, *just* to deal with the consequences of pollution.

III.c Limiting the Number of Policy Instruments

In what follows, I allow for the use of at most two instruments, an emissions tax and an import tariff, by Country D. (In terms of the domestic welfare function (19), I delete αq.) In the context of this model, once it is deprived of an output tax, Country D generally can no longer decentralize the solution to the Planner's problem.

III.c.1 General Form of the Decentralized Solution

In the decentralized solution, the government maximizes the welfare function by choosing the import tariff (β), and the domestic emissions tax (t). The necessary first-order conditions for a maximum are given by:

$$
(24)\quad
\begin{aligned}
&(a)\quad \frac{\partial W}{\partial \beta} = -\, L' B_\beta + Q + \beta Q_\beta + t(h_1 q_\beta + h_2 a_\beta) \\
&\qquad - (Q + q) * p'(Q_\beta + q_\beta) + \pi_\beta = 0, \ \textit{and} \\
&(b)\quad \frac{\partial W}{\partial t} = -\, L' B_t + \beta Q_t + t(h_1 q_t + h_2 a_t) \\
&\qquad - (Q + q) * p'(Q_t + q_t) + \pi_t = 0;
\end{aligned}
$$

where

$$
(25)\quad
\begin{aligned}
B_\beta &= r_1(H_1 Q_\beta + H_2 A_\beta) + (1 - r_2)(h_1 q_\beta + h_2 a_\beta), \ \textit{and} \\
B_t &= r_1(H_1 Q_t + H_2 A_t) + (1 - r_2)(h_1 q_t + h_2 a_t).
\end{aligned}
$$

The expressions (25) describe the marginal change in the domestic ambient *level* of pollution with respect to a change in the import tax and the emissions tax, respectively. Note that differences in the pollution generating functions of the two countries play an important role here: the marginal change in the domestic pollution level does *not* depend solely on the relative magnitudes of the source-receptor coefficients. Large differences across countries in relative responsiveness of pollution to the choices of output level and pollution abatement technology, together with significantly different local pollution policies (which determine the level of abatement chosen by each firm) may lead to domestic ambient pollution levels that are almost completely determined by domestic pollution sources (or by foreign source pollution), regardless of the relative magnitudes of the source-receptor coefficients.[12]

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[12] Clearly, this will only hold true if the source-receptor coefficients are not zero or one.

The following relationships, obtained by differentiating the first-order conditions for profit maximization by the domestic firm ((6a)-(6b)) with respect to t and β, may be used to simplify the expressions in (24):

$$(26)\quad \begin{aligned} (a)\quad \pi_t &= pq_t + q(Q_t + q_t)*p' - c'q_t - f'a_t - h - t(h_1q_t + h_2a_t) \\ &= qp'Q_t - h; \\ (b)\quad \pi_\beta &= pq_\beta + q(Q_\beta + q_\beta)*p' - c'q_\beta - f'a_\beta - t(h_1q_\beta + h_2a_\beta) \\ &= qp'Q_\beta, \end{aligned}$$

where the second equality in both (26a) and (26b) follows directly from the domestic firm's first-order conditions.

Solving the two equations in (24) simultaneously, and making use of the relationships in (26), yields the optimal emissions tax, t^*, and the optimal emissions tax, β^*:

$$(27)\quad t^* = \frac{1}{e_tQ_\beta - e_\beta Q_t}\left[(Q + q)(p_tQ_\beta - p_\beta Q_t) + L'(B_tQ_\beta - B_\beta Q_t) + QQ_t\right]$$

and

$$(28)\quad \begin{aligned} \beta^* &= Qp' - \frac{Qe_t}{e_tQ_\beta - e_\beta Q_t} \\ &+ \frac{1}{e_tQ_\beta - e_\beta Q_t}\left[(Q + q)p'(e_tq_\beta - e_\beta q_t) + L'(B_\beta e_t - B_te_\beta)\right], \end{aligned}$$

where

$$(29)\quad \begin{aligned} e_t &= h_1q_t + h_2a_t \\ e_\beta &= h_1q_\beta + h_2a_\beta. \end{aligned}$$

The expressions in (29) describe the change in domestic *production* of pollution resulting from a change in the emissions tax and tariff, respectively.

Interestingly, in the general decentralized solution (27), the optimal emissions tax is *not* equal to zero even when the marginal damage from *domestic* ambient pollution is zero. Interpretation of the solutions for the optimal taxes will be made more readily accessible by the study of special cases, which we now proceed to undertake.

IV. Special Cases

IV.a No Incoming Foreign Pollution

As with the three-instrument case analyzed in Section III, I begin with the assumption of no foreign spillovers into Country D (that is, $r_1 = 0$).[13] Here, in contrast with the general solutions given by Equations (27) and (28), we are naturally suppressing the importance of any differences between the two countries' pollution generating technology. Advantages due to technological differences in production and abatement technology that might be exploited in the general case will play no role in the determination of the optimal emissions tax or tariff here. (This will become evident in Section IV.b, below.)

LEONTIEF POLLUTION FUNCTION. First, I examine the special instance -- the case typically studied by others -- in which domestic pollution is generated by a "Leontief"-type (fixed coefficients) production function with respect to output. In this case, abatement *technology* plays no role:

---

[13] Note that this does not necessarily imply that r_2 is also zero. For example, Great Britain is an exporter of air pollution to the Scandinavian countries; but, because of the prevailing movement of air currents, emissions from the Scandinavian countries do not pollute Great Britain. Hence, we allow for the possibility of flows of domestic pollution out of Country D. We do not, however, concern ourselves with where r_2% of the domestic pollution ends up.

$$e = kq, \quad k > 0. \tag{30}$$

Emissions are simply a constant fraction (k) of output. (In what follows analysis, we do not generally restrict ourselves to the same form of pollution generating function for the foreign firm.)

By setting r_1 to zero in (25), and using (30) in (29), the expressions for the optimal emissions tax (27) and tariff (28) simplify to:

$$(a) \quad t^* = L'(1 - r_2) + \frac{(Q + q)p'}{k(q_t Q_\beta - q_\beta Q_t)} + \frac{QQ_t}{k(q_t Q_\beta - q_\beta Q_t)},$$

(31)

and

$$(b) \quad \beta^* = Qp' - \frac{Q' q_t}{q_t Q_\beta - q_\beta Q_t}.$$

Both Markusen (1975), and Krutilla (1991), study the form of the optimal emissions tax in a setting where emissions are assumed to be determined in this way. Both show that, with the assumption of perfect competition among firms, the optimal emissions tax in the absence of incoming transboundary pollution is simply the Pigouvian tax. For the optimal emissions tax given by (31a), this clearly no longer is so. But, from the analysis in Section III, the grounds for the alteration in result are reasonably clear. In a *closed* economy, relaxation of the assumption of perfect competition leads to a *non*-Pigouvian optimal emissions tax in the *absence of* an output tax (which the Planner had at its disposal in Section III but does not have here).[14] Thus, while the availability of an output tax in Section III allowed the Planner to decentralize the first-best solution in an *open* economy (as Buchanan showed it could in a closed economy), in

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[14] See Baumol and Oates (1988).

an open economy the absence of the output tax *also* leads to a non-Pigouvian emissions tax. So it is not surprising that Markusen's (and Krutilla's) results disappear in the presence of imperfect competition. In an open economy with imperfect competition, the emissions tax reflects the presence of distortion caused by market power, as output is curtailed so as to raise price above marginal cost. When, in addition, there is competition between international rivals, so that the activities of the participants are not confined entirely to the domestic market, the optimal emissions tax will reflect "profit-shifting" motives as well.

These features are reflected in (31a). The first term:

$$(1 - r_2)L'((1 - r_2)kq), \tag{32}$$

is what can be regarded as the Pigouvian portion of the tax. The second term:

$$\frac{(Q + q)p'}{k(q_t Q_\beta - q_\beta Q_t)}, \tag{33}$$

reflects the change in consumer surplus, both from the change in the price of G and the change in domestic and foreign production. This change is weighted by the (inverse of) the marginal product of pollution with respect to domestic output, k. The expression (33) may be re-written in terms of the domestic price elasticity of the polluting good, G:

$$\left[\frac{(Q + q)p'}{k(q_t Q_\beta - q_\beta Q_t)}\right]\left(\frac{\frac{1}{p}}{\frac{1}{p}}\right) = \frac{p\varepsilon_D^P}{k(q_t Q_\beta - q_\beta Q_t)}. \tag{34}$$

When expressed in this fashion, we obtain a result that isn't surprising: the more elastic the demand for G, the larger the optimal emissions tax. That is, the more elastic the demand, the smaller price the distortion from resulting the imperfectly competitive market. Consequently, in the absence of an output tax, the emissions tax need compensate less for the price distortions induced by reductions in output stemming from imperfect competition.

The third term in the optimal emissions tax:

$$\frac{QQ_t}{k(q_t Q_\beta - q_\beta Q_t)}, \tag{35}$$

takes into account the domestic firm's profitability through the effect of the emissions tax on foreign production. This may be thought of as the "profit shifting" component of the optimal emissions tax.

The optimal tariff in the case where there is no incoming foreign pollution is a simple variation on the "usual" import tariff.

While these observations are illuminating, the most important feature of the optimal taxes given in (31) is that, as in the closed economy, in an open economy (even with *no* trans-boundary pollution), imperfect competition prevents the Planner from decentralizing the first-best solution unless an output tax is available.

MORE GENERAL POLLUTION FUNCTIONS. In this section, I consider a more general form for the pollution generating function in the domestic country, still assuming that there are no foreign spillovers of pollution into Country D.

In the solution to the model, the optimal emissions tax in the case of no foreign spillovers, obtained by setting $r_1 = 0$ in the expressions in (23) and substituting the appropriate expressions into Equations (26) and (27) yields:

$$(36)\qquad t^{*} = (1 - r_2)L' + \frac{1}{e_tQ_\beta - e_\beta Q_t}\left[(q + Q)p'(q_tQ_\beta - q_\beta Q_t) + QQ_t\right].$$

As in the Leontief case, it is easy to see that the optimal emissions tax may be thought of as consisting of three different components. The first component is the Pigouvian tax; the second captures the change in consumer surplus; and the third is a profit-shifting component. The difference between the expression in (36) and that in (31) is that, now, domestic abatement technology plays a role in the determination of the optimal tax. Note that the denominator in the (36) may be written as:

$$(37)\qquad h_2(a_tQ_\beta - a_\beta Q_t).$$

Furthermore, it is clear that in the absence of incoming foreign pollution ($r_1 = 0$), the optimal emissions tax is independent of A.

The optimal import tax in the case of no foreign spillovers is given by:

$$(38)\qquad \beta^{*} = Qp' - \frac{xe_t}{e_tQ_\beta - e_\beta Q_t} + \frac{1}{e_tQ_\beta - e_\beta Q_t}\left[(q + Q)p'(e_tq_\beta - e_\beta q_t)\right].$$

The first two terms in (38) may be thought of as the "usual" optimal import tax given in a model of perfect competition. That is, the optimal tariff is a function of the price elasticity of imports in the domestic country.

In contrast with the Leontief technology case, the optimal tariff contains an additional term which may be re-written in the following form:

$$(39)\qquad \frac{(q + Q)p'(e_tq_\beta - e_\beta q_t)}{e_tQ_\beta - e_\beta Q_t} = \frac{p\varepsilon_D^p(a_tq_\beta - a_\beta q_t)}{e_tQ_\beta - e_\beta Q_t}.$$

This additional term takes into account the price elasticity of demand of the polluting good, as well as the relative impact of the two policy instruments on the level of abatement technology employed by the domestic firm.

What appears to be occurring is that, even in the absence of foreign spillovers into Country D, the optimal emissions tax and optimal tariff no longer collapse into their "usual" forms. Although the optimal emissions tax continues to contain a Pigouvian term, because of the imperfectly competitive nature of the market, other factors also influence the form of the tax. These include the demand elasticity, which affects the degree of price distortion induced by the market imperfection, and the ability of the domestic government to affect import levels, thereby shifting profits to the domestic firm in the interest of increasing domestic welfare. Similarly, the import elasticity is not the only thing that determines the optimal tariff. Profit shifting motives are evident, as well as the trade-off between the domestic production of pollution due to marginal changes in the emissions tax and tariff.

IV.b Leontief Pollution Technology With Foreign Pollution

To emphasize the role of different abatement technology across countries, I consider the case where the domestic country has a Leontief production function for pollution (no abatement technology), but assume a more general pollution function for the foreign country. In this more general case, I allow for incoming foreign pollution ($r_1 > 0$). The optimal emissions tax and import tariff are now given by:

$$
\begin{aligned}
t^{*} &= (1 - r_2)L'(r_1 H(Q,A) + (1 - r_2)h(q,a)) \\
&\quad + \frac{(Q + q)p'}{k(q_t Q_\beta - q_\beta Q_t)} + \frac{QQ_t}{k(q_t Q_\beta - q_\beta Q_t)} \\
&\quad + r_1 H_2 \frac{(A_t Q_\beta - A_\beta Q_t)}{k(q_t Q_\beta - q_\beta Q_t)} L'(r_1 H(Q,A) + (1 - r_2)h(q,a)), \qquad (40) \\
\beta^{*} &= Qp' - \frac{Q' q_t}{q_t Q_\beta - q_\beta Q_t} + r_1 H_1 L'(r_1 H(Q,A) + (1 - r_2)h(q,a)) \\
&\quad + r_1 H_2 \frac{(A_\beta q_t - A_t q_\beta)}{q_t Q_\beta - q_\beta Q_t} L'(r_1 H(Q,A) + (1 - r_2)h(q,a)).
\end{aligned}
$$

Note that, in this case, an additional term appears in both the expressions for the optimal emissions tax and import tariff, a term that takes into account both the marginal inflow of foreign pollution through the source-receptor coefficient r_1, and the marginal effectiveness of the foreign country's abatement technology, captured in H_2. In this extreme example, where the domestic country has no abatement technology at its disposal, and by virtue of the fact that the foreign country has some abatement technology, the domestic country has an incentive to exploit the those differences by trying to affect the level of abatement installed abroad and thereby to affect the domestic ambient level of pollution.

IV.c. Case 3: Third Best Policies

In this section, I look at "third best" policies for transboundary pollution when only one instrument is available to the domestic government for dealing with both trade and environmental issues. The two instruments that I analyze are emissions taxes and import taxes. The results are presented and discussed, below.

Optimal Emissions Taxes. There are many circumstances under which trade taxes may no longer be considered a viable policy instruments for which the government may use to achieve its goals. For instance, one might consider conditions under GATT or other trade agreements where the flexibility of trade tariffs and subsidies are greatly hindered. In this case, I consider an environment where the only instrument available to the domestic government are emissions taxes. Here β is set equal to zero.

The social welfare function facing the domestic government is now given by:

$$W = \int_{0}^{q+Q} p(x)dx - (q + Q)*p(q + Q) - L(r_1 H(Q,A) + (1 - r_2)h(q,a)) + th(q,a) + \pi. \tag{41}$$

The optimal emissions tax, found by optimizing only over t, is given by:

$$t^* = \frac{1}{e_t}\left[p_t(q + Q) - qp'Q_t + L'B_t\right]. \tag{42}$$

Once again, note the similarity between the expression for the optimal emissions tax given in Equation (42) to the general expression for the optimal tax in the two instrument case, given in Equation (28). The optimal tax in (42) is partly made up of the Pigouvian tax and a component that takes into account the effect that the emissions tax has on the domestic price of G. Furthermore, note how in the case where only an emissions tax is available to the domestic government, the profit shifting component of the optimal emissions tax becomes more readily identifiable:

$$-\frac{qp'Q_t}{e_t}. \tag{43}$$

The domestic firm's profitability is accounted for through the change in the level of imports due to a change in the optimal emissions tax.

OPTIMAL IMPORT TAXES. For political reasons, such as pressure from industrial lobbyists, it is often infeasible for the government to set environmental policies in an optimal fashion. Or, due to technical difficulties, it may be impossible to accurately monitor emissions at each of pollution source. In either case, a trade tax may be the only instrument available to the government to achieve its goals. Once again, to examine the components of the optimal trade tax in this case, I will assume for simplicity that all emissions taxes, t and T, are set equal to zero. Now, the social welfare function facing the domestic government is given by:

$$W = \int_0^{q+Q} p(x)dx - (q + Q)*p(q + Q) - L[r_1 H(Q,0) + (1 - r_2)h(q,0)] + \beta Q + \pi. \tag{44}$$

I solve for the optimal import tax in the usual fashion; the resulting β^* is given below:

$$\beta^* = p'Q + \frac{1}{Q_\beta}[L'B_\beta + p'q_\beta(q + Q) - Q]. \tag{45}$$

The optimal import tax in the one instrument case is also similar to the optimal import tax in the two instrument case. Both taxes are functions of the price elasticity of imports. Because I have assumed away all emissions taxes, abatement technology is implicitly assumed to equal zero in both countries; hence, Equation (45) does not include a factor that takes into account the marginal valuation of abatement. The optimal tax in Equation (45) does, however, account for the marginal damage of pollution in the domestic economy. Equation (45) can be re-written in the following way:

(46) $$\beta^* = \frac{Q(p_\beta - 1)}{Q_\beta} + \frac{p'qq_\beta}{Q_\beta} + \frac{L'B_\beta}{Q_\beta},$$

where p_B is the derivative of the price with respect to the import tax. Now, it is apparent that the optimal import tax takes into account both tariff revenues and profit shifting motives through the effect of β on domestic output, q. Furthermore, the sign of the optimal tariff is not unambiguous. For example, the optimal tariff may become an optimal import "subsidy" if p_B is less than one and domestic pollution levels *fall* with respect to an increase in β. In the one policy instrument case, the trade-offs between domestic profits and transboundary pollution are exacerbated.

VI. Conclusion

In the joint determination of trade and environmental policy, in a setting characterized by transboundary pollution and imperfect competition, several trade-offs may exist. When the polluting industry is imperfectly competitive, two distortions may lead to policy prescriptions that are in tension with one another. Increased domestic production leads to higher levels of pollution, suggesting that a positive emissions tax is appropriate to deal with the pollution externality; on the other hand, imperfect competition leads to pricing above marginal cost, due to restriction of production, suggesting the need for a corrective output subsidy. These tensions are complicated by the existence of transboundary flows of pollution. If the polluting good is traded, the domestic government must then weigh the consequences of increased domestic output, which would induce higher levels of domestically produced production, against increased foreign output, which could lead to elevated flows of incoming foreign pollution.

Previous study of these issues has led to the conclusion that the optimal emissions tax, in the absence of incoming foreign pollution and with perfect competition, is the Pigouvian tax.

In a more general framework -- in particular, where the polluting good is traded in a market characterized by imperfect competition, and environmental and trade policies are jointly determined -- I find the Pigouvian tax to be optimal only where the domestic government may set an emissions tax, import tariff, *and* an output subsidy, and where, in addition, there exist no incoming flows of foreign pollution. Once we admit inflows of foreign pollution, or when the government no longer has access to all three policy instruments, the optimal emissions tax ceases to be the Pigouvian tax. Furthermore, in that setting, the optimal import tariff plays a role in correcting for foreign pollution, acting as a kind of "countervailing" tax.

The notion of a countervailing tax is further highlighted by our generalization of the possible forms of the pollution function, which in the past has typically been restricted to a fixed coefficients production function that does not allow for the effects of abatement technology. In this paper, I allow for both the existence of abatement technology, and for differences in pollution functions across countries. What I find is that the optimal emissions tax and tariff both exploit differences in abatement technology between countries.

These are just a subset of the issues that may arise from the joint determination of trade and environmental policy. The model developed here produces interesting results, that suggest that prior findings in the literature on this subject may (by reason of their restrictive assumptions) prove to be somewhat misleading. In particular, the form of "optimal" emissions taxes and tariffs may have several components, that reflect trade-offs that may exist between the policy objectives of environmental quality and firm profitability. Untangling the relationships between those trade-offs may prove important to improving our understanding of how trade and environmental taxes ought (at least optimally) to be jointly determined.

Appendix A

The second-order conditions that are sufficient for the solutions to the equations given in (6) to yield a local maximum for each firm are that the Hessian matrices of the respective profit functions be negative semi-definite.[15] That is:

(A.1)

$$\pi_{qq}\pi_{aa} - \pi_{qa}\pi_{aq} \geq 0; \textit{ and}$$

$$\Pi_{QQ}\Pi_{AA} - \Pi_{QA}\Pi_{AQ} \geq 0.$$

We assume that the equilibrium defined by Equation (6) is locally strictly stable,[16] which implies that the Hessian matrix for the entire system must be negative semi-definite:

(A.2)

$$DET \begin{pmatrix} \pi_{qq} & \pi_{qQ} & \pi_{qa} & \pi_{qA} \\ \pi_{aq} & \pi_{aQ} & \pi_{aa} & \pi_{aA} \\ \Pi_{Qq} & \Pi_{QQ} & \Pi_{Qa} & \Pi_{QA} \\ \Pi_{Aq} & \Pi_{AQ} & \Pi_{Aa} & \Pi_{AA} \end{pmatrix} \geq 0.$$

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[15] See Mathematical Appendix to Varian, H.R.; *Microeconomic Analysis, Second Edition*; W. W. Norton and Company, New York, 1984.

[16] The stability condition guarantees that the firms' reaction functions are sloped in the same direction and that they intersect only once (for a unique equilibrium). See Tirole, (1988) for more detail.

Appendix B

Comparative statics may be performed on the first-order conditions for profit maximization by the domestic and foreign firms. By completely differentiating the first order conditions for both firms given in Section II, Equation (6), the following comparative static matrix results:

$$\begin{pmatrix} \pi_{qq} & \pi_{qQ} & \pi_{qa} & \pi_{qA} \\ \pi_{aq} & \pi_{aQ} & \pi_{aa} & \pi_{aA} \\ \Pi_{Qq} & \Pi_{QQ} & \Pi_{Qa} & \Pi_{QA} \\ \Pi_{Aq} & \Pi_{AQ} & \Pi_{Aa} & \Pi_{AA} \end{pmatrix} \begin{pmatrix} dq \\ dQ \\ da \\ dA \end{pmatrix} = \begin{pmatrix} h_1\, dt + d\alpha \\ h_2\, dt \\ H_1\, dT + d\beta \\ H_2\, dT \end{pmatrix}. \tag{B.1}$$

Using the assumption of the equilibrium being locally strictly stable (Equation (A.2), Appendix A), we know that the determinant of the leftmost matrix in (B.1) is positive. For ease in notation, we will simply refer to this matrix as the systems matrix, S.

To obtain comparative static results for the set of first-order conditions for each firm, we apply Cramer's Rule to the above comparative static matrix. To enable us to sign the comparative static results, we make use of the conditions and assumptions below:

$$\pi_{qQ},\ \Pi_{Qq} \le 0;$$

$$(h_1 \pi_{aa} - h_2 \pi_{qa}) \le 0;$$

$$|\pi_{jj}| \ge |\pi_{jk}|,\ j \ne k;$$

$$|\Pi_{jj}| \ge |\Pi_{jk}|,\ j \ne k;$$

$$|h_{jj}| \ge |h_{jk}|,\ j \ne k.$$

Table B-I

Summary of Comparative Static Results

Term	Expression[17]	Sign[18]
q_ι	$\dfrac{(\pi_{aa}h_1 - \pi_{qa}h_2)(\Pi_{QQ}\Pi_{AA} - \Pi^2_{AQ})}{Det\ S}$	< 0
a_ι	$\dfrac{(\pi_{qq}h_2 - \pi_{qa}h_1)(\Pi_{QQ}\Pi_{AA} - \Pi^2_{AQ}) - \pi_{qQ}\Pi_{Qq}\Pi_{AA}h_2}{Det\ S}$	> 0
Q_ι	$-\dfrac{(\pi_{aa}h_1 - \pi_{qa}h_2)\Pi_{AA}\Pi_{Qq}}{Det\ S}$	> 0
A_ι	$\dfrac{(\pi_{aa}h_1 - \pi_{qa}h_2)\Pi_{AQ}\Pi_{Qq}}{Det\ S}$	> 0
q_β	$-\dfrac{\pi_{aa}\pi_{qQ}\Pi_{AA}}{Det\ S}$	> 0
a_β	$\dfrac{\pi_{aq}\pi_{qQ}\Pi_{AA}}{Det\ S}$	> 0
Q_β	$-\dfrac{\Pi_{AA}(\pi^2_{qa} - \pi_{aa}\pi_{qq})}{Det\ S}$	< 0
A_β	$\dfrac{\Pi_{AQ}(\pi^2_{qa} - \pi_{qq}\pi_{aa})}{Det\ S}$	< 0

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[17] In all expressions in Table I:

$$Det\ S = (\Pi_{QQ}\Pi_{AA} - \Pi^2_{AQ})(\pi_{aa}\pi_{qq} - \pi^2_{aq}) - \pi_{aa}\pi_{qQ}\Pi_{Qq}\Pi_{AA} > 0.$$

[18] All assumptions needed to sign the derivatives are outlined in Appendix B.

Table B-I

Summary of Comparative Static Results
(con't)

Term	Expression	Sign
q_α	$\frac{\pi_{aa}(\Pi_{QQ}\Pi_{AA} - \Pi^2_{QA})}{Det\ S}$	< 0
a_α	$\frac{- \pi_{aq}(\Pi_{QQ}\Pi_{AA} - \Pi^2_{AQ})}{Det\ S}$	< 0
Q_α	$- \frac{\pi_{aa}\Pi_{AA}\Pi_{Qq}}{Det\ S}$	> 0
A_α	$\frac{\Pi_{AQ}\Pi_{Qq}\Pi_{AA}}{Det\ S}$	> 0

Appendix C

To re-write the domestic firm's profit maximization problem in terms of its best-response function, we start by implicitly solving for the optimal level of abatement as a function of the output level and emissions tax:

$$(C.1) \qquad -f'(a) - th_2(q,a) = 0 \rightarrow a = a(q;t).$$

Once we have found the optimal abatement level for each output level (and given emissions tax), we can determine how a changes with a change in either q or t:

$$(C.2) \qquad \begin{aligned} \frac{da}{dq} &= -\frac{th_{12}}{f'' + th_{22}} \geq 0; \\ \frac{da}{dt} &= -\frac{h_2}{f'' + t'h_{22}} \geq 0. \end{aligned}$$

Now, let:

$$(C.3) \qquad j = c(q) + f(a) + th(q,a) + \alpha,$$

then, the domestic firm's first-order condition for profit maximization can now be written as:

$$(C.4) \qquad p' + qp' - j_q = 0 \rightarrow q = q(Q;t,\alpha),$$

where $q(x;t)$ is the domestic firm's best-response function. The best-response function for the foreign firm may be derived in exactly the same manner.

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CHAPTER TWO:

Gains From Trade and the Optimal Abatement of Pollution under a Tradeable Permit System: Simulation Evidence on Acid Rain Abatement in the Eastern United States and Canada

I. Introduction

Airborne sulfur dioxide, the primary precursor to acid rain, is not in the habit of respecting national boundaries. Efforts to date to control acid rain in both the United States and Canada have been hindered by the fact that sulfur dioxide emissions (and other airborne pollutants) migrate in *both* directions across the two countries' common border. That bilateral movement complicates the relationship between domestic *production* of emissions and domestic *ambient levels* of pollution. Domestic "autarkic" acid rain abatement policies inherently cannot and obviously do not address this aspect of the problem.

It has been suggested that a *joint* U.S.-Canadian program might offer a more promising approach to the problem of controlling acid rain. For over twenty years, however, the United States and Canada have been unable to reach agreement on a coordinated policy for the reduction of sulfur dioxide emissions. An apparent obstacle to that effort has been a general belief that the costs to the United States of reducing emissions under any "mutually agreeable" joint policy would be higher than under a single-nation program (and might objectively be prohibitive). That belief has been prevalent even though the potential savings in abatement costs under a joint acid rain abatement program have never actually been quantified. In this paper I develop evidence that the prevailing preconceptions are wrong. What I do find, however, is that obstacles of a quite different sort -- potentially serious problems in negotiating a division of the gains from trade -- *may* stand in the way of reaching agreement on a joint program of abatement. I investigate a simple model of a joint U.S.-Canadian acid rain policy based on a particular species of tradeable permit system.[19] Using that model, together with data from which I fit cost functions for the abatement of sulfur dioxide emissions at North American point sources, and estimates of the dispersion of those emissions, I employ simulation techniques to estimate the costs of abatement for both countries, acting both jointly and alone. Consistent with evidence that transboundary flows of acid rain precursors are an important feature of North American acid rain concentration, my findings suggest that the transboundary character of the problem is an important aspect of any optimized program of acid rain control. What I find is that, by exploiting that feature, and the very different structures of the polluting industries in the two countries, there are substantial savings to be achieved through a joint program of abatement.

I initially estimate the (optimal) annualized cost to each country of achieving 15 percent reductions in acid rain concentration in what a number of scientists have deemed "sensitive receptor regions" -- of which there are four in the Northeastern United States and four in Eastern Canada[20] -- under autarkic programs of abatement. Each initial simulation indicates the presence of substantial "spillover" benefits to the other country, driven primarily by transboundary flows of the pollutants. Through additional simulations I estimate the savings in abatement costs from those spillover effects to each recipient country. In each instance, I find the savings to be more than 2 1/2 times the cost of implementing the autarky policy itself.

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[19] As described in Section III, the tradeable permit system that I simulate imposes controls *not* simply on aggregate *emissions*, but on the resulting levels of *ambient pollution*.

[20] These regions were identified in the *Canada - United States Memorandum of Intent on Air Pollution, Atmospheric Modelling Work Group 2*, (1981).

By estimating the costs of achieving comparable reductions under *joint* programs of abatement, I then find (among other things) that for a 15 percent reduction in acid rain concentration in all eight sensitive receptor regions, joint action would reduce the total (annualized) costs of abatement facing Canada by more than $1.1 billion for 30 years -- nearly a 98 percent reduction in cost -- when compared to the Canadian autarky program. The estimated savings to the United States are less dramatic but are nevertheless substantial: annualized costs are reduced by nearly $400 million -- almost 40 percent -- for 30 years. Contrary to prevailing beliefs, the estimates suggest that, to the *United States*, the gains to be realized from trade are sufficiently great as to be worth seriously pursuing.

My findings also suggest, however, the presence of a possibly serious obstacle to a joint program of abatement quite different from what is commonly supposed. The spillover benefits (in terms of avoided abatement costs), while substantial from both the U.S. and Canadian autarkic programs that I simulate, are far more pronounced in the case of the U.S. autarky program. The simulations suggest that those spillover benefits are so substantial as to tempt *Canada* to refrain from reaching an agreement, and simply to "free ride" off U.S. abatement efforts. That fact, together with the fact (also disclosed by my estimates) that acid rain in one U.S. sensitive receptor region might *only* be controlled through abatement at Canadian point sources, suggests the existence of powerful incentives for the United States to come to an agreement, if by doing so it can secure Canadian cooperation in any joint program to abate sulfur dioxide emissions of the sort studied here.

Data for my simulations were derived from actual inventories of U.S. and Canadian point sources of sulfur dioxide emissions, "transfer matrices" (derived from long-range transportation modelling of acid rain precursors) that relate emissions in different parts of North America to acid rain concentrations in the eight sensitive-receptor regions in the Northeastern United States and Canada, and estimates of the costs of abating sulfur dioxide emissions at the inventoried point sources.

The balance of the paper is divided into six sections. Section II provides background on the acid rain problem in the United States and Canada. Section III describes the methodology that I use to simulate a marketable permit system for sulfur dioxide, including a brief discussion of the role of transfer matrices in specifying source-receptor relationships. Sections IV and V describe the data that I used in fashioning the simulations, including the methodology used to fit abatement cost functions for each point-source emitter in my sample. Section VI sets out the results of the simulations, and compares the estimated abatement costs facing each country under autarky and an internationally tradeable permit system. Section VII discusses methods used to test the sensitivity of the results presented in Section VI. A concluding section summarizes the findings of the simulations and discusses some policy implications of the findings.

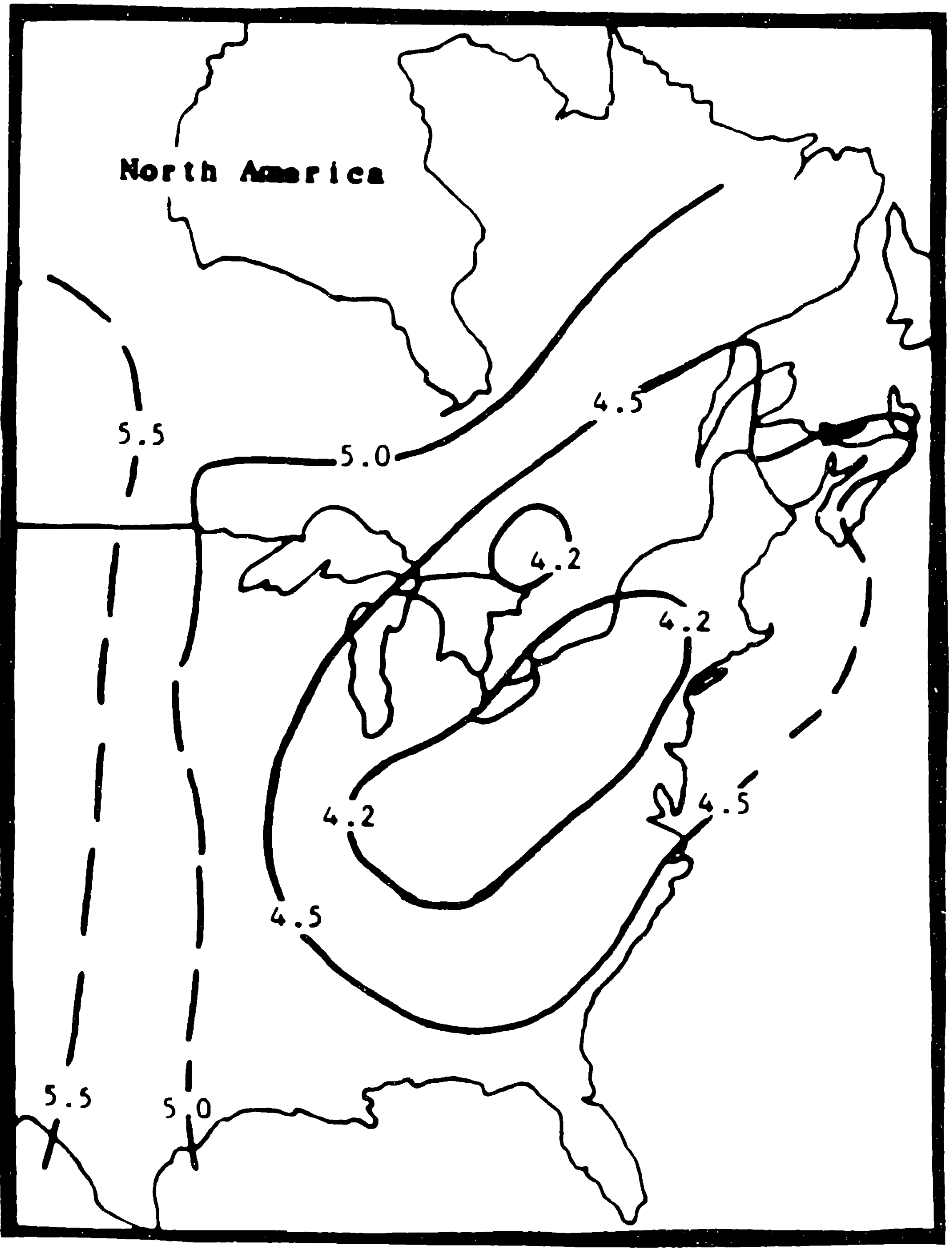
II. Background and Motivation

The primary components of acid rain are sulfur oxides and nitrogen oxides, denoted (respectively) SO_x and NO_x. When SO_x and NO_x are released into the atmosphere from either natural or anthropogenic sources, they can settle out as either dry or wet deposition. Dry deposition occurs through the release of the oxide particulates into the environment, creating a potential health hazard through the accumulation of those particulates in the lungs. It is believed to be responsible for a number of respiratory ailments.

Wet deposition occurs when sulfur and nitrogen oxide particulates mix with atmospheric moisture, forming an acidic solution that enters the environment as rain, snow, or even mist. In solution, SO_x and NO_x are responsible for the acidification of lakes and the resulting death of

Figure I

The Average pH of Precipitation in North America (1980)[21]



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[21] Source: U.S - Canada Work Group Two compilation and analysis of 1980 data from NADP, APN, MAP3S, and CANSAP atmospheric monitoring networks for the U.S. - Canada Memorandum of Intent on Transboundary Air Pollution.

fish, the destruction of crops, and the deterioration of human structures. There is also evidence that higher levels of acidity in water supplies lead to elevated concentrations of toxic metals in the water.

Wet deposition has become especially serious in the Northeastern regions of the United States and in Eastern Canada. Eight "sensitive receptor" regions have been identified in the eastern regions of both countries, four in each country. The rainfall in these eight regions typically exhibits an average pH level well below 5, whereas "unpolluted" rainfall typically has a pH level of at least 5.6.[22] Figure I displays average 1980 pH levels of rainfall for various regions in North America. More recent figures on the average pH level of rainfall in the Northeastern United States and Eastern Canada suggest that there has been no significant change in acid rain concentrations over the past decade.

Policy for the mitigation of acid rain has focused primarily on the reduction of sulfur dioxide emissions, even though both Canada and the United States have primary and secondary ambient air quality standards for both nitrogen and sulfur dioxide emissions. There are two plausible reasons for this fact. First, sulfur dioxide is more evident than nitrogen oxides: sulfur dioxide affects visibility and smells bad, whereas nitrogen oxides are both invisible and odorless. Moreover, the output of sulfur dioxide is more than twice nitrogen oxide emissions in both Canada and the United States. In 1985, for example, sulfur dioxide emissions in the U.S. were

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[22] The pH scale is logarithmic, with lower pH values denoting higher levels of acidity. In 1980, acid rain concentrations in the northeastern United States and Eastern Canada were recorded at average pH levels that ranged from 4.2 to 5. To put these numbers into perspective, it may help to note that battery acid has a pH of approximately 1.2, lemon juice of 2.3, and vinegar of 2.9. Distilled water, which is neutral, has a pH of 7. Rainfall with a pH below 5.6 is considered to by acid rain. The lowest measured rainfall pH in the United States was recorded at Wheeling, West Virginia in the Fall of 1978, and was approximately 1.9. (See Wetstone and Rosencranz.)

approximately 23 million tons, whereas nitrogen oxide emissions were only about 10 million tons.[23] The 6:1 ratio of sulfur dioxide to nitrogen oxide emissions in Canada is even more stark.

Anthropogenic sources of sulfur dioxide vary greatly between Canada and the United States. In the United States, since the 1960s, the bulk of the emissions has been generated by coal-fired electric generating plants.[24] Because Canada relies more heavily on other sources (such as hydro-electricity) for power, most Canadian sulfur dioxide emissions come from industrial and manufacturing sources, in particular from non-ferrous smelters. Table I summarizes the sources of sulfur dioxide emissions from both countries for 1985. During that year, electric power generation accounted for approximately 69 percent of total U.S. sulfur dioxide emissions, but only 20 percent of Canadian emissions. In contrast, industrial and manufacturing processes accounted for 67 percent of Canadian emissions and for less than 13 percent of U.S. emissions. In the aggregate, Canadian emissions were less than 20 percent of U.S. emissions. These differences in the sources of sulfur dioxide emissions in the United States and Canada will prove to be important, because they lead to differences in the two countries' cost structures for the *abatement* of those emissions. (*See* Table II, below.)

One major difficulty in controlling acidic deposition stems from the complex nature of the "source-receptor" relationship between the emitters of precursors to acid rain and the resulting acidic precipitation. For U.S. and Canadian authorities, this intrinsic difficulty in formulating policy has been further complicated by the transboundary flows of the pollutants. Scientists have

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[23] Data were taken from the *1985 National Acid Precipitation Assessment Program (NAPAP) Emissions Inventory Version 2*, described in greater detail in Appendix C.

[24] Before that time, the largest source of sulfur dioxide emissions in the United States was industrial/manufacturing processes (including non-ferrous smelters).

Table I

1985 NAPAP Emissions Inventory Version 2[25]
Point and Area Source Emission by Major Category

Source	SO_2 Emissions (10^3 tons/year)	
	United States	Canada
Electric Utilities	16,055	819
Industrial Combustion	2,679	340
Comm. / Res. / other Combustion	613	69
Industrial / Manuf. Processes	2,931	2,731
Transportation	864	99
Other	4	0
Total	23,146	4,058

Table II

Estimates of the Incremental Costs of Removing Pollutants From New Sources[26]

Sulfur Dioxide Source	1980 Dollars per Metric Ton Removed
Electric Utilities: Eastern Coal Western Coal	265-298 1,167-1,414
Iron and Steel Coking	184-579
Primary Copper	22
Primary Lead	315
Primary Zinc	222
Paper	92 - 12.437

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[25] Source: U. S. Environmental Protection Agency; *1985 National Acid Precipitation Assessment Program, Version 2.*

[26] Environmental Protection Agency, "The Incremental Cost Effectiveness of Selected EPA Regulations;" (EPA, January 23, 1981).

estimated that the United States exports twice as much acid rain to Canada as it imports. Nevertheless, transboundary pollution between the United States and Canada is unambiguously a two-way street.

Evidence for the bilateral nature of these flows has been developed from studies using "long-range transportation" (or "LRT") modelling of the migratory patterns of acid rain precursors and the resulting "source-receptor" relationships. In general, there are two classes of LRT models currently in use. The first is based on a "Eulerian" grid, that models air masses moving over a fixed grid of points. The second is based on a "Lagrangian" method, which traces out the trajectory of moving air masses. Each type of LRT model takes into account such factors as the elevation (usually denoted "stack height') of emissions sources, the surface contours of the terrain, temperature, and general weather patterns that prevail in the areas of interest. Each also takes into consideration rates at which chemical reactions occur in the atmosphere in predicting where the dry or wet deposition will occur. Although these models have not been perfected, and the choice of methodology remains somewhat controversial, LRT modelling has afforded policy - makers improved insights into the importance of both inter-state (or inter-provincial) and foreign pollution spillovers in achieving domestic ambient pollution goals.

To date, acid rain abatement programs have not been sensitive to the transboundary nature of the problem or to differences in the sources of sulfur dioxide emissions in Canada and the United States. In the United States, pollution abatement efforts have been dominated by "command and control" strategies that have mandated the expenditure of billions on pollution abatement with very little evidence of achieving any substantial reduction in acid rain concentration in domestic sensitive receptor regions. The *Survey of Current Business* recently estimated that, in 1990, the United States expended more than $68 billion, or 1.7 percent of Gross Domestic Product, on pollution abatement, of which over $23 billion was allocated to air pollution control.[27] Between 1970 and 1988, the U.S. achieved only a 27 percent aggregate reduction in sulfur dioxide emissions, an average annual reduction of only 1.5 percent;[28] whereas air pollution abatement *costs* rose at an average annual rate of 5.4 percent between 1972 and 1981, and at an average annual rate of 2.3 percent between 1972 and 1990.[29] Policies in Canada have been even less structured, in the sense that Canadian *industries* have furnished the primary impetus for more stringent pollution abatement. There is, however, as little evidence as for the United States that those actions have reduced acid rain concentrations in any of the Canadian sensitive receptor regions.

Efforts by the United States and Canada to reach a joint agreement on the mitigation of acid rain have extended over nearly twenty years, but have been uniformly unsuccessful. During the Carter Administration, the two countries initialled a Memorandum of Intent on Transboundary Air Pollution (MOI), that required each to study the causes and consequences of acid rain in a number of pre-determined sensitive receptor regions in both countries. The MOI also required common commitments to take all possible actions to reduce transboundary pollution through individual domestic pollution control policies. The stated objective of the MOI was to increase awareness and understanding of the transboundary nature of the acid rain problem, and to bring the two countries closer to a joint agreement on abatement. With the Reagan Administration, however, whatever progress had been made apparently came to a halt.[30]

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[27] *Survey of Current Business*, June 1992, p. 25. Figures are originally given in $1987 but have been adjusted to $1991 using the CPI.

[28] Sulfur dioxide emissions were at a high in 1970 at 31.2 million tons.

[29] Expenditures on air pollution abatement have remained fairly constant at approximately $23 billion (in $1990) since 1981.

[30] In a 1982 memorandum, Mr. Raymond Robinson, then Executive Chairman of Canada's Federal Environmental Assessment Review Office, wrote regarding the U.S. stand on acid rain research and policy development that:

Political considerations aside, two technical considerations have hindered progress towards any joint U.S.-Canadian agreement: gaps in the scientific understanding of acid rain, and a lack of data on point source emitters of sulfur dioxide. Perhaps more importantly, however, anecdotal evidence suggests that the reluctance of the United States to reach a joint agreement has been fueled by the simultaneous apprehension that the abatement costs would be enormous, and would produce no significant improvement in environmental quality, despite the fact there has been no concrete evidence to suggest that either supposition is so. With recent improvements in scientific understanding of the problem, and the recent availability of appropriate data, we are now in a position to begin investigating the extent to which such apprehensions are founded in fact or in fear.

III. An Alternative: A System of Tradeable "Licenses to Pollute"

In this section I describe the model I shall use to estimate the possible gains to be achieved from a joint, U.S.-Canada program of pollution abatement. My model makes use of a system of tradeable permits as the means of achieving those gains. As a result of the 1990 Amendments to the Clean Air Act, the United States has, of course, authorized the use of tradeable permits as a means of dealing with domestic pollution. That system consists of what in effect are "emissions licenses": they allow the holder to produce specified levels of *emissions*,

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> . . . A pattern of external interference or inadequate support of the work has continued over the past year and a half. Our scientific experts have attended scheduled meetings and had virtually no one turn up on the United States' side or had people arrive whom they had never before seen. Despite the frustration of operating under such conditions, our people have occasionally succeeded in laboriously putting together a draft only to have it greatly changed by United States officials who had not been involved in the discussions that produced it. . .

Robinson, R.M., *The Rule of Law Between Nations - An Acid Test*, presented at the Seventh Symposium on Statistics and the Environment, National Academy of Sciences, Washington, D.C., October 4-5, 1982.

irrespective of the actual *impact* of those emissions on ambient environmental quality. What this paper is focused on, however, is the cost of achieving a specified reduction in *ambient pollution*, possibly in several distinct geographic regions. In particular, I seek a model for a program of acid rain abatement (1) that may be undertaken by either a single country, or by two countries jointly, (2) that can target specific reductions in acid rain *concentration* in each of several different regions, and (3) that is cost effective. To motivate the choice of marketable permit system that I employ, I first describe the shortcomings of a marketable permit system based on "emissions licenses," and then describe the model that I actually use.

III.a The Shortcomings of Emissions Licenses

Typically, the goal of an environmental policy is to achieve an "acceptable" level of environmental *quality* in some region -- which (borrowing terminology used in connection with North American acid rain abatement) I simply denote a "sensitive receptor" region. In terms of air pollution, this means achieving a given level of *ambient* air quality in the sensitive receptor region. The principal strength of a marketable permit system for dealing with an environmental objective is that, while it *cannot* specify what the *optimal* level of *abatement* should be, in principle it can, for a *given* level of abatement, achieve it in a cost-efficient way. The "usual" marketable permit system operates by imposing an exogenously given limitation on the aggregate level of *emissions* by restricting the number of permits that are issued. Each polluter must hold one permit for every unit of emissions produced. Each polluter then buys (or sells) permits until the marginal cost of the permits (their price) to the polluter equals the marginal savings in abatement cost from being able to emit one additional unit. If the objective of the system is to control for the ambient level of pollution in a given region, this means that controlling the aggregate level of emissions will work *only if* there is a one-to-one relationship between emissions and ambient pollution.

Several different complications may, however, disrupt the relationship between emissions from sources of pollution and the level of ambient pollution in the receptor region. The first is that the marginal contribution to ambient pollution in the receptor region may differ across emitters. (This complication might arise simply because of locational differences among polluters.) If the marginal rates of substitution for emissions among emitters in creating ambient pollution are not all equal to one, controlling for the ambient level of pollution in a receptor region will no longer be as simple as controlling aggregate emissions. Furthermore, the least-cost solution to achieving a particular reduction in aggregate *emissions* will no longer necessarily be the least-cost solution for achieving a particular reduction in *ambient pollution*. This problem obviously can be further complicated by the existence of multiple sensitive receptor regions, in addition to multiple sources of pollution.

A second complication arises if the sensitive receptor regions lie in different countries, and are (differentially) affected by pollution from sources in both countries. Once again, the direct link between aggregate emissions and ambient levels of pollution no longer exists. Moreover, any autarkic policy to control ambient levels of pollution may prove ineffective at achieving program objectives, at least if the flows of transboundary pollution from foreign emitters are large. Here, political considerations may stand in the way of achieving a solution.

Under such conditions, a simple system of emissions license may simply be incapable of achieving a particular level of ambient pollution in the sensitive receptor regions in a cost efficient manner. As it happens, the acid rain problem in eastern North America is characterized both by the existence of multiple sensitive receptor regions and by marginal rates of substitution of emissions in creating ambient pollution that differ across polluters.

III.b A Market for Licenses to Pollute

The model I now describe makes use not of "emissions licenses," but of what may be denoted "licenses to pollute." It draws heavily on theoretical work by Montgomery (JET 1972). The distinguishing feature of a system of permits of this form is that they confer on the holder the right to pollute, but *only* as long as doing so does not lead to an increase in acid rain *concentrations* above some exogenously specified level, in any receptor region specified by the administering authority as being of concern. Given the data needed for its implementation, such a system allows the administrator to prescribe not merely the levels of emissions to be permitted, but to fix those levels in a manner calculated to achieve a pre-specified improvement in ambient environmental quality in one or more regions, taking into account the natural migratory patterns of the pollutant.

Consider, then, a region in which there are n point-source emitters of sulfur dioxide, indexed by $i \ (= 1, \ldots, n)$. The total annual emissions of sulfur dioxide from point source i is denoted by e_i, and the vector of emissions from all point sources is given by $E = (e_1, \ldots, e_n)'$. There are m sensitive receptor areas in the region, indexed by $j \ (= 1, \ldots, m)$. Exogenously determined ambient air quality standards for sulfur dioxide for *each* of the m sensitive receptor areas are given by $S^* = (s_1^*, \ldots, s_m^*)'$, which I shall take to be measured in micrograms/cubic meter/year (μg/m^3/year). Emissions at point source i are related to average concentrations of sulfur dioxide in receptor region j by a "source-receptor" coefficient, h_{ji}. The coefficients h_{ji} are furnished by LRT studies of North American migration of sulfur dioxide. The array of source-receptor coefficients is thus an m x n matrix H with non-negative entries each of which relates the contribution of one unit of sulfur dioxide emitted at point source i to the average concentration of sulfur dioxide in receptor region j:

(1) $$H = \begin{pmatrix} & \cdot & \\ \cdot\ \cdot & h_{ji} & \cdot\ \cdot \\ & \cdot & \end{pmatrix}_{m\ x\ n\ (m<n)}$$

Hence, $H \cdot E = S$.

The program objective is to construct a policy such that an emissions vector will be chosen that will bring air quality standards into compliance in each of the m receptor regions, at *least total cost* for the entire geographic system. The emissions vector, E^*, that achieves these objectives will then be efficient *for the given ambient air quality standards*, S^*.[31] The standards imposed by S^* imply that, if all sensitive receptor areas are in compliance with the prescribed environmental standards, then $H \cdot E \leq S^*$.

I assume that associated with each point source is a cost function, denoted by C_i, that describes the cost of achieving a given level of abatement for a given level of output. So, for source i with output level y_i:

(2) $$C_i = C_i(e_i, y_i)$$ [32]

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[31] I emphasize here that I am *not* attempting to simulate optimal implementation of an *optimal* program of abatement, which would entail equating the marginal costs of abatement to the marginal *damage* from ambient pollution. I instead take the program objective (captured in S^*) as exogenously determined and seek optimal *implementation* of *that objective*.

[32] Although the cost function is a function of output, I assume in the simulations that output remains constant (at 1985 levels). Consequences of this assumption are discussed in Section VII.

The cost function is a minimum value function that describes the least cost technology, or combination of technologies, by which to achieve a given level of abatement.[33]

The level of emissions for each point source is bounded above by a maximum that (at each level of output) is given by the emissions assuming that *no* abatement technology were adopted (the "base" level); and is bounded below by the maximum reduction that could be achieved, using the most efficient available abatement technology, expressed as a percentage of the base level:

$$[1 - PR_i^{max}]\,base_i \leq e_i \leq base_i \tag{3}$$

where PR_i^{max} is the maximum percentage reduction in sulfur dioxide emissions possible using the best available control technology.

The least-cost strategy is then given by the solution to:

$$\text{Minimize} \quad \sum_{i=1}^{N} C_i\left(e_i, y_i\right) \tag{4}$$

$$\begin{gathered} \text{Subject to} \quad H \cdot E \leq S^{*}_{m \times 1}\,, \text{ and} \\ [1 - PR_i^{max}]\; base_i \leq e_i \leq base_i; \quad (i = 1, \ldots, n) \end{gathered} \tag{5}$$

The contribution of Montgomery is to show that, with a modest set of assumptions, the efficient vector of emissions may be attained through a system of marketable licenses to pollute, using a competitive market for the licenses, relative to any initial allocation of those licenses.

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[33] This is a general formulation of the problem. As discussed in Section V, below, the actual simulations were run using cost functions that were estimated for each point source using specific assumptions about the actual choice of abatement technology.

Proofs of the existence and efficiency of this market can be found in Montgomery (1972). Given the existence of a policy that can be decentralized to achieve E^*, one can calculate the aggregate (optimal) cost of that policy by solving the minimization problem specified in (4)-(5).

IV. Data: The 1985 National Acid Precipitation Assessment Program

The data used in this paper are derived from a series of studies conducted under the *1985 National Acid Precipitation Assessment Program, Version 2* ("NAPAP"). NAPAP was established in 1980 by the U. S. Congress (pursuant to Title VII of P.L. 96-294) to study acidic deposition in the United States and Canada. Under this program, over 93 data tapes were compiled, containing detailed information on *every* area and point source emitter of more than 100 tons of any criterion pollutant in 1985, located in *either* the United States or Canada. Information on over 370,000 sources of sulfur dioxide are inventoried in the NAPAP tapes.

Point source emissions account for approximately 92 percent of total U.S. sulfur dioxide emissions and 90 percent of total Canadian sulfur dioxide emissions in 1985. Because of the very different characteristics of area sources (which include mobile sources) of pollution, such sources have been excluded from this study. For the simulations presented in Section VI, moreover, only a subsample of the point source data is used.

Data for the U.S. were restricted to electric utility generating point sources. These sources are easily the largest single class of contributors to sulfur dioxide emissions in the United States. In 1985, they accounted for 69 percent of aggregate U.S. sulfur dioxide emissions. Detailed data on this class of U.S. point sources was obtained from a NAPAP study referred to as the 1985 National Utility Reference File ("NURF"). NURF contains unique information on electric utility generating plants that had not previously been available. It contains detailed, unit-level data for 10,778 electric generating units in the United States (of which 9,755 were existing units, and 1,023 had been announced at the time of the study).[34]

In contrast with the United States, Canadian sulfur dioxide emissions are not dominated by electric utility sources (as shown in Table I). As has been already mentioned, the composition of Canadian industry, and the contributions of different industrial sectors to Canadian sulfur dioxide emissions, furnish some reason to believe *a priori* that there might be significant gains to be achieved from free trade in pollution licenses. In Table I, notice that only 20 percent of all sulfur dioxide emissions in Canada are accounted for by electric utility generating facilities; industrial and manufacturing processes account for approximately 67 percent of Canadian emissions.

Canadian data for the study reported in this paper were not restricted by source. Data on the point sources used in the study are obtained primarily from the 1985 NAPAP Annual Canadian Point Source Inventory ("ACPSI").[35] No counterpart to the NURF data set is available for Canadian electric utilities. It is, however, less important to obtain detailed information about Canadian electric generating sources, because (as reflected in Table I) the primary Canadian sources of sulfur dioxide emissions are industrial processes, in particular, non-ferrous smelters.

To create the matrix H, described in the preceding section, source-receptor transfer coefficients were obtained from a study conducted by the Canada - United States Atmospheric Modelling Work Group 2 ("Group 2"), for the *Canada - United States Memorandum of Intent on Transboundary Air Pollution*. Several long-range transportation models were developed by Group 2 to study the impact of sulfur dioxide emissions in both the United States and Canada on

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[34] A more detailed description of the NURF files are in Appendix C.

[35] See Appendix C for more detailed information on the contents of the ACPSI.

eight regions in the eastern half of the two countries, four each in Canada and the United States.[36] (See Figure II.) Although different models generally did not yield identical transfer coefficients for each of those regions, the relative magnitudes of importance of the different contributing states and provinces proved to be fairly similar. In this paper, the transfer coefficients that were used were developed by the Ontario Ministry of the Environment, based on a simple statistical model that incorporates both Lagrangian and Eulerian techniques, to simulate long term ambient concentration and wet deposition patterns on a regional scale for eastern North America. The transfer coefficients, displayed in Table III, relate the concentration of sulfur dioxide in wet deposition (micrograms per meter cubed per year) from a one teragram (10^{12} grams) emission of sulfur dioxide from a given source region. So, for example, one teragram of sulfur dioxide emitted from Ohio would lead to an annual average increase in wet sulfur dioxide deposition in Region I by 0.22 micrograms per cubic meter, 0.51 micrograms per cubic meter in Region II, and so on. Figure II shows the geographic center of each of the sensitive-receptor regions.

There are some noteworthy features to the source-receptor coefficients that I use. In Region I (Algoma), on a "per teragram of sulfur dioxide emissions" basis, Ontario is the most significant contributor of acid rain -- with Michigan and Florida-Missouri-Minnesota making almost as large a contribution.[37] In Region II (Muskoka), Ontario is once again the most significant contributor, with Michigan being the second largest. Region IV (Southern Nova Scotia) is dominated by emissions from New York to Maine. Ontario and Quebec are primary contributors to both Regions V and VI (Pennsylvania and the Smokie Mountains, respectively),

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[36] The eight regions are Algoma, Muskoka, Quebec, Southern Nova Scotia, Vermont/New Hampshire, the Adirondacks, Pennsylvania, and the Smokie Mountains.

[37] By most significant "contributor", I mean simply, a one unit reduction in emissions in Ontario will lead to the greatest reduction in acid rain concentration in Region I.

both of which are located in the United States. What the source-receptor coefficients indicate are that there are potentially significant transboundary flows of acid rain between the two countries in *both* directions -- which, if they can be exploited, may play an important role in a joint program for acid rain abatement.

The sub-sample of the data used in the following simulations includes a total of 400 point sources. They consist of the 200 largest *utility* generating point source emitters of sulfur dioxide in the United States; and the 200 largest *general* point source emitters of sulfur dioxide in Canada. For 1985, this sub-sample accounts for 65 percent of all sulfur dioxide emissions from U.S. electric utility generating plants, and over 45 percent of all U.S. sulfur dioxide emissions; it accounts for over 95 percent of all Canadian sulfur dioxide emissions. Despite the relatively small nature of this subsample, it accounts, in the aggregate, for over 53 percent of *all* 1985 U.S.-Canadian point source emissions of sulfur dioxide.

Table III

Source-Receptor Coefficients for
Annual Sulfur Dioxide Concentration ($\mu g/m^3$)
per unit emission (Tg.S/yr)

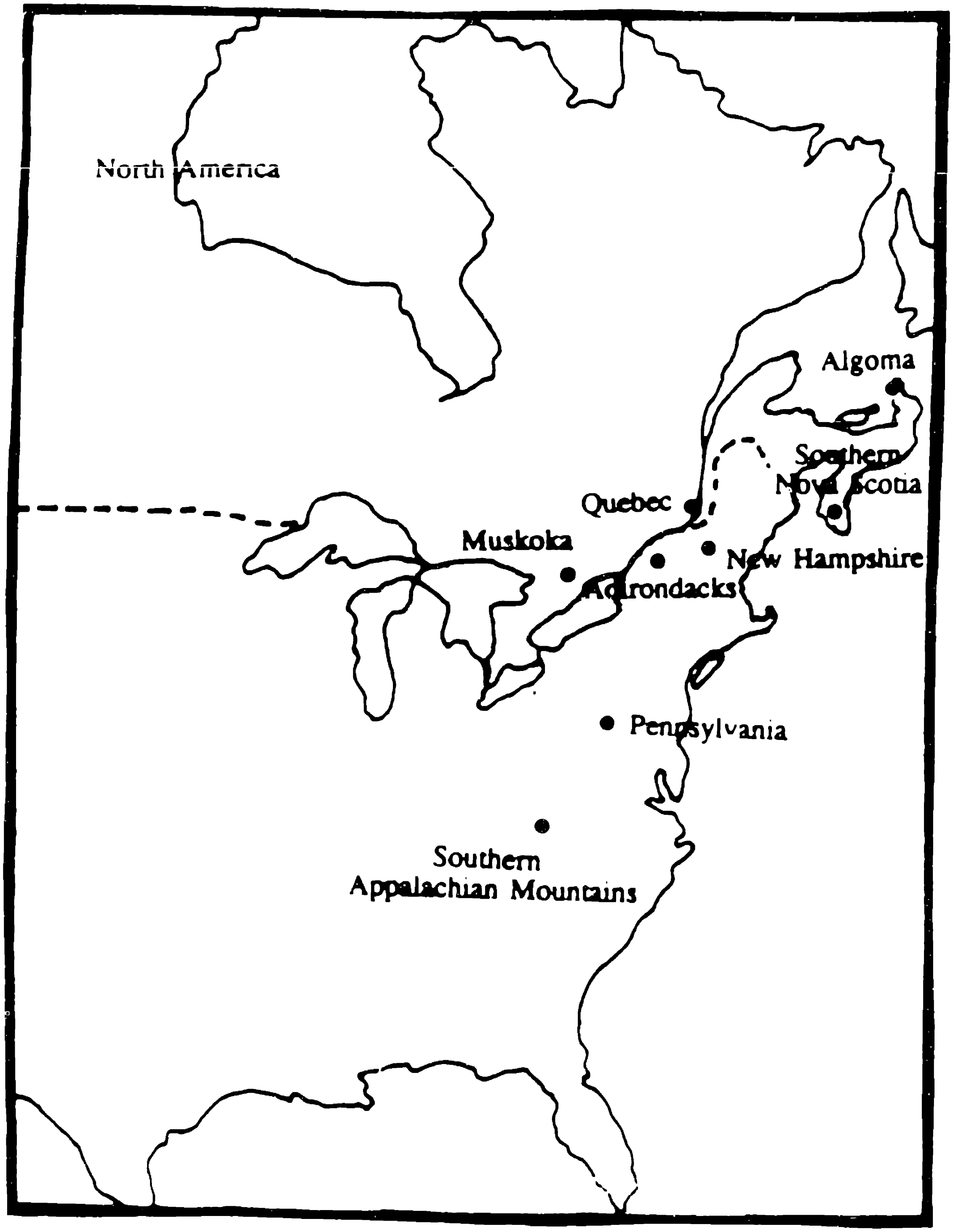
	Sensitive Receptor Areas							
Source Region	RI	RII	RIII	RIV	RV	RVI	RVII	RVIII
Michigan	0.70	1.70	0.50	0.57	0.91	1.50	3.30	0.16
Illinois Indiana	0.34	0.49	0.19	0.22	0.31	0.46	1.30	0.80
Ohio	0.22	0.51	0.25	0.40	0.48	0.78	4.00	0.37
Penn.	0.17	0.46	0.30	0.62	0.63	0.99	9.20	0.16
New York to Maine	0.10	0.33	0.40	1.90	1.00	1.60	0.62	0.06
Kentucky Tennessee	0.12	0.19	0.10	0.15	0.17	0.23	0.74	3.20
W. Virg. to N.C.	0.10	0.22	0.17	0.40	0.33	0.46	1.70	0.26
Florida to Mo. to Minn.	0.68	0.55	0.20	0.18	0.28	0.38	0.62	1.90
Ontario	1.00	3.20	1.90	0.91	2.00	2.20	0.96	0.06
Quebec	0.30	0.57	3.00	1.30	4.70	1.10	0.18	0.03
Atlantic Provinces	0.03	0.07	0.26	1.50	0.26	0.15	0.05	0.01

RI: Algoma; RII: Muskoka; RIII: Quebec; RIV: Southern Nova Scotia; RV: Vermont/New Hampshire; RVI: Adirondacks; RVII: Pennsylvania; RVIII: Smokies (Southern Appalachians).

Figure II

Sensitive-Receptor Regions

(Geographic Centers)



V. Estimating Control Costs

In general, the term "point source," as used in the sets from which the data for this study were derived, denotes emissions from a single boiler unit or smoke stack. It is important to note that any particular "facility" -- utility, industrial, or residential -- may consist of more than a single point source. Unfortunately, there are virtually no current studies available on the cost of abatement functions for different industries. Therefore, I must rely upon engineering estimates and methodology to estimate the cost functions needed for the simulations. As a result, a number of somewhat restrictive (although reasonable) assumptions must be made. In estimating the cost of reducing sulfur dioxide emissions, I assume that a single abatement technology will be adopted for *each point source*, rather than for each "facility" as a whole. It seems to be agreed upon within the engineering community that it is more efficient, from both a cost and process point of view, to adopt abatement technologies by point source, at least as long as each point source is reasonably large, rather than routing all emissions from all point sources within a given plant facility through a single cleaning facility. This is especially true of pre-existing facilities, to which pollution abatement equipment must be retrofitted.

Cost functions were therefore estimated for each *point source*. Those cost functions relate the aggregate annual cost of abatement to the *percentage* reduction in emissions from the "base level," defined as the level of emissions that would be produced in the absence of any abatement technology. The estimated cost functions, which draw on engineering estimates and methodology, take into account the costs of installing the basic control equipment (*e.g.*, a scrubber) together with auxiliary equipment or "add-on" controls (such as fans, hoods, and ductwork), all annualized over the equipment's operating life; operating and supervisory labor costs; maintenance costs, raw material inputs, and electricity. So-called "retrofit factors," which scale up basic installation costs to reflect the additional expense entailed in outfitting pre-existing point sources, were also taken into account.

To estimate cost functions for the reduction of sulfur dioxide emissions, the emissions data were separated by point source into one of three categories: (1) utility-owned electric generating plants, (2) non-ferrous smelters, and (3) other industrial/manufacturing processes. Different abatement technologies were assumed to be adopted within each category. What is more, in many instances there is a wide range of possible means by which to achieve a given level of abatement, so that I was obliged to make a number of other assumptions regarding the technology adopted at each category of point source. These assumptions (and their justifications) are described in detail in Appendix B, and are summarized briefly below.

V.a Electric Utility Generating Facilities

A number of *feasible* technologies and processes are available to reduce sulfur dioxide emissions from electric generating facilities. From among the possibilities (and for reasons developed in Appendix B.a), I assumed that abatement was *not* achieved at such point sources either by switching (when technically feasible) from high- to low-sulfur coal; or by resorting to chemical cleaning of high sulfur coal in advance of combustion. Instead, I assumed the adoption of one of two general types of "flue gas desulfurization" (FGD) -- or "scrubber" -- technologies that are used to remove sulfur dioxide from electric utility waste gas streams. Scrubbers are classified as either "dry" or "wet" scrubbers. Dry scrubbers generally are installed in smaller facilities ($\leq$ 100 MW design capacity) that characteristically use low sulfur coal. Since, however, the sample data that are used in the current simulations include only the largest emitters, which tend to use *high* sulfur coal, I assumed that wet scrubbers would characteristically be installed. Installation costs were annualized over the life of the equipment (or, if less, in the case of retrofitted equipment, the life of the plant on which it was installed). I assume also that the cheapest reagent, limestone -- the more expensive alternative is lime -- would be used as the primary chemical reagent in the system. I assume that a linear relationship holds between percentage reduction of emissions and total annualized costs of abatement; and, on that assumption (and as described in Section V.d), I estimate cost functions for each point source.

V.b Non-Ferrous Smelters

For purposes of controlling sulfur dioxide emissions, non-ferrous smelters fall into one two general categories: strong gas stream and weak gas stream smelters. Strong gas stream smelters are generally classified as those with gas streams with greater than a 5 percent acid concentration. For that category, the cheapest sulfur dioxide abatement technology is the construction of an on-site metallurgical sulfuric acid plant. For such smelters the costs of that form of abatement were used. The same option generally is not available for smelters with weak gas streams, unless they were also to install technology to strengthen the acid concentration of their exit gas. For them, abatement costs were estimated on the assumption that they installed an FGD system using wet scrubber technology.

Available information[38] was used to match the NAPAP point source data on non-ferrous smelters with their company name so as to identify any equipment currently in use. For smelters that had sulfuric acid plants in operation as of 1981, I assumed that the same technology would continue to be used. For smelters with no abatement technology in place, acid concentrations typical for the type of process in place were used to determine whether or not the installation of

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[38] Data were obtained from the *Canadian Mining Handbook* (1985), and the *Canada - United States Memorandum of Intent on Air Pollution, Emissions Costs and Engineering Assessment Interim Report, Work Group 3B* (1981).

an acid plant facility would be feasible. That information was then used to estimate the costs of installing the appropriate technology.

V.c Other Industrial/Manufacturing Processes

In contrast with utilities and (to some extent) non-ferrous smelters, there is very little general information available on the costs of pollution abatement technology for industrial sources. I therefore relied heavily on engineering cost estimates and the methodologies outlined in Vatavuk (1990). One of the difficulties in determining the costs of reducing sulfur dioxide emissions in manufacturing and industrial sectors is determining the appropriate allocation of costs to different pollutants, when several are removed using a single abatement technology. Given the range of possibilities, wet scrubbers of a "venturi" or "double venturi" sort (see Appendix B.c), which are suitable for removing both particulates and gaseous emissions, but are somewhat less efficient at gaseous removal than other sorts of scrubbers were generally used. The choice between the two technologies was determined by the maximum volumetric flow rate of the point source's exit gas. I also chose to allocate all costs of installing the equipment to sulfur dioxide removal, despite the fact that this technology is also suitable for the removal of other pollutants. Clearly, this assumption will impose an upward bias on the estimate of the costs of abating sulfur dioxides. Once the abatement technology was chosen, cost estimates from Vatavuk (1990) were used to determine equipment costs.

V.d Methodology for Estimating the Cost Functions

Once the choice of abatement technology had been fixed for each point source, I fitted a *linear* function to relate that point source's total annualized costs of abatement to its percentage reduction in sulfur dioxide emissions. In general, the cost of abatement is not linear in abatement: kinks may exist beyond a particular level of abatement, particularly when a technology is pushed beyond its maximum reliable level of abatement. Because, however, the simulations restrict the levels of abatement to be no greater than the maximum reliable efficiency level for each technology's design, it is reasonable to linearize the cost of abatement function in this area.

Estimates (generally based on information from engineering sources) were developed of the costs of installing and operating the abatement equipment. These estimates encompassed the capital outlay to install the abatement system (including control and auxiliary equipment); fixed operating and maintenance costs (*i.e.* those incurred at any positive level of abatement, once the equipment was installed) (or *FOMC*); and operating and maintenance costs that varied with the level of abatement (or *VOMC*). To annualize the capital cost of the abatement system, I used a capital recovery factor (*CRF*) of the form:

(6)
$$CRF = \frac{i(1 + i)^m}{(1 + i)^m - 1},$$

where i is the (allowed) rate of return and m is the lifespan of the project in years.[39] The "correct" value for m is typically taken to be the *lesser of* (1) the estimated remaining operating life of the point source, or (2) the estimated operating life of the abatement system itself.[40]

Total *annualized* costs are therefore given by:

(7)
$$Total\ Annualized\ Costs_i = ACC_i + FOMC_i + VOMC_i,$$

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[39] The rate of return used in the preparing the cost estimates was assumed to be constant over the relevant time period at 5 percent.

[40] Note, also, that by annualizing the capital expenditures to acquire the pollution abatement equipment, our *cost* functions do not capture the actual pattern of *outlays* to implement the simulated programs of abatement.

where *ACC* is simply the initial capital outlay for the equipment, multiplied by the appropriate Capital Recovery Factor (as given by (6)).

Operating cost estimates are typically given in the engineering literature for operating an abatement system at its *maximum* reliable level of efficiency. To estimate the costs of operating each abatement technology at lower levels of efficiency, a number of assumptions (outlined in Appendix B) were made for each of the different technologies used in the simulation. In short, however, I assumed that, to operate at a lower efficiency, smaller amounts of reagents would used in the case of FGD, Venturi, and Double Venturi scrubber systems.[41] Reduced reductions in emissions were more generally assumed to bear a linear relation to *variable* operating and maintenance costs[42] (but not, obviously, to fixed operating costs or to annualized capital costs).

Consequently, I estimated total annualized costs of abatement at levels of abatement below the maximum reliable level of efficiency (computed by five percent decrements), by adding reduced variable costs to annualized capital costs and fixed operating and maintenance costs. The cost functions implied by this procedure are obviously non-linear. Hence, the final step was to calculate a linearized cost function by estimating, for each point source *i*, the linear equation:

$$TAC_i = \alpha_i + \beta_i PA, \quad i = 1,\ldots,n, \tag{8}$$

where *PA* is percentage abatement of emissions, determined by reference to the maximum reliable operating efficiency for the technology assumed to be adopted by point source *i*. By restricting

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[41] For contact sulfuric acid plants, the plants are simply shut down (not producing) for short periods of time.

[42] For example, if limestone were to account for 20 percent of variable operating and maintenance costs of a wet scrubber, and if engineering estimates of all variable costs were \$1 million for a 90 percent reduction, the calculated variable costs for an 80 percent reduction were taken to be \$0.2 million*(8/9) + \$0.8 million.

the cost function to this form, I am assuming a constant marginal cost of abatement. Furthermore, linearizing the cost functions in this manner allows me to formulate the problem described in equation (4) as a linear programming problem.[43] Note that I assume that the operating load at each point source remains *constant* (at 1985 levels) for the entire period over which the abatement equipment is depreciated. As such, the cost functions give the minimized cost of achieving a specified percentage abatement of emissions *for the given (1985) level of output* reflected in the NAPAP inventory data. Hence, in the simulations, the cost functions (2) are actually of the form:[44]

$$C_i = C_i(e_i, \bar{y}_i), \qquad \text{(2A)}$$

where $\bar{y}_i$ = 1985 operating load. Accordingly, I do not consider the possibility of reducing emissions by reducing output levels (or by shutting down any point source). I consider the sensitivity of the results to this assumption in Section VII.

VI. Simulations and Results

Several different simulation experiments are described in this section, based on the marketable permit system for licenses to pollute described in Section III. The simulations are categorized into three sets, each described below. In the first set I estimated the cost of abatement to the United States and Canada under "autarkic" programs of abatement. Each

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[43] Note that corner solutions will dominate the solution for the cost minimization problem due to the linearization of the cost function with constant marginal cost. The importance of estimating the total annualized cost for each point source's abatement technology at maximum reliable efficiency, therefore, is somewhat important. Although some of the total annualized cost estimates for the point sources were not 100 percent accurate for estimating the cost of running the chosen abatement technology at its maximum reliable removal rate, the estimates were typically within five percent of the actual costs. Sensitivity analysis on the cost estimates are discussed further in Section VII.

[44] Note that this requires assumptions on the separability of the cost function.

country was assumed to implement its own tradeable permit system, taking the emissions of the other country as fixed at its 1985 level. The constraint imposed on each country was a minimum 15 percent reduction in average annual acid rain concentration in *each* of *its own* four sensitive receptor regions. In terms of Equation (5), this implies that S^* is given by:

(9) $$S^*_{m \times 1} = 0.85(S^{1985})_{m \times 1}$$

where S^{1985} is a vector of actual 1985 concentrations of acid rain in each of the sensitive receptor regions, as calculated (below) for the sub-sample of 400 point source emitters in the United States and Canada, and $m = 4$ for both the United States and Canada.[45]

In the second set of simulations I estimated the savings in abatement costs to each country of the "spillover" effects, attributable to transboundary flows of pollutants, from the autarkic policy pursued by the other (as calculated from the first set of simulations). Two different kinds of simulations are carried out. The first estimates the optimal abatement cost to each country of achieving the reduction in acid rain concentration in each of *its* sensitive receptor regions that was produced as a byproduct of the autarkic program implemented by the other. That is, I ask the question -- what is the dollar savings to country *i* of the reduction in acid rain concentrations in country *i* from the autarkic policy implemented by country *j*. The second estimation looks at the

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[45] The 15 percent reduction in acid rain concentrations across each of the eight sensitive receptor regions is a somewhat arbitrary policy goal. Without an explicit damage function which allows some "valuation" of the reductions in acid rain concentrations, optimal abatement levels cannot be determined within this system. Given the sample size used for the simulations presented here, a 15 percent reduction was the largest reduction that could be achieved across the board under autarkic policies implemented by each country. Note that there is no reason why each sensitive receptor region must face the same reductions. The "weight" given to a sensitive receptor region, for example, may be determined by the population or land mass of the area. Another alternative might be to have a policy goal that required that all eight regions have some pH floor that must be attained -- again, determined by some damage function.

benefits from being a "free-rider" by estimating the cost of abatement to country *j* of pursuing what might be described as a "Stackelberg" - type approach to abatement. I estimate the cost to country *j* of an autarkic policy to achieve a 15 percent reduction in acid rain concentration in its own sensitive receptor regions, *taking into account* the spillover reductions from country *i*'s autarkic policy.

The third set of simulations calculates the costs to each of the two countries under a joint tradeable permit system. Again, two different calculations were carried out. The first simulates the total cost of achieving at least a 15 percent reduction in acid rain concentration in all eight sensitive receptor regions. The second calculates the total cost of achieving the *largest* reduction in acid rain concentration, in *each* of the eight sensitive-receptor regions, that was achieved under *either* country's initial autarkic program.

The methodology used to fix the initial conditions for the simulations and the results from those simulations are described and presented below. All tables referred to in this section may, unless otherwise noted, be found in Appendix A.

VI.a. Methodology

Each simulation consists of the solution to a linear version of the constrained cost minimization problem given in equation (4) and outlined in Section III. One preliminary calculation was carried out before running any of the simulations. Using the 200 largest (electric utility) point source emitters in the United States and the 200 largest emitters in Canada (as given by the 1985 NAPAP data), I first calculated the concentrations of acid rain attributable to those point sources, in each of the eight sensitive receptor regions, based on 1985 levels of emission. To do this, I utilized the source-receptor coefficients summarized in Table III (in Section IV, above). I applied the appropriate coefficient to each point source, multiplied it by that point source's *actual* 1985 emissions, and then summed over all point sources for each receptor region. This procedure yields the average annual acid rain concentration, attributable to all point sources in the sample, in each sensitive receptor region. The resulting 1985 estimates of acid rain concentration in the eight sensitive receptor regions are summarized in Table A.I.

In two of the four Canadian sensitive receptor regions, Regions I and IV (Algoma and Southern Nova Scotia), U.S. emissions of sulfur dioxide are responsible for more than 50 percent of the resulting acid rain concentrations -- 69 and 57 percent, respectively. And in Region III (Quebec), U.S. emissions are responsible for almost 49 percent of the resulting concentration. Two considerations drive these results: (1) the volume of sulfur dioxide emissions in the U.S. and (2) the source-receptor relationships between point sources in the U.S. and sensitive receptor regions located in Canada. A similar, although less pronounced, pattern is seen in the U.S. sensitive receptor regions. In Region V (Vermont/New Hampshire), Canadian emissions contribute to 59 percent of acid rain concentrations. It is interesting to note, on the other hand, that in Regions VII and VIII (Pennsylvania and the Smokie Mountains), Canadian emissions contribute less than 5 percent to acid rain concentrations; in those regions acid rain is primarily due to "local" (U.S.) emissions. The estimates reported in Table A.I support the belief that transboundary migration of emissions is an important feature of the North American acid rain problem.

All simulations were carried out using linear programming.[46]

VI.b. Simulation of Autarkic Pollution Policies

First, I examine autarkic abatement programs implemented separately by the United States and by Canada. For each policy, the simulations assume that:

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[46] A simplex algorithm furnished by MATLAB™ was used in carrying out all the simulations.

> (1) the program objective is to reduce average acid rain concentrations in each of the four sensitive receptor regions *in the implementing country* by at least 15 percent from 1985 levels, and
>
> (2) each country, in formulating its program, takes the other country's emissions as fixed at 1985 levels.[47]

The first assumption is just that, under autarky, each country is concerned exclusively with improving its own environmental quality. The second is that, under autarky, each country assumes it must achieve its objective on its own. Neither can rely on any spillover effect from a reduction in emissions by the other country, due to the transboundary migration of pollutants.

Table A.II summarizes the simulation results for the United States; Table A.III summarizes the results for Canada; Table A.IV reports the dual values on the constraints for both autarkic policies. Under an autarkic program of marketable licenses to pollute, the total annualized cost to the United States of achieving a 15 percent reduction in acid rain concentrations in Regions V - VIII is $0.977 billion. In the solution to the cost minimizing program, Regions V and VIII achieve the minimum reduction of 15 percent in acid rain concentration. Region VI experiences a reduction in acid rain concentration (from base 1985 levels) of nearly 25 percent, and Region VII achieves a reduction of more than 45 percent. The annual cost to Canada of an autarkic policy is $1.186 billion. The resulting concentration in Region I reflects the minimum 15 percent reduction; whereas, for Regions II - IV, final concentrations are reduced by between 20 and 40 percent over base 1985 emissions levels.

The autarky results exhibit some striking features. The annual cost to the United States under an autarkic policy is almost $200 million, or 20 percent, lower than the annual cost to Canada. In part, this can be explained by the volume of U.S.-generated emissions polluting Canadian sensitive receptor regions, beyond autarkic control by Canadian authorities. To meet

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[47] The four sensitive receptor regions in Canada are regions I-IV; those in the United States are regions V-VIII.

its autarkic objectives, it appears that Canada must reduce *domestic* emissions by significantly more than would otherwise be necessary if foreign pollution did not contribute to Canadian acid rain. This view is consistent with the large dual value on the constraint for Canadian Region I, set out in Table A.IV, of more than $600 million per $\mu g/m^3$/year.

Equally striking are the substantial spillovers from both autarkic policies. The U.S. autarkic policy produces a spillover reduction in acid rain concentration of more than 15 percent in all but one (Region III) of the Canadian sensitive receptor regions. The Canadian autarkic policy leads to significantly more than a 15 percent reduction in two of the U.S. sensitive receptor regions -- Region V and VI -- but has negligible effects in the others. The dual values summarized in Table A.IV suggest, moreover, that the value of the spillover effects due to the transboundary nature of the pollution -- especially in Regions I and V -- may be sizeable for both the United States and Canada.

VI.c. Estimating the Spillover Effects

There are two ways in which one can measure the cost savings that arise from the spillovers that occur from each country's separate autarkic policy. The first is by simulating the cost that country *i* would (optimally) have incurred to achieve the reductions in acid rain concentration in each of its own sensitive receptor regions that appeared as spillovers from the autarkic policy implemented by country *j*, assuming that country *j*'s emissions remain fixed at 1985 levels. The value I calculate here is *not* the value of *additional* reductions in acid rain, beyond the reductions achieved by country *i* under its own autarkic policy (described above). The value of the spillover, as measured here, may instead be thought of as a lower bound on the annual cost savings to country *i* from the domestic abatement policy of country *j*.[48] A second way in which to measure the cost savings due to the spillover effects is to estimate the "free-rider savings," by which I mean that the costs country *j* would incur to implement an autarkic policy, *knowing* that country *i* will *also* implement an autarkic policy (with a 15 percent reduction), and *knowing also* how country *i*'s policy will affect country *j*'s acid rain concentrations. Under this "Stackelberg"-type simulation, country *j* is "free-riding" off of the reductions in acid rain that occur from country *i*'s program of abatement, and can therefore reduce its own abatement *effort*, while still achieving an aggregate reduction of 15 percent in acid rain concentration in each of its own sensitive-receptor regions. I present both forms of estimates below.

V.c.1 Spillover Savings

Table A.V summarizes the first measurement for the United States, that is, the simulated costs to the United States of attempting to achieve on its own the spillover effects of the Canadian autarkic policy. The attempt turns out to be infeasible. What I find is that, to achieve the acid rain reductions produced as spillovers from the Canadian autarkic policy, the United States would have to reduce emissions at *all* point sources in the sample by *more than the maximum technically feasible percentage*. The problem is with U.S. Region V. Given the results from the autarky simulations this finding is not altogether surprising. Recall from Table A.I that Canadian emissions were responsible for just under 60 percent of the acid rain concentration in Region V. The Canadian autarkic policy produced a sizable spillover reduction in that region; in contrast, the U.S. autarkic program achieved the minimum reduction, and a large dual value -

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[48] That is, since, in the simulations, abatement is occurring *optimally*, lowest cost (to abate) emissions are abated first. If, then, the value of the spillovers were estimated assuming that country *i already* had a program of abatement in place, the cost savings from the spillover effects of country *j's* program of abatement would be valued by abating emissions from *higher* cost point sources.

- approximately $20 million per unit reduction in concentration -- was associated with that reduction. This simulation makes explicit the conclusion that, if the U.S. *wanted* to achieve a reduction in acid rain concentration equal to that produced as a side-effect of the Canadian autarkic policy, it could not do so through an autarkic policy alone. The cost of abatement associated with the maximum *feasible* reduction in emissions at all U.S. point sources is estimated at in excess of $3.00 billion.

The cost savings associated with the spillover effects from the U.S. autarkic policy on the Canadian sensitive receptor regions is presented in Table A.VI. The savings from the spillovers is estimated at approximately $2.851 billion. This figure may, however, be misleading. Comparing the final concentration levels achieved under this program with the final concentrations of acid rain achieved under the Canadian autarkic policy in the previous section, the noticeable fact is that the final concentrations here are only slightly lower. The cost of these modest improvements, however, is almost $2 billion per year. The additional cost is due largely to the small, incremental reduction in acid concentration in Canadian Region I, the region that exhibited an enormous dual value on the constraint in the simulation of the Canadian autarkic policy.

One especially striking feature of both these simulations is the magnitude of the savings to *both* the United States and Canada from the other country's autarkic program of abatement. In each instance the spillovers *savings* are more than 2 1/2 times the *cost* to the implementing country of their autarkic program of abatement.[49] This is dramatic evidence for the importance of transboundary flows in achieving cost-effective abatement of emissions, a question I address more directly in Section VI.d, below.

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[49] This clearly is *not* to suggest that the aggregate spillovers are worth the *sum of* these savings, since the spillover benefits in some measure duplicate the local abatement achieved by each country's autarkic policy itself.

V.c.2. "Free-Rider" Estimates

The results for the two "free-rider" estimates are summarized in Table A.VII. When the U.S. assumes that Canada will implement a 15 percent reduction in acid rain concentrations in the Canadian sensitive-receptor regions, the U.S. needs only to reduce acid rain concentrations in U.S. Regions VII and VIII to obtain a 15 percent reduction (from 1985 levels) in acid concentrations in all four of its sensitive receptor regions. The annualized costs to the U.S. under this simulation decline to approximately $231 million, a savings of more than $600 million over the U.S. autarkic program. When the situation is reversed -- that is, when Canada assumes that the U.S. will implement its own autarkic policy, and free-rides off the U.S. spillover reductions -- the annualized costs facing Canada are only $1.8 million, annualized savings of over $1.0 billion. These numbers suggest that there may exist powerful incentives for each countries to seek to free-ride off the other, leading to possibly substantial hold-up obstacles to the achievement of a joint U.S.-Canadian agreement on acid rain reduction.

VI.d Joint Programs of Abatement

Here, I present the results from simulations that estimate the cost of abatement facing the United States and Canada under two different joint programs of abatement, each involving a system of internationally tradeable permits. The objective of the first program is a minimum 15 percent reduction in acid rain concentration in each of the eight North American sensitive receptor regions; the second seeks to achieve a reduction in acid rain concentration in each of those eight regions at least equal to the maximum reduction for that region actually achieved by *either* the Canadian or U.S. autarkic program of abatement (as simulated in Section VI.b). In both instances the savings are dramatic.

Table A.VIII depicts the costs savings from a joint program calling for at least a 15 percent reduction in all eight sensitive receptor regions. What I find is that, jointly and optimally carried out, the *aggregate* annual cost of a joint program to achieve at least a 15 percent reduction in each region is only $632 million annually, of which about $608 million is incurred by the United States and $25 million by Canada. The aggregate savings over the two autarkic policies are more than $1.5 billion annually, of which $389 million are enjoyed by the United States, and about $1.157 billion are experienced by Canada. The savings to both countries are obviously substantial.

Table A.IX summarizes the findings from a joint U.S.-Canada program of abatement that seeks to achieve acid rain concentrations in the eight sensitive receptor regions *at least as low* as the lowest concentration under either of the autarkic programs summarized in Tables A.I and A.II. Under this program, the total annual cost of abatement is only $1.145 billion, $1.09 billion for the United States, $55 million for Canada. For this program two comparisons are worth pursuing. Compared to the maximum abatement possible under an autarkic program of abatement (the results of which are set out in Table A.V), this represents an annual savings to the United States of nearly $2 billion (although, for some U.S. sensitive receptor regions, the reductions in acid rain concentrations would be less).[50] For Canada, a comparable comparison (see Table A.VI) discloses annual savings of nearly $2.8 billion, *together with* the achievement of lower acid rain concentrations in all but one of its sensitive receptor regions. Equally compelling are the comparisons of these costs to the costs of the basic autarkic programs, implemented to achieve a 15 percent reduction in acid rain. Canada achieves larger reductions in acid rain concentration in every sensitive receptor region, despite a $1.13 billion reduction in

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[50] The dual values on the constraint facing Region III suggests, moreover, that further cost savings could be generated if the concentration constraint here could be made less restrictive.

annual cost. The United States experiences *substantial* gains in reducing acid rain concentration in all but one of its sensitive receptor regions. The price of these gains is modest, not (as commonly supposed) substantial: a $100 million increase in annualized cost.

A different way in which to compare the costs associated with the joint programs and the autarkic policies is summarized in the pay-off matrix contained in Figure III:

Figure III

Annualized Costs (in $1990 Billions) For Different Options to
Achieve a Minimum 15 Percent Reduction in Acid Rain Concentration[51]

	Canada	
United States	($0.977, $1.185) (Autarky, Autarky)	($0.977, $0.002) (Autarky, Stackelberg)
	($0.231, $1.185) (Stackelberg, Autarky)	($0.608, $0.025) (Joint Policy)

Aggregate combined costs of achieving a 15 percent over-all reduction of acid rain concentration in all eight sensitive-receptor regions is clearly minimized by a joint program and is maximized through separate autarkic policies. These results are not surprising. What is, striking, however, is the very substantial differences in annualized savings to the two countries from free-riding off the other country's autarkic policy. These are summarized in the off-diagonal elements in Figure III. Canada's annualized costs become trivial (approximately $2 million) if it acts on the assumption that the U.S. will implement a 15 percent reduction through an autarkic policy. In this instance, Canada need only be concerned with Region III, the only Canadian region in which,

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[51] Note that the upper left entry to the pay-off matrix is *not* an equilibrium, whereas the other three entries are, in fact, possible equilibrium outcomes.

under a U.S. autarkic policy, a 15 percent reduction does not occur. In terms of aggregate joint costs, this is the second least costly solution overall.

For the United States, reliance on a Canadian autarkic policy produces savings of over $600 million annually over a U.S. autarkic policy that is implemented on the assumption that Canadian emissions remain fixed at 1985 levels. The savings are less dramatic than in the Canadian "free-rider" case.

VI.e Autarkic Control of All Point Sources

Given that there are both gains from trade and large incentives to free-ride off the other country's autarkic policy, one final question that might be asked is: how much would country *i* pay country *j* to assist country *i* in achieving a 15 percent reduction in acid rain concentration in country *i*'s sensitive receptor regions. To estimate the "pay-offs" that might occur, I return again to autarkic programs implemented by each country to achieve a 15 percent reduction in acid rain concentration in its own sensitive receptor regions. In this instance, however, I simulate the aggregate costs for each country assuming that in can implement a tradeable permit system that involves *all 400 point sources* in the sample, and compare those costs with the costs facing the country under the autarkic policy optimized only over domestic point sources.

On these assumptions, Table A.X summarizes the simulation results of achieving a 15 percent reduction in acid rain concentration in the U.S. sensitive receptor regions. The aggregate annualized cost is $454 million, of which $443 million is incurred for abatement at U.S. point sources and $11 million at Canadian sources. The difference between this figure and the annualized cost to the United States of its domestic autarkic policy for a 15 percent reduction ($0.977 billion) is $523 million. Table A.XI summarizes the results of a comparable simulation, this time to achieve a 15 percent reduction in acid rain concentrations in the Canadian sensitive receptor regions. When all 400 point sources are caused to participate in a Canadian abatement program, the total annualized cost of the program is $385 million (of which about $350 million consists of abatement at U.S. sources), a savings of about $800 million over the cost to Canada of a pure autarkic program.

One way of looking at these simulations is that, in principle (and for a program calling for a 15 percent reduction in U.S. domestic acid rain), the United States should be willing to pay up to $523 million (annually) to obtain Canadian participation in abatement; conversely, Canada should be willing to pay as much $800 million to obtain U.S. participation. But the simulation results exhibit several other interesting features that suggest that neither of those outcomes is likely.

Looking first at Canada, the numbers confirm again that, consistent with the fact that much of Canadian ambient pollution arises from U.S. sources, it would be far more efficient for Canada to improve its domestic ambient air quality by reducing emissions at U.S. point sources. While such a program would be more costly to Canada than simply free-riding off U.S. abatement efforts, it would also achieve compliance in all four Canadian sensitive-receptor regions.

More interesting are the U.S. numbers. For the United States, efficient abatement still involves reducing emissions predominantly at U.S. point sources. Nevertheless, the United States can reduce its aggregate annualized cost of abatement by approximately 50 percent by securing a relatively trivial measure of abatement at Canadian sources. This suggests that it would be extremely advantageous to the United States to secure Canadian participation in any joint program of abatement. Short of outright cash transfers, one way in which the United States might secure that participation would be to offer to allocate initially to *all* Canadian point sources permits sufficient to allow them to continue emitting at baseline levels, so that, in effect, U.S. emitters would have to *pay* Canadian emitters for any abatement they undertook. This would produce a pareto-improvement in the cost of abatement, since the net cost to Canada would be zero.

Such an agreement would not, however, bring all Canadian regions into compliance. But an additional annualized expenditure of about $150 million (mostly at U.S. point sources) would. It is not obvious whether Canada might successfully insist that the United States specify a 15 percent reduction in *all* eight sensitive-receptor regions as part of the price of its participation; or whether, on the other hand, the United States might be in a position to insist that Canada bear the annualized costs of that respecification of the objective.

VII. Sensitivity Tests and Other Considerations

In interpreting the results presented in Section VI, it is important to keep in mind the three significant assumptions that have been made. In the paper, I have assumed, over the 30-year period during which the abatement technology is in place (and over which the equipment is depreciated), that (1) output remains at 1985 levels, and (2) industrial processes remain stable -- including fuel mix. Both of these assumptions are required for estimated base levels of emissions to remain constant over the lifespan of the abatement equipment (or, if shorter, the lifetime of the plant). A third assumption is that I assume that firms do not engage in activities that will alter their source-receptor relationships with any of the sensitive receptor regions.

In general, options available to polluters do include reducing output, or even shutting down. Under the tradeable permit system that I describe in this paper, shut down should occur if the value of production from any point source is less than the cost of the permits the point source is required to hold. In that instance it would be financially more attractive simply to sell the permits and discontinue operation. By assuming that output remains constant at 1985 levels, I clearly do not allow for that possibility.[52] Imposing this condition does allow one to side-step the more complicated welfare considerations that arise when point sources actually shut down in response to a tradeable permit system. For that very reason, moreover, shut down decisions can (and, in some instances, probably would) be affected not just by purely economic but by political considerations, which might be expressed in the form of special exemptions for particular facilities.

Assumption (2) ensures that technological changes do not occur that affect the way in which the base emissions are calculated. Changes in industrial processes *can*, of course, have a dramatic effect on emission levels, as can alterations in fuel mix. Allowing the base level of emissions to change over time would complicate the calculations significantly. Because, however, I have no way of predicting what changes in process design or fuel mixes might actually occur, I have not allowed for flexibility in either of these conditions.[53]

The third assumption that I make restricts firms to the same h_{ji} coefficient over time. So, for example, firms are not given the option of moving or changing the height of their smoke stack in order to "abate" emissions via changing their h_{ji} coefficient. This assumption has important consequences for the long-run analysis of the results. Location issues will be important if it is possible for firms to reduce the costs of abatement that they face by simply moving to a region that has a lower impact on the sensitive-receptor regions.

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[52] For electric utilities, this is not necessarily a bad assumption. The demand for electricity will generally not decline over time, however, due to technology that allows electricity to be transported very efficiently over long distances, one may want to allow changes of output amongst plants within a region so long as over-all output remains constant within that region. Regional boundaries, however, would be determined wholly on the state of transmission technology, and may be somewhat arbitrary.

[53] As pointed out in Appendix B, there is anecdotal evidence for the proposition that there may exist local political obstacles to the relatively simple step of switching from high to low sulfur coal.

Unfortunately, the shortage of data and other information concerning abatement costs limits the number and quality of the sensitivity tests that may be conducted on the results. The area in which most concern lies with regards to the estimations is in the cost of abatement functions. Some simple tests that were carried out included testing how robust the results were to changes in the rate of return, which affects the capital recovery factor I used to annualize the capital outlays. The base cost of abatement functions were calculated using a 5 percent rate of return. No significant changes resulted when a 7 percent rate of return was used. Upper and lower bounds on the cost estimates were also calculated, using the general rule of thumb that engineering cost estimates are accurate to within ± 20 percent. Allowing the estimated constant marginal cost abatement to vary by ± 20 percent, I re-ran the linear programming simulation for a joint program for a 15 percent reduction in acid rain concentrations in all eight sensitive receptor regions testing all eight combinations of cost functions. The reductions in acid rain concentrations remained the same as in the base cost simulation in all eight cases -- the only difference being in the shadow values of the constraints in some of the simulations. The basic differences in the cost saving of moving from an autarkic policy to a joint policy remained robust in all eight tests.

There are two other considerations that merit thought. First, electric utilties are a regulated industry in the United States and, therefore, are not necessarily cost minimizers. The simulations assume that all polluters will behave in a cost efficient manner. If this assumption is violated for the electric utilities, the cost estimates will underestimate the costs associated with the tradeable permit programs. The second consideration is that I assume that trades only occur between polluters -- outsiders (for example, the Sierra Club) are not included in the trading system. If individuals or organizations are allowed to buy and sell permits, and have higher valuations for less acidic rain, then the price of the permits will be driven upward and the cost of abatement should correspondingly also rise.

VIII. Conclusion and Implications

The simulation results presented in this paper tend strongly to contradict the belief that it would be prohibitively costly to the United States to participate in a joint program of acid rain abatement with Canada. To the contrary, I find that *both* the U.S. *and* Canada would experience substantial reductions in annualized abatement costs under a joint program, when compared to the costs of comparable autarkic policies. The gains from trade appear to be driven primarily by (1) the transboundary nature of the pollution, and (2) structural differences in the primary sulfur dioxide producers operating in the two countries.

The evidence, however, is consistent with the possibility that the two countries *might* have been thus far unable to reach agreement on a joint program of abatement because of substantial *differences* in the magnitude of the savings that would accrue to each. Given the differences disclosed by the simulations, both countries -- but especially Canada -- may be confronted with substantial incentives to "free-ride" off an autarkic program of acid rain pursued by the other.[54] This may create potential hold-up problems, turning on difficulties in allocating the gains to be realized from trade. All this suggests that arriving at a joint agreement may prove to be far more complicated than would be suggested by the simple magnitude of the cost savings that are there to be realized. Unfortunately, if whatever differences that have forestalled agreement to date are driven by an inability to allocate gains from trade, and if it should prove politically infeasible for each country simply to free-ride off the other, the worst-case scenario might be the one that

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[54] As noted in Section II, while existing U.S. efforts have been of questionable effectiveness, they have been relatively substantial; whereas Canada has yet to adopt a national program of acid rain abatement.

society ends up actually observing. Each country might end up implementing an autarkic program of abatement, a course that would, at least on the basis of the evidence presented here, *maximize* the joint costs of achieving target reductions in acid rain concentration in each country's sensitive regions.

Although the potential gains from trade suggested by the simulation evidence are large, it remains important to determine how robust those estimates are to variations in the assumptions, especially the assumptions concerning the cost of abatement functions facing the different categories of emitters in the sample (and more generally in the NAPAP inventory). To augment the confidence in the conclusions, it will be important to develop more accurate characterizations of the cost functions than can be obtained from engineering estimates alone -- even if the results are robust to at least a ± 20 percent change in the estimated marginal cost of abatement. That is the obvious next step. With such data one can arrive at an even more accurate assessment of the gains from trade between the United States and Canada through a joint program of abatement; and of whether, as my simulations strongly suggest, difficulties in arriving at an agreement on the division of those gains may by what has actually stood in the way of an agreement.

Appendix A

This Appendix contains tables that summarize the simulation results that were presented in Section VI of the text. All dollar values are given in constant $1990 values.

Table A.I

1985 Acid Rain Concentrations Derived from Sample Data

Sensitive Receptor Region	Total Canadian Contribution (%)	Total U.S. Contribution (%)	Concentration (μg/m^3/year)
RI: Algoma	30.88	69.12	0.4165
RII: Muskoka	51.20	48.80	0.7613
RIII: Quebec	70.06	29.94	0.5452
RIV: Southern Nova Scotia	43.29	56.71	0.4734
RV: Vermont/New Hampshire	58.97	41.03	0.7818
RVI: Adirondacks	37.15	62.85	0.7673
RVII: Pennsylvania	4.74	95.26	2.0817
RVIII: Smokie Mountains	0.42	99.58	0.9458

Table A.II

U.S. Autarky Policy for a 15% Reduction of Acid Rain Concentrations in Regions V-VIII

Region	1985 Base Concentration (μg/m^3/yr)	Autarky Limit (μg/m^3/yr)	Final Concentration (μg/m^3/yr)	% Change from Base
Region I	0.41646		0.3521	- 15.44
Region II	0.76132		0.6389	- 16.07
Region III	0.54510		0.4851	- 10.99
Region IV	0.47328		0.3585	- 24.24
Region V	0.78181	0.66450	0.6645	- 15.00
Region VI	0.76740	0.65219	0.5816	- 24.20
Region VII	2.08182	1.76946	1.1362	- 45.42
Region VIII	0.94559	0.80390	0.8039	- 15.00
Total Cost: $0.977 Billion				

Table A.III

Canadian Autarky Policy for a 15% Reduction of Acid Rain Concentrations in Regions I-IV

Region	1985 Base Concentration ($\mu g/m^3/yr$)	Autarky Limit ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change from Base
Region I	0.4165	0.3540	0.3540	- 15.00
Region II	0.7613	0.6471	0.5770	- 24.20
Region III	0.5451	0.4634	0.3289	- 39.65
Region IV	0.4733	0.4024	0.3768	- 20.37
Region V	0.7818		0.4920	- 37.07
Region VI	0.7674		0.6123	- 20.20
Region VII	2.0818		2.0263	- 2.66
Region VIII	0.9456		0.9416	- 0.40
Total Cost: $1.185 Billion				

Table A.IV

Dual Values of Sensitive Receptor Constraints in $/($\mu g/m^3/yr$)

Region	Shadow Value From U.S. Autarky Policy	Shadow Value From Canada Autarky Policy
Region I		6.17801×10^8
Region II		0
Region III		0
Region IV		0
Region V	0.19923×10^8	
Region VI	0	
Region VII	0	
Region VIII	0.01707×10^8	

Table A.V

Estimated Value to the United States of the Spillover Effects
From the Canadian Autarky Policy on U.S. Sensitive Receptor Regions V-VIII

Region	Spillover Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	Dual Value ($\$/\mu g/m^3/yr$)
Region I		0.1501	
Region II		0.4042	
Region III		0.3835	
Region IV		0.2217	
Region V	0.4920	0.4963*	0.7571
Region VI	0.6123	0.3374	0
Region VII	2.0263	0.3006	0
Region VIII	0.9416	0.1016	0
Total Cost: $3.00 Billion			

Table A.VI

Estimated Value to Canada of the Spillover Effects From The United States Autarky Policy on Canadian Sensitive Receptor Regions I-IV

Region	Spillover Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	Dual Value ($\$/\mu g/m^3/yr$)
Region I	0.3521	0.3515	0
Region II	0.6389	0.5709	0
Region III	0.4851	0.3128	0
Region IV	0.3585	0.3585	0
Region V		0.4704	
Region VI		0.6046	
Region VII		2.0241	
Region VIII		0.9413	
Total Value: $2.851 Billion			

Table A.VII

Annual Costs under "Free-Rider" Assumptions

	United States (μg/m^3/yr)			Canada (μg/m^3/yr)		
	Resulting Concentration Under Canadian Autarkic Policy	15 Percent Reduction of Base	Final	Resulting Concentration Under U.S. Autarkic Policy	15 Percent Reduction of Base	Final
RI	-	-	0.3520	0.3521	0.3540	0.3481
RII	-	-	0.5832	0.6389	0.6471	0.6286
RIII	-	-	0.3341	0.4851	0.4634	0.4633
RIV	-	-	0.3668	0.3585	0.4024	0.3489
RV	0.4920	0.6645	0.4666	-	-	0.6542
RVI	0.6123	0.6522	0.5746	-	-	0.5936
RVII	2.0263	1.7695	1.7695	-	-	1.1525
RVIII	0.9416	0.8039	0.8039	-	-	0.7722
Cost	$0.231 Billion			$0.002 Billion		

Table A.VIII

Joint U.S. - Canada Policy For a 15% Reduction in Acid Rain Concentrations in all Eight Sensitive Receptor Regions

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I	0.3540	0.3416	- 17.98	0
Region II	0.6470	0.6470	- 15.00	9.8052×10^6
Region III	0.4634	0.4061	- 24.50	0
Region IV	0.4023	0.3893	- 17.74	0
Region V	0.6445	0.5636	- 27.91	0
Region VI	0.6522	0.6406	- 16.52	0
Region VII	1.7696	1.7696	- 15.00	0.3826×10^6
Region VIII	0.8039	0.8039	- 15.00	1.3385×10^6
Total Cost for the U.S.: $0.608 Billion				
Total Cost for Canada: $0.025 Billion				

Table A.IX

Joint U.S. - Canada Policy
For a Maximum Reduction in Acid Rain Concentrations in all Eight Sensitive Receptor Regions as Determined Under the Two Autarkic Policies

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I	0.3521	0.3048	- 26.81	0
Region II	0.6389	0.5447	- 28.45	0
Region III	0.4351	0.3289	- 15.00	3.7574×10^7
Region IV	0.3585	0.2684	- 43.29	0
Region V	0.4920	0.4205	- 46.21	0
Region VI	0.6123	0.4576	- 40.37	0
Region VII	1.1362	0.7819	- 62.44	0
Region VIII	0.8039	0.7922	- 16.22	0
Total Cost for the U.S.: $1.090 Billion				
Total Cost for Canada: $0.055 Billion				

Table A.X

Achieving a 15 Percent Reduction in U.S. Sensitive Receptor Regions Using all 400 Point Sources

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I		0.3742	-10.16	
Region II		0.6936	-8.89	
Region III		0.4248	-22.07	
Region IV		0.3740	-20.98	
Region V	0.6645	0.5771	- 26.18	0
Region VI	0.6522	0.6522	- 15.00	6.6892×10^6
Region VII	1.7695	1.7695	- 15.00	0.1734×10^6
Region VIII	0.8039	0.8039	- 15.00	1.8005×10^6
Total Cost (U.S. sources): $0.443 Billion				
Total Cost (Canadian sources): $0.011 Billion				

Table A.XI

Achieving a 15 Percent Reduction in Canadian Sensitive Receptor Regions Using all 400 Point Sources

Region	Maximum Allowable Concentration ($\mu g/m^3/yr$)	Final Concentration ($\mu g/m^3/yr$)	% Change From Base	Dual Values ($\$/\mu g/m^3/yr$)
Region I	0.3540	0.3489	- 16.23	0
Region II	0.6471	0.6471	- 15.00	1.3663×10^7
Region III	0.4634	0.4056	- 25.59	0
Region IV	0.4024	0.3951	- 16.52	0
Region V		0.5669	- 27.49	
Region VI		0.6476	- 15.61	
Region VII		1.8722	- 10.07	
Region VIII		0.8566	- 9.41	
Total Cost (U.S. sources): $0.349 Billion				
Total Cost (Canada sources): $0.036 Billion				

Table A.XII

Summary of Simulation Results:
Changes in Acid Rain Concentrations from 1985 Base Levels from Various Policy Options and Total Annualized Costs

	Percentage Change in Acid Rain Concentration from 1985 Base levels							
Region	U.S. Autarky Policy	Canada Autarky Policy	Joint Policy: 15% Reduction	Joint Policy: Max Reduction	15% U.S. Reduction (All Sources)	15% Can. Reduction (All Sources)	U.S. Free-Rider Policy	Canada Free-Rider Policy
Region I	- 15.44	- 15.00	- 17.98	-26.81	-10.16	-16.23	-15.49	- 16.42
Region II	- 16.07	- 24.20	- 15.00	-28.45	-8.89	-15.00	-23.39	- 17.43
Region III	- 10.99	- 39.65	- 24.50	-15.00	-22.07	-25.59	-38.72	- 15.02
Region IV	- 24.24	- 20.37	- 17.74	-43.29	-20.98	-16.52	-22.52	- 26.30
Region V	- 15.00	- 37.07	- 27.91	-46.21	-26.18	-27.49	-40.32	- 16.32
Region VI	- 24.20	- 20.20	- 16.52	-40.37	-15.00	-15.61	-25.11	- 22.64
Region VII	- 45.42	- 2.66	- 15.00	-62.44	-15.00	-10.07	-15.00	- 44.64
Region VIII	- 15.00	- 0.40	- 15.00	-16.22	-15.00	-9.41	-15.00	- 18.35
Total Cost: U.S. Point Sources (Annual)	$0.977 B		$0.608 B	$1.090 B	$0.443 B	$0.349 B	$0.231 B	$0.977 B
Total Cost: Canadian Point Sources (Annual)		$1.185 B	$0.025 B	$0.055 B	$0.011 B	$0.036 B	$1.185 B	$0.002 B

Appendix B

This section outlines some of the assumptions that were used in order to construct estimates of the cost functions for each point source used in the simulations presented in the text. Appendix B is presented in three sections -- one section for each category of point source: (1) utility generating facility, (2) non-ferrous smelters, and (3) other industrial/manufacturing processes.

B.a Utility Generating Facilities

A number of *feasible* technologies and processes to reduce sulfur dioxide emissions are available to electric generating facilities. These include switching from high-sulfur coal to low-sulfur coal; physically cleaning coal to remove pyritic sulfur; and installing dry or wet scrubbers, which may use either lime or limestone as a primary reagent, to remove the SO_2 from the waste gas stream prior to its release into the environment. Each of these alternatives has varying capacities for reducing sulfur dioxide emissions, and each carries its own characteristic costs. Various studies conducted by ICF and the EPA have shown that the least cost abatement choice would be to switch from high sulfur coal to low sulfur coal. Anecdotal evidence supports this finding, as indicated by an article appearing in the "Environment" column of the *Wall Street Journal* which reported that high sulfur coal producing states were offering tax incentives to industries that would install scrubber technology to reduce sulfur dioxide emissions in lieu of switching to low sulfur coal.[55]

Other than the political opposition to coal switching, there are also difficulties due to the long term contracts that exist between most utility plants and coal mines. In 1985, more than 78

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[55] Rosewicz, Barbara; "Environment;" *Wall Street Journal*, Tuesday November 12, 1991.

percent of electric utility plants with larger than 50 MW capacity purchased *under* 30 percent of their coal on the spot market.[56] All other coal was purchased through long term contracts. Given these circumstances, I do not consider coal switching to be a viable alternative for electric utility plants.

Coal scrubbing is another possible alternative for electric utility plants. Chemically cleaning coal can remove up to 20 percent of the pyritic sulfur content of high pyritic content coal. This process requires that the coal be crushed and a chemical "wash" be applied to the pulverized coal. Unfortunately, this process is prohibitively expensive for low and medium sulfur coals. The cost per ton of coal cleaned increases by a factor of more than 900 percent for these categories of coal.[57] Given the limited ability to remove sulfur from the coals and the costs associated with physically cleaning coal, scrubber technologies are assumed to be adopted by all electric utility point sources, unaccompanied by any switch to low-sulfur coal.

There are two general categories of "flue gas desulfurization" (FGD) or scrubber technologies that are used to remove sulfur dioxide from electric utility waste gas streams -- a dry scrubber system and a wet scrubber system. Dry scrubber systems are generally installed in small facilities ($\leq$ 100 MW design capacity) that use low sulfur coal. Given that the sample data that are used in this paper consist of only the largest emitters of sulfur dioxide that also tend to use high sulfur coal, I assume that a wet scrubber system will be installed. Furthermore, I assume that the cheapest reagent, limestone, will be used.

Several factors can affect the cost of installing and operating a wet scrubber system that uses limestone. The most important (apart from the sulfur content of the coal being used) are

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[56] See 1985 *Cost and Quality of Fuels for Electric Utility Plants.*

[57] See *United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B*, February 1981.

(1) the design capacity of the scrubber; (2) the scrubber's operating load; (3) the percentage removal rate of the sulfur dioxide, and (4) the "retrofit factor." The design capacity is simply the maximum capacity (in MW) for which the scrubber was designed. Scrubber systems are always sized as to be able to process emissions produced at maximum operating capacity of the unit on which it is installed. Installation costs vary with design capacity. The load factor (or operating load) describes the percentage of that maximum capacity that is utilized (on average) during a given year. The load factor will affect the costs of operating and maintaining the scrubber. The maximum percentage removal of sulfur dioxide varies with the abatement technology, which in this setting includes not only the kind of device being installed, but also both the choice and amount of primary reagent employed. For wet scrubbers the maximum reliable removal rate is 90 percent. A reduction in the amount of limestone will produce a lower removal rate, and will reduce the costs of operating the system.

Data on the design capacity of each U.S. utility unit is found in the 1985 NURF. Similar data are not available for Canadian utility point sources, however, throughput values are available for 1985. In order to estimate the design capacity for the Canadian utility sources, I start by assuming a 60 percent load factor for 1985. By using the average BTU content for the coal found in the Province in which the point source is located, and by assuming an 8760 hr/year operating schedule, an estimate for the design capacity can be found using the following equation:

$$\text{(B.1)} \qquad \textit{Design Capacity}\ (\textit{MW}) = \left(\frac{\textit{Average BTU}}{\textit{ton of coal}}\right) \textit{throughput} * \left(\frac{1}{8700\ \textit{hrs}}\right)\left(\frac{292.88\ W}{\textit{BTU/hr}}\right)10^{-6}$$

where throughput is measured in tons of coal.

Retrofit factors are provided for only a select number of units in the 1985 NURF. For point sources where actual estimated retrofit factors were not available, general "rule of thumb" retrofit factors, developed by ICF and the EPA, were used. Retrofit factors are used to adjust 100 percent of the capital costs and 75 percent of the fixed operating and maintenance costs. Engineering estimates of the installation and equipment costs of wet scrubber systems were also taken from an ICF report prepared for the EPA. These estimates are set out in Table B.I. The costs in Table B.I are reported in early 1986 dollars, but are escalated to 1990 dollars using the CPI for the actual simulation experiments.

Annualized costs are calculated in the following manner.[58] The average lifetime of a wet scrubber system is 50 years. The "correct" time period over which the scrubber system should be depreciated is the shorter of the remaining lifespan of the plant and the lifetime of the scrubber. When the data for the remaining lifespan of the plant (as measured from 1992) was available I used this time period as the relevant period over which to calculate the annualized capital costs. When data were not available, or if the remaining lifespan data were questionable (e.g. negative years reported as remaining lifespan measured from 1985), the full lifespan of the scrubber system of 50 years was used. The cost of capital was assumed to be constant at 5 percent over the relevant time period.

To determine the annualized costs associated with different levels of abatement I use the fact that one simple way of altering abatement levels is to change the amount of limestone used in the abatement process. Through talks with operating managers of utilities, it was determined that the limestone reagent accounts for approximately 20 percent of the operating

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[58] The capital recovery factor is given by:

$$CRF = [i(1+i)^m]/[(1+i)^m - 1].$$

costs of the scrubber system. Using the figures in Table B.I which correspond to a 90 percent reduction in emissions, a ten percent reduction in limestone (calculated as a 2 percent reduction in the variable operating and maintenance costs) corresponds to an 80 percent reduction in sulfur dioxide emissions.

Table B.I

Wet Scrubber Costs for New Utility Power Plants

	Sulfur Level						
	Very Low	Low	Low Medium	Medium	High Medium	High	Very High
Capital Costs ($/kw)	108	110	110	124	133	145	154
Fixed O&M Costs ($/kw)	4.92	4.98	5.00	5.45	5.74	6.11	6.39
Variable O&M Costs (mills/kwh)	0.25	0.32	0.46	0.69	0.92	1.36	1.80

Sulfur Level	Lbs. SO_2/mmBtu
Very Low Sulfur	< 0.80
Low Sulfur	0.80-1.08
Low-Medium Sulfur	1.09-1.66
Medium Sulfur	1.67-2.50
High-Medium Sulfur	2.51-3.33
High Sulfur	3.34-5.00
Very High Sulfur	> 5.00

Size	Capital Cost Relative to a New Scrubber	Fixed O&M Cost Relative to a New Scrubber
Greater than 400 Mw	110%	107.5%
Between 150 - 399 Mw	140%	130.0%
Less than 150 Mw	200%	175.0%

Source: EPA estimates as reported by ICF Resources Inc. for 90% removal of sulfur dioxide using a Wet Limestone FGD system.

B.b Non-Ferrous Smelters

Air pollution control for non-ferrous smelters has primarily been focused on the control of sulfur dioxide emissions. For the purpose of controlling sulfur dioxide emissions, non-ferrous smelters fall into two general categories: strong gas stream smelters and weak gas stream smelters. Strong gas stream smelters are generally categorized as smelters with gas streams of greater than 5 percent acid concentration. Typically for this category of smelter, the cheapest abatement technology for sulfur dioxide removal is the construction of an on-site metallurgical sulfuric acid plant. The drawbacks of this technology are related to whether there exists a market for the sulfuric acid from the smelters (which may be of a higher cost than sulfuric acid from other sources). Neutralization disposal costs of the sulfuric acid may substantially raise the costs of this technology.

Costs for three different control options on a single contact acid plant for a strong off-gas smelter are used. The first option assumes a continuous gas stream and requires a minimum of 12 percent gas concentration, the second is for a variable gas stream which requires between 5 and 8 percent gas concentration, and the third option is for both a continuous and variable gas stream which requires between 6 and 12 percent gas concentration.

Smelters with weak off-gas streams (acid concentrations < 5 percent) do not have the option of using an on-site sulfuric acid plant to control for sulfur dioxide emissions unless they wish to put into place technology that will strengthen the acid concentration of their exit gas. Another option that is available to these smelters is a flue gas desulfurization system (FGD) which uses wet scrubber technologies.

Data from the *Canadian Mining Handbook* (1985) and the *Canada - United States Memorandum of Intent on Air Pollution, Emissions Costs and Engineering Assessment Interim Report, Work Group 3B* (1981) were used to match the NAPAP point source data from the non-ferrous smelters to their company name in order to identify the process equipment used at the site. For smelters that had sulfuric acid plants in operation as of 1981, I assumed that this technology would continue to be used. For smelters with no abatement technology in place, typical acid concentration figures from each type of process equipment was used to determine whether or not an acid plant facility *could be used* for the particular point source. If the typical off-gas stream acid concentration was larger than 5 percent, I then determined which control option for the acid plant could be used. Cost information for each control option is given in at the end of this Appendix.

Point sources from non-ferrous smelters that could not be outfitted with an acid plant were assumed to install a wet scrubber system. Costing for the scrubbers were assumed to be the same as for other industrial and manufacturing processes and is described briefly below. Costs are annualized using the same methodology described in Section B.a. Sulfuric acid plants are taken to have a maximum reliable removal rate of sulfur dioxide of 90 percent. The average lifetime of an acid plant is given to be 30 years.

B.c Other Industrial/Manufacturing Processes

Unlike utilities and to some extent, non-ferrous smelters, there is very little general information available on the costs for pollution abatement technology for industrial sources. For this section, I rely heavily on the engineering cost estimates and methodology outlined in Vatavuk, (1990). One of the difficulties involved with determining the costs associated with the reduction of sulfur dioxide emissions in the manufacturing and industrial sectors is in the appropriate allocation of costs between various pollutants that are removed using the same abatement technology. For example, electric static precipitators (ESPs) are often used to remove particulates, but can also remove sulfur dioxide from exhaust gases. For point sources associated with industrial and manufacturing processes, I allocate abatement costs for sulfur dioxide by accounting for the *full* cost of the primary technology associated with sulfur dioxide removal, regardless of whether this technology is also responsible for the removal of other pollutants. Clearly, this will bias the cost of abatement for sulfur dioxide upward.

There are numerous technologies available to remove sulfur dioxide emissions from different industrial and manufacturing processes. For purposes of this paper, I concentrate only on wet scrubbers, which in general, can be categorized as particulate scrubbers or gaseous scrubbers. Particulate scrubbers (e.g. spray towers or venturis) are designed primarily to remove particulate matter from the exhaust stream, however, are also capable of removing gaseous emissions. Gaseous scrubbers (packed or tray-type columns) are designed to be more effective at removing gases of low concentrations.

Packaged scrubber systems are priced according to the "maximum gas volumetric flowrate" (measured in actual cubic feet per minute, ACFM) that the system can accommodate. Equipment costs include the actual scrubber system along with auxiliary equipment such as pumps, internal piping, and separators. The costing procedures for equipment (add-on controls and auxiliary equipment), operation, and maintenance are taken from Vatavuk (1990). Typical gas flow design rates are assumed for each process design and are given in later in this Appendix. Gas flow rates are usually given in standard cubic feet per minute (SCFM), which describes the volumetric flow rate at standard temperature and pressure. Conversion from SCFM units to ACFM units are necessary and was done by assuming typical temperature and pressure values for each process for each point source.

Each point source was assumed to be retrofitted with either a Venturi or Double Venturi scrubber system. The choice between the two technologies was determined by the estimated maximum volumetric flow rate of the waste gas stream measured in ACFM. Those with estimated ACFM larger than 59,000 ACFM were assumed to install Double Venturi systems. This is a technical assumption, that takes into account the capacity of the point source. Once the abatement technology was chosen, linear cost estimates from Vatavuk were used to determine equipment costs. The estimated equipment costs for Venturi and Double Venturi systems (including auxiliary equipment) is given (in June 1988 dollars) by:

Venturi Scrubber:

$$P(\$) = 8180 + 1.41Q$$

where $600 \leq Q$, ACFM $\leq 19{,}900$

or

$$P(\$) = 84.2Q^{0.612}$$

where $19{,}000 \leq Q \leq 59{,}000$.

Price includes venturi, mist eliminator, fan (direct or belt driven), recirculation liquid pump, and sump. Construction material is carbon steel.

"Double Venturi" Collision Scrubber:

$$P(\$) = 492Q^{0.450}$$

where $2000 \leq Q$, ACFM $\leq 120{,}000$.

Price includes Collision Scrubber throat, diffuser, entrainment separator, and all internals. Construction material is carbon steel.

To calculate the total cost of the scrubber system, I use the "adjustment" factors given in Table B.II, below:

Table B.II

Total Cost Calculations Used for Venturi and Double Venturi Scrubber Systems*

Total Capital Investment (installation factor and purchased equipment cost)	1.91 times equipment cost
Labor:	
Operating	4 hrs/shift
Maintenance	2 hrs/shift
Supervisory	15% of operating labor costs
Maintenance Material	100% of maintenance labor
Electricity, Waste Management, Raw Materials	50% of all labor costs

* Vatavuk (1990)

The maximum reliable removal rate for Venturi and Double Venturi scrubbers is taken to be 80 percent. Total costs are annualized using the methodology described earlier in Section B.a. The average lifetime of a scrubber is 30 years.

Table B.III

Summary of Canadian Copper and Nickel Smelter Statistics

Smelter Location	Process Equipment	Control	% Containment
Hudson Bay Mining and Smelting Company Ltd. Flin Flon, Manitoba	13 Multihearth roasters 1 Reverberatory furnace 3 Converters	Nil	
Inco Limited Thompson, Manitoba	5 Fluid Bed Roasters 5 Electric Furnaces 7 Converters	Nil	
Inco Limited Copper Cliff, Ontario	33 Multihearth roasters 6 Reverberatory furnaces 1 Inco Oxygen Flash 19 Converters	Liquid SO_2 Plant, Acid Plant	44
Falconbridge Nickel Mines, Ltd. Sudbury, Ontario	2 Fluid Bed Roasters 2 Electric Furnaces 4 Converters	Acid Plant	56
Noranda Mines, Ltd. Noranda, Quebec	2 Reverberatory furnaces 1 Noranda reactor 5 Converters	Nil	
Noranda Mines, Ltd. Murdochville, Quebec	1 Fluid Bed Roaster 1 Reverberatory furnace 2 Converters	Acid Plant	59
Afton Mines Ltd. Kamloops, B.C	1 Top Blow Rotary Converter	Scrubber	80
Kidd Creek Mines Ltd., Timmins, Ontario	Mitsubishi Continuous Smelting Process	Acid Plant	95+

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.IV

Summary of Canadian Lead - Zinc Smelter Statistics

Smelter Location	Process Equipment	Control	% Containment
Cominco, Ltd. Trail, British Columbia	2 Sinter Machines 2 Fluid Bed Roasters 2 Blast Furnaces	Acid Plants	94+
Brunswick Mining & Smelting Corporation, Ltd. Belledune, New Brunswick	1 Sinter Machine 1 Blast Furnace	Acid Plants	95+
Kidd Creek Mines, Ltd. Timmins, Ontario	2 Fluid Bed Roasters	Acid Plants	95+
Canadian Electrolytic Zinc, Ltd., Valleyfield, Quebec	4 Fluid Bed Roasters	Acid Plants	95+

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.V

Abatement Costs: Sulfuric Acid Plants (1981 $s)

Control Options (Single Contact Acid Plant)	SCFM	% SO_2 in Gas Stream	Capital Cost (10^6 $)	Operation Cost (10^6 $)
Continuous Gas Only	27 000	12	17	1.5
Variable Gas Only	49 000	5 - 8	28	2.2
Continuous Gas and Variable Gas	36 000	6 - 12	22	1.8

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Table B.VI

Canadian Copper - Nickel Smelter SO_2 Off-Gas Strength by Emitting Equipment

Metal	Emitting Equipment	SO_2 Off-Gas Strength %	
		Min - Max	Typical
Copper	Multiple Hearth Roaster	1 - 3	less than 2
	Fluid Bed Roaster	10 - 14	12
	Reverberatory Furnace	0.5 - 2.5	1.5
	Electric Furnace	4 - 8	-
	Inco Flash Furnace	10 - 14	-
	Mitsubishi 3 - Furnace System	10	-
	Noranda Furnace	8 - 20	13
Nickel	Multi-Hearth Roaster	1 - 3	less than 2
	Reverberatory Furnace	1 - 2	1.5
	Fluid Bed Roaster	10 - 14	-

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Emissions Costs and Engineering Assessment Interim Report, Work Group 3B, (Feb. 1981).

Appendix C

This appendix contains information on the data available on the data tapes used in the simulations presented in this paper. More information on these tapes may be found through the National Technical Information Systems and the United States Environmental Protection Agency.

U.S. Point Source Annual Inventory Format

1. NEDS state code
2. NEDS county code
3. Air quality control region
4. Plant ID code
5. City code
6. UTM zone
7. Ownership type for plant
8. Plant contact
9. Plant name and address
10. NEDS plant comment
11. Point ID code
12. Standard industrial classification code (SIC)
13. IPP code
14. UTM easting, km
15. UTM northing, km
16. Latitude, degrees
17. Longitude, degrees
18. Winter thruput, %
19. Spring thruput, %
20. Summer thruput, %
21. Fall thruput, %
22. Hours/day in operation
23. Days/week in operation
24. Weeks/year in operation
25. Boiler design capacity, MMBtu/hr
26. Space heat, %
27. Stack height, feet
28. Stack diameter, feet
29. Stack temperature, F
30. Flow rate, cubic feet/min
31. Stack gas velocity, ft/sec
32. Plume height, feet
33. Range of points with a common stack, AAZZ
34. NEDS point comment
35. Source classification code (SCC)
36. Operating rate, SCC units/year
37. Maximum design rate, SCC units/hour
38. Sulfur content, %
39. Ash content, %
40. Heat content, MMBtu/SCC unit
41. Confidentiality code
42. Source code, B,S,P,O
43. NEDS SCC comment
44. Number of pollutants
45. SO2 primary control equipment code

46. SO2 secondary control equipment code
47. SO2 control efficiency
48. SO2 emissions estimation method
49. SO2 emissions factor
50. SO2 emissions, tons/year
51. NOx primary control equipment code
52. NOx secondary control equipment code
53. NOx control efficiency
54. NOx emissions estimation method
55. NOx emissions factor
56. NOx emissions, tons/year
57. VOC primary control equipment code
58. VOC secondary control equipment code
59. VOC emissions estimation method
60. VOC emissions factor
61. VOC emissions, tons/year
62. TSP primary control equipment code
63. TSP secondary control equipment code
64. TSP control efficiency
65. TSP emissions estimation method
66. TSP emissions factor
67. TSP emission, tons/year
68. CO primary control equipment code
69. CO secondary control equipment code
70. CO control efficiency
71. CO emissions estimation method
72. CO emissions factor
73. CO emissions, tons/year
74. SO4 Primary control equipment code
75. SO4 secondary control equipment code
76. SO4 control efficiency
77. SO4 emissions estimation method
78. SO4 emissions factor
79. SO4 emission, tons/year
80. HCL Primary control equipment code
81. HCL secondary control equipment code
82. HCL control efficiency
83. HCL emissions estimation method
84. HCL emissions factor
85. HCL emission, tons/year
86. HF Primary control equipment code
87. HF secondary control equipment code
88. HF control efficiency
89. HF emissions estimation method
90. HF emissions factor
91. HF emission, tons/year
92. NH3 Primary control equipment code
93. NH3 secondary control equipment code

94. NH3 control efficiency
95. NH3 emissions estimation method
96. NH3 emissions factor
97. NH3 emission, tons/year
98. THC Primary control equipment code
99. THC secondary control equipment code
100. THC control efficiency
101. THC emissions estimation method
102. THC emissions factor
103. THC emission, tons/year
104. Year plant info last updated
105. Year point info last updated
106. Year control info updated
107. Year emissions info updated
108. Year production info updated
109. Year regulatory info updated
110. Original NEDS hydrocarbons
111. NOx emission factor updated code

Canadian Point Source Annual Inventory Format

1. NEDS province code
2. Plant ID code
3. Point ID code
4. Standard industrial classification code (SIC)
5. Latitude, degrees
6. Longitude, degrees
7. Stack height, feet
8. Stack diameter, feet
9. Stack temperature, F
10. Flow rate, cubic feet/min
11. Stack gas velocity, ft/sec
12. Plume height, feet
13. Source classification code (SCC)
14. Thruput units
15. Sulfur content, %
16. Ash content, %
17. Heat content, MMBtu/SCC unit
18. Number of pollutants
19. Canadian temporal profile code
20. SO2 primary control equipment code
21. SO2 secondary control equipment code
22. SO2 control efficiency
23. SO2 emissions estimation method
24. SO2 emissions, tons/year
25. NOx primary control equipment code
26. NOx secondary control equipment code

27. NOx control efficiency
28. NOx emissions estimation method
29. NOx emissions, tons/year
30. VOC primary control equipment code
31. VOC secondary control equipment code
32. VOC control efficiency
33. VOC emissions estimation method
34. VOC emissions, tons/year
35. TSP primary control equipment code
36. TSP secondary control equipment code
37. TSP control efficiency
38. TSP emissions estimation method
39. TSP emission, tons/year
40. CO primary control equipment code
41. CO secondary control equipment code
42. CO control efficiency
43. CO emissions estimation method
44. CO emissions, tons/year
45. SO4 Primary control equipment code
46. SO4 secondary control equipment code
47. SO4 control efficiency
48. SO4 emissions estimation method
49. SO4 emission, tons/year
50. HCL Primary control equipment code
51. HCL secondary control equipment code
52. HCL control efficiency
53. HCL emissions estimation method
54. HCL emission, tons/year
55. HF Primary control equipment code
56. HF secondary control equipment code
57. HF control efficiency
58. HF emissions estimation method
59. HF emission, tons/year
60. NH3 Primary control equipment code
61. NH3 secondary control equipment code
62. NH3 control efficiency
63. NH3 emissions estimation method
64. NH3 emission, tons/year
65. THC Primary control equipment code
66. THC secondary control equipment code
67. THC control efficiency
68. THC emissions estimation method
69. THC emission, tons/year
70. Original hydrocarbons

National Utility Reference File:

1. Identification/Location
    - a. Unit sequence number
    - b. DOE plant code (ORIS)
    - c. Unit identification code
    - d. FIPS state code
    - e. FIPS county code
    - f. NAPAP plant identification code
    - g. NEDS point identification code
    - h. DOE respondent (old utility) code (ORIS)
    - i. Plant name
    - j. NEDS plant name

2. Unit Operation Characteristics
    - a. Prime mover
    - b. Technology code
    - c. Nameplate capacity (MW)
    - d. Design Capacity (MMBtu/h)
    - e. Current capacity factor (fraction)
    - f. Generation (GWh)
    - g. Unit heat rate (Btu/kWh)
    - h. Bottom type code
    - i. Firing type code

3. Unit Lifetime Data
    - a. Year on-line
    - b. Retirement year

4. Primary Fuel Data
    - a. Primary fuel code
    - b. Primary fuel heating value (MMBtu/SCC unit)
    - c. Primary fuel sulfur content (%)
    - d. Primary fuel ash content (%)
    - e. Primary fuel deliverd price (cents/MMBtu)
    - f. Primary fuel quantity consumed (SCC units)
    - g. Fuel consumed at capacity factor = 1.0 (SCC units)

5. Secondary Fuel Data
    - a. Secondary fuel code
    - b. Secondary fuel heating value (MMBtu/SCC unit)
    - c. Secondary fuel sulfur content (%)
    - d. Secondary fuel ash content (%)
    - e. Secondary fuel delivered price (cents/MMBtu)
    - f. Secondary fuel quantity consumed (SCC units)

6. Third Fuel Data
   a. Third fuel code
   b. Third fuel heating value (MMBtu/SCC unit)
   c. Third fuel sulfur content (%)
   d. Third fuel ash content (%)
   e. Third fuel delivered price (cents/MMBtu)
   f. Third fuel quantity consumed (SCC units)

7. First Coal Data
   a. Btu Fraction of coal use for first coal
   b. First coal heating value (MMBtu/ton)
   c. First coal sulfur content (%)
   d. First coal ash content (%)
   e. First coal delivered price (cents/MMBtu)
   f. First coal supply region

8. Second Coal Data
   a. Btu Fraction of coal use for second coal
   b. Second coal heating value (MMBtu/ton)
   c. Second coal sulfur content (%)
   d. Second coal ash content (%)
   e. Second coal delivered price (cents/MMBtu)
   f. Second coal supply region

9. Regulatory Information
   a. SO2 regulatory category
   b. SO2 emission limit (lbs/MMBtu)
   c. Annaul equivalent SO2 standard (lb/MMBtu)
   d. NOx regulatory category
   e. NOx emission limit (lbs/MMBtu)
   f. TSP regulatory category
   g. TSP emission limit (lbs/MMBtu)

10. Pollution Control Data
   a. SO2 control device
   b. SO2 control efficiency (%)
   c. SO2 emisison rate (lbs/MMBtu)
   d. SO2 emission (1000 tons)
   e. Scrubber retrofit factor (fraction)
   f. Future scrubber planned? (1 = yes)
   g. Future scrubber date on-line (yymm)
   h. Future scrubber removal efficiency (%)
   i. Primary NOx control device
   j. Secondary NOx control device
   k. NOx control efficiency (%)
   l. NOx emission rate (lbs/MMBtu)
   m. NOx emission (1000 tons)
   n. TSP control device

- o. TSP control efficiency (%)
- p. TSP emission rate (lbs/MMBtu)
- q. TSP emissions (1000 tons)
- r. VOC emission (1000 tons)

11. Ownership Data
    - a. Operating utility code
    - b. Operating utility name
    - c. Primary owner utility code
    - d. Primary owner state (Postal Code)
    - e. Ownership by primary owner (%)
    - f. Secondary owner utility code
    - g. Secondary owner state (Postal Code)
    - h. Ownership by secondary owner (%)
    - i. Tertiary owner utility code
    - j. Tertiary owner state (Postal Code)
    - k. Ownership by tertiary owner (%)

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