Smart Emission Trading for Toxins

Spatial Heterogeneity and Hybrid Regimes

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Abstract

Tradeable emission permits provide an efficient allocation of abatement activities across firms in the presence of informational asymmetry between firms and environmental regulator. While tradeable emission permits are well-suited for uniformly mixed pollutants such as greenhouse gases, theory suggests the use of tradeable ambient concentration permits for non-uniformly mixed pollutants such as toxins. However, numerous practical obstacles impede the use of tradeable ambient concentration permits, most of all the potential illiquidity of the many small markets created by the necessary geographic segmentation. This paper develops two 'smart' (second-best) alternative trading regimes using two permit markets—the attainment market and the non-attainment market—separated either by plant-level attainment targets or hazard zones. Analytic solutions and simulation results demonstrate the practicability of the concepts and their ability to approximate the first-best solution. The concept is applied to analyze emissions of metallic toxins in Central Canada.

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SECTION ON HAZARD ZONES STILL INCOMPLETE.

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1 Introduction

Tradeable emission permits provide an efficient allocation of abatement activities across firms in the presence of informational asymmetry between firms and environmental regulator. Emission permits are best suited for uniformly mixed pollutants such as greenhouse gases. However, conventional emission permits for non-uniformly mixed pollutants such as toxins are not optimal, and instead "ambient permits" in which permits are contracted in fractions of emission concentrations have been suggested (Tietenberg, 2006, chap. 4). In the presence of spatial heterogeneity, defined by the location of emission points (plants) and receptor points (people), ambient permit markets suffer from numerous practical limitations. This paper develops a 'smart' alternative to overcome these practical limitations.[1]

What are the shortcomings of ambient permit markets? Spatial heterogeneity necessitates multiple ambient permit markets to allow for different emission concentrations and varying population densities across the country. Tietenberg (1995) recognized that

> [...] while the design of the ambient instrument is not very complicated, implementing an ambient permit system is complicated. With an ambient permit system an emitter would have to acquire separate permits for each affected receptor. When the number of receptors is large, the result is a rather complicated set of transactions.

Fracturing of the ambient permit market lowers the "liquidity" of these markets and prevents cross-market transactions, and the multiplicity of markets increases the overall transaction costs of the trading system. Furthermore, unlike emission permits, ambient permits are also difficult to monitor and enforce as the contributions to pollution concentrations at a given location may be impossible to track down to a particular source (i.e., permit violator). While ambient permit markets are a theoretically sound solution in a world of perfect enforceability and abundant market liquidity, in the presence of strong spatial heterogeneity these markets will be too costly, impractical, and ultimately infeasible.

This paper proposes two practical 'second-best' alternative using two separate conventional emission permit markets in which the contracts are denominated in emission units of the pollution source. These two markets—an attainment market and a non-attainment market—are separated either through plant-specific emission attainment targets or through plant-specific emission contribution shares to hazard zones. Such hybrid systems provide for some of the efficiencies of emission permit trading while limiting the consequences on the ambient emission concentrations and their corresponding health impact. Why are such hybrid systems 'smart'? They combine the political appeal of emission attainment targeting (either at the plant level or by defining hazard zones) with the efficiency of market-based

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[1] For those who think that calling the proposed emission permit system 'smart' is a little bit too pretentious, let SMART simply be the acronym for "System for Market-based Attainment of Reductions of Toxins."

instruments, in particular emission permits trading. Analytical work in section 3 and numerical simulations in section 4 aim to establish the feasibility and *relative* efficiency of the proposed emission permit trading system.

Emission permit trading for toxins faces numerous challenges. Which toxins should be covered? Should the trading system cover only a single or multiple pollutants? How does firm entry and exit affect the trading system? How can the trading system accommodate high variability in emissions over time? This paper will shed some light on these questions in section 5. Section 6 proceeds to illustrate the practicability of emissions trading for toxins by looking at twelve dangerous metallic toxins in Central Canada. Looking at this region is meant as an illustration of practical concerns. To date, Canada has extremely limited experience with emission permit trading (see appendix A), and thus consideration—or adoption—of an emission permit system for toxins is unlikely unless politicians recognize a greater urgency of the problem.

2 Background

Emission permit trading systems are demonstrably more efficient than conventional command-and-control regulation. In the presence of spatial heterogeneity in emissions and non-uniformly mixed pollutants, ambient concentration permits are more efficient than simple emission permits. Nevertheless, the efficiency rank order of these regulatory interventions may be greatly affected by large differences in transaction costs. The key argument advanced in this paper is that transaction costs for ambient concentration permit trading systems would be prohibitively high, and therefore other solutions such as the hybrid emission trading systems proposed in this paper may provide good approximations to the first-best policy instrument.

The importance of transaction costs is well understood. Nevertheless, Stavins (1995) points out that even complicated trading systems with relatively high transaction costs will likely dominate command-and-control regulation because there is substantial heterogeneity in abatement cost (i.e., abatement technology) across plants. A trading system provides flexibility to plants in choosing the pollution abatement technology best suited for the particular environment.

Transaction costs for permit trading systems consist of a variety of specific costs, which in turn are driven by particular economic factors. Adapted from a list by Egenhofer (2003), these transaction costs include:

1. *search costs*: the cost of matching buyer and seller, greatly reduced through organized exchanges, but crucially dependent on the liquidity and transparency of the market.
2. *negotiation costs*: contracting and standardization of contracts through permit exchanges, which depends on the clarity of the property rights assigned by the contracts
3. *approval costs*: trades may be subject to government approval.
4. *monitoring costs*: verification of compliance.

5. *enforcement costs*: in case of non-compliance (i.e., emissions exceed purchased permits), the regulator needs to enforce compliance or fine violators.
6. *information costs*: cost of monitoring market; cost of involuntary sharing of private or confidential technical information.
7. *insurance costs*: plants must insure against technical risk of accidental non-compliance (e.g., unpredictable leaks, spills, or accidents).

While some of these transaction costs are similar across different types of regulatory intervention, different types of emission permit markets differ most strongly with respect to search and information costs. Here it is the potential illiquidity of the market which may reduce trading opportunities and in the extreme case may turn such a market into bilateral bargaining.

Trading costs, combined with market and regulatory uncertainty, may reduce the efficiency of permit trading systems. Montero (1997) shows that these frictions can have a non-negligible impact on abatement outcomes: trade volume decreases, and total compliance cost increases. They also find that in the presence of transaction costs the initial allocation is not neutral with respect to efficiency.

Gangadharan (2000) consider a variety of the aforementioned transaction costs in the context of the RECLAIM market in the Los Angeles basin. The presence of transaction costs influences the participation decision of plants. The author finds that various types of transaction costs can be identified as the reason for an overall 32% reduction in the probability of trading in the RECLAIM market in 1995.

The importance of transaction costs can also be explored using experimental methods. Cason and Gangadharan (2003) employ laboratory double auction markets to investigate both the efficiency of markets as well as the importance of initial allocation schemes. Transaction costs drive a wedge between buyers' and sellers' marginal costs of emission control, which lead to deviations of prices and final allocations from the zero transaction cost equilibrium. It matters what type of transaction costs plants face: costs for compliance, reporting, and information acquisition imply actual deadweight losses, whereas that is not the case if costs are transfers (e.g., brokerage fees). The first type of costs is reduced by getting the initial allocation of permits as accurate as possible. Auctioning, and to a lesser degree grandfathering, is the best method to accomplish an accurate initial allocation.

The composition of costs may also shift over time, and then it is important whether marginal transactions costs are constant or decreasing. Cason and Gangadharan (2003) argue that the search and information costs are decreasing in trading volume, whereas brokerage costs typically are proportional to trading volume. Search and information costs are larger at the early stages of a market, and thus it is during these early stages when the accuracy of the initial allocation matters most.

A variety of 'second-best' alternatives to the ambient concentration permit trading system have been proposed. In addition to simply using a conventional emission permit trading system, zonal permit systems have been proposed. However, zonal permits suffer from the problems of defining zonal boundaries and implicitly the size of each zone, and the uniform treatment of all sources within the zone. Whereas smaller zones are more efficient in theory by providing better targeting, smaller zones would also reduce the liquidity of the permit markets substantially. A further complication is the question of allowing trading across zonal boundaries, perhaps through pre-defined trading ratios. Other potential instruments described in Atkinson and Tietenberg (1987) and Tietenberg (1995) include, non-degradation offsets, three-dimensional zones, and constrained trading rules. All of these market-based second-best approaches offer environmental improvements at much reduced compliance cost relative to traditional command-and-control interventions. The proposed dual-market hybrid system proposed in this paper offers yet another workable solution.

In an UNCTAD report Tietenberg et al. (1999, pp. 105-7) comment on design principles for a permit trading system:

> The emissions trading system should be designed to be as simple as possible. The historic evidence is very clear that simple emissions trading systems work much better than severely constrained ones. The transaction costs associated with implementing and administering an emissions trading system rise with the number of constraints imposed, and as transactions costs rise, the number of trades falls. As the number of trades falls, the cost savings achieved by the programme also decline. [...] Transaction costs play a key role in the success or failure of an emissions trading system. In the past, only emissions trading programmes with low transaction costs have succeeded in substantially lowering the cost of compliance.

Most 'second-best' alternatives to the ambient concentration permit market suffer from the same problem: they would institute a large number of parallel markets, with our without complicated exchange mechanisms between these markets. These models would very likely come at a high, if not prohibitively high, level of transaction costs. The market system proposed in this paper limits the number of markets to two, virtually guaranteeing liquidity in these markets and keeping transaction costs low. The regulator carries a somewhat larger burden, however, because of the need to set separate emission attainment targets for each plant.

3 Model

3.1 Regulator's Objective

Consider the regulator's problem of controlling the health hazard of emissions emanating from plants $i = 1, .., I$. The regulator is concerned about the total health hazard to all people[2] living in $j = 1, .., J$ regions. Assume that each region is

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[2] Regulators may not only be concerned about the health hazard of people. More broadly, they may wish to control hazard to the ecosystem that also includes animals and plants. Toxins will have negative effects on animals, plants, and humans. Thus regulators may want to assign appropriate weights to ecosystem units and compute an aggregate measure of environmental hazard. If the environmental risk to non-human ecosystem units is difficult to quantify, a minimalistic safe-

homogenous in terms of emission concentrations and is populated by P_j people.[3]

$$H_j = P_j \left[\sum_i d_{ij} E_i \right]^2 \tag{1}$$

Here, E_i is the emission of plant E_i, d_{ij} is the dispersion factor between plant i and person j–a function of distance—that maps raw emissions at location i into contributions to the ambient emission concentrations at location j. Thus the regulator does not target ambient emission concentrations, but the cumulative health hazard of the people 'at risk.' The above hazard model (1) is marked by two critical deviations from the existing literature on ambient emission level control:

(a) The health hazard for each individual j is a function that is increasing non-linearly, as the health hazard of toxins is clearly not linear in dose. The medical literature often stipulates either quadratic or sigmoidal dose-response curves as suitable approximations; see for example Hoel and Portier (1994). A quadratic approximation appears particularly suited to the low-dose end that is the target of environmental regulation.

(b) The economy-wide health hazard is not merely a function of ambient concentrations, but also a function of the number of people exposed to that ambient concentration. It is thus crucially important to allow for population densities in a model of health hazard.

The regulator is also concerned about the abatement cost $B = \sum_i B_i$ incurred by plants in meeting the desired environmental footprint. The regulator's objective then is to minimize the 'welfare loss' L from health hazard H and abatement cost B:

$$L = \sum_i B_i + \gamma \sum_j H_j + T \tag{2}$$

Here, γ is the marginal cost of a unit of health hazard to the population. The last term T captures the transaction cost of the regulatory system, which ultimately is a function of the number of markets and their trading volume. For emissions trading, transaction cost depends on the market size of traded permits. Given equal abatement cost and health hazard, a regulator will prefer the regulatory intervention with the lowest transaction cost. As transaction costs are specific to each type of intervention, during the analysis of each trading system the T term will be dropped. Nevertheless, as argued earlier, the size of T is crucially important in choosing the most appropriate permit trading system.

3.2 Absolute and Relative Efficiency of Different Regimes

The outcome of different policy interventions is reflected in the loss as computed through (2). For any given preference parameter γ, the policy with the lower loss

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guard would be to assign a minimum human population $P_j^{\min}$ to loosely populated or ecologically sensitive regions.

[3] At the margin, each person in the economy can be considered a separate region if each person's location was known with precision. In practice, small regional units such as census tracts.

is the more efficient policy. However, it is also possible to compare two competing regimes through the relative cost of achieving a certain amount of hazard reduction. Let $H(\emptyset)$ and $H(\mathcal{R})$ be the hazard without regime and with regime $\mathcal{R}$ respectively, and let $B(\emptyset)$ and $B(\mathcal{R})$ denote the corresponding abatement expenditure. Then policy $\mathcal{R}_A$ is relatively more efficient than $\mathcal{R}_B$ if

$$\frac{B(\mathcal{R}_A) - B(\emptyset)}{H(\emptyset) - H(\mathcal{R}_A)} < \frac{B(\mathcal{R}_B) - B(\emptyset)}{H(\emptyset) - H(\mathcal{R}_B)} \tag{3}$$

that is, when policy $\mathcal{R}_A$ has a lower unit cost of hazard reduction than policy $\mathcal{R}_B$.

3.3 The Plant

Plant i's emissions are a function of its abatement effort $\theta_i \in [0, 1[$ so that emissions E_i are

$$E_i = (1 - \theta_i) z_i q_i \tag{4}$$

with original unabated emission intensity z_i and output (scale) q_i. Plant i faces related abatement costs of

$$B_i = b_i[-\ln(1 - \theta_i)] z_i q_i \tag{5}$$

with cost factor b_i. With (5) it makes no difference if the regulator determines policy with respect to emission intensity (z_i) or with respect to total emissions ($z_i q_i$). The regulator does not observe b_i, whereas z_i is directly observable. The abatement cost function has the property that as $\theta \to 1$ (complete abatement), abatement costs rise to infinity. This implies that plants are unable to completely abate emissions. Furthermore, $B'(\theta) > 0$ and $B''(\theta) > 0$ imply that abatement costs are increasing in abatement effort at an accelerating. Figure 1 illustrates the abatement cost function. At low levels of effort, the cost function is almost linear, but as the effort level approaches total elimination of pollutants, abatement costs rise steeply.

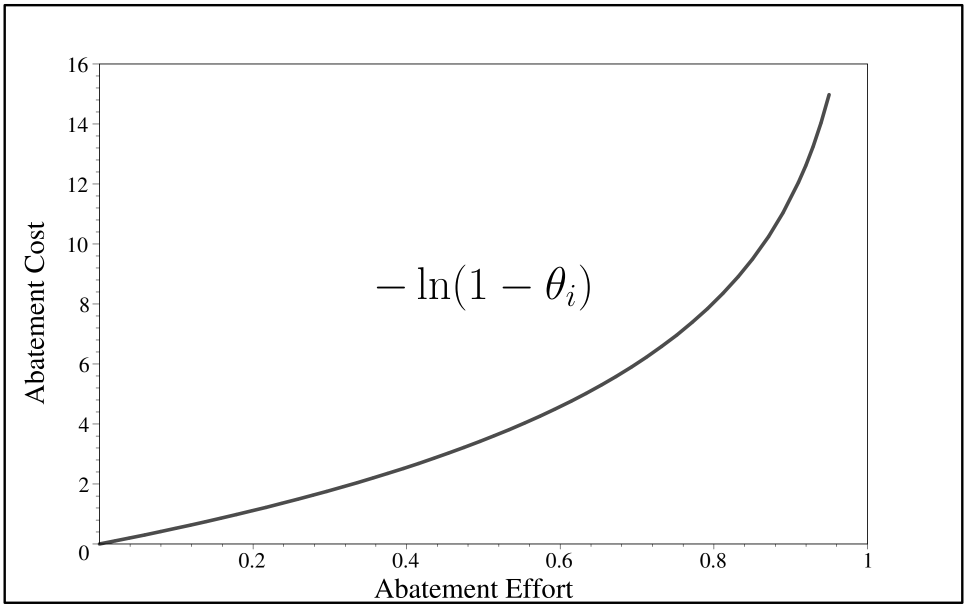
A further assumption is that abatement costs rise proportional with output; there are no increasing or decreasing returns to scale in abatement activity. Choosing a specific functional form for abatement costs generates a more tractable analytic solution while retaining the underlying economic intuition.

To simplify the analysis further, assume that the abatement decision is independent of the output decision. This is not necessarily an unrealistic assumption when abatement costs are sufficiently small compared to overall costs. Furthermore, assume that abatement costs do not trigger firm entry or exit or have other market structure effects. Introducing the necessary algebra to account for output variation and market structure effects overshadows the economic intuition that this simplified model is trying to capture. By introducing these modelling restrictions it is possible to focus exclusively on the firm's pollution abatement decision.

3.4 Command-and-Control Regulation

Suppose the regulator imposes a binding and fully enforced emission intensity limit $\bar{z}_i$ on each plant. Then $E_i \leq \bar{z}_i q_i$, and if the constraint is binding, $\theta_i = 1 - \bar{z}_i / z_i$

Figure 1: Abatement Cost Function



and the abatement costs are $B_i = \ln(z_i/\bar{z}_i) b_i z_i q_i$. The constraint is not binding if $\bar{z}_i > z_i$ and the unabated emission intensity is below the emission limit. Hence:

$$L = \sum_i \max\left\{0, \ln\left(\frac{z_i}{\bar{z}_i}\right)\right\} b_i z_i q_i + \gamma \sum_j P_j \left[\sum_i d_{ij} \min\{\bar{z}_i, z_i\} q_i\right]^2 \tag{6}$$

This command-and-control (CAC) regulation is optimal if the regulator has perfect and complete information about the plants' abatement cost factors. The optimal emission intensity limits can be obtained by differentiating (1) with respect to $\bar{z}_i$. Let $\bar{z}_i^*$ denote the optimal full-information intensity limits. Then

$$\bar{z}_i^* = \frac{b_i z_i}{2\gamma \sum_j P_j d_{ij} \sum_k d_{kj} \min\{z_k, \bar{z}_k^*\} q_k} \tag{7}$$

Expression (7) defines I equations in I unknowns as the optimal emission intensity limits are determined simultaneously. Solving this equation system poses a complex numerical problem for the regulator. The regulator typically has no precise information about the abatement cost factors b_i, which of course is the reason why CAC interventions (and emission taxes) are inferior to tradeable emissions permits.

It may be helpful to look at the case of only a single plant ($I = 1$). Then, dropping the i subscript,

$$\bar{z}^* = \sqrt{\frac{bz}{2\gamma q \sum_j P_j d_j^2}} \tag{8}$$

The emission intensity cap increases with original emission intensity and abatement cost; it decreases with the scale of the plant and the surrounding population, which is weighted with the square of the dispersion rate. As d_j declines rapidly with distance, the local population surrounding the plant weighs heavily in the intensity cap decision.

The key challenge for the regulator is the lack of precise knowledge of abatement costs. Whereas z_i can be inferred from observation (through mandatory reporting to pollutant release inventories), the regulator can only conjecture an average abatement cost factor $\hat{b} = \mathcal{E}\{b_i\}$. Based on this expectation, the regulator's choice of emission intensity standard replaces b_i with $\hat{b}$ in equation (7), and the ideal targets $\bar{z}_i^*$ with the effective (but approximate) targets $\bar{z}_i$. The lack of full information causes an obvious economic inefficiency.

Further insight is gained from summing (7) over all plants. Denoting $\zeta_i = \min\{\bar{z}_i/z_i, 1\}$ as the "abatement avoidance" rate and $E^0 = \sum_i q_i z_i$ as the initial total emissions before abatement, it can be shown that the total hazard after imposing the emission standards turns out to be

$$H = \frac{\hat{b}E^0}{2\gamma} \tag{9}$$

If the regulator had perfect knowledge about the b_i, the expression in the numerator would be $\sum_i b_i z_i q_i$ instead of $\hat{b}E^0$. Put another way, the 'correct' $\hat{b}$ would be the weighted average of the abatement cost factors b_i, weighted by each plant's total pre-abatement emissions. Knowledge about the distribution or range of abatement cost factors would not be sufficient to set the optimal policy; in the presence of significant size and/or emission intensity heterogeneity across plants it is necessary to know each plant's abatement cost factor in order to set the right policy.

3.5 Conventional Emission Permit Trading

A useful benchmark case for comparison purposes is the conventional emission permit trading ('cap-and-trade', or CAT) regime in which plants receive an initial allocation A_i so that

$$A \equiv \sum_i A_i = \sum_i E_i \equiv E \tag{10}$$

with total allocation A being equal to total emissions E. The method of allocation—grandfathering or auction—is not relevant for efficiency, although it does have important distributional implications. The equilibrium price of a unit emission permit is determined by the permit market as τ. Then the plant wishes to minimize its environmental costs

$$C(\theta_i) = B_i(\theta_i) + \tau\left[E_i(\theta_i) - A_i\right] \tag{11}$$

Profit maximization implies that the optimal abatement effort is $\theta_i^* = 1 - b_i/\tau$.[4] Emissions then are $E_i = b_i z_i q_i/\tau$ and the corresponding abatement cost is $B_i =$

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[4] Note that $\tau > b_i$ for the plant to engage in any abatement effort. If the permit price is too low, the plant will merely purchase the permits but not engage in emission reductions.

$\ln(\tau/b_i)b_i z_i q_i$. The policy maker's loss function is now determined as

$$L = \sum_i \ln(\tau/b_i)b_i z_i q_i + \gamma \sum_j P_j \left[\sum_i d_{ij} b_i z_i q_i/\tau\right]^2 \tag{12}$$

The equilibrium price for the tradeable permits can be obtained by differentiating (12) with respect to τ, the same procedure as for a full-information emission tax.

$$\tau = \left[\frac{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i z_i q_i\right)^2}{\sum_i b_i z_i q_i}\right]^{1/2} \tag{13}$$

Noting that

$$E = \sum_i E_i = (\sum_i b_i z_i q_i)/\tau = A \tag{14}$$

it follows that

$$\tau = \left[2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i z_i q_i\right)^2\right]^{1/3} A^{-1/3} \tag{15}$$

The emission permit price τ is proportional to the inverse third root of the permit allocation A. With a permit system the regulator chooses A. The optimal allocation of permits can be found by using (14), inserting it into (12), and then solving $dL/dA = 0$ for A.

$$A^* = \sqrt{\frac{\left(\sum_i b_i z_i q_i\right)^3}{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i z_i q_i\right)^2}} \tag{16}$$

To simplify notation, denote initial plant emissions as $E_i^0 \equiv z_i q_i$ and initial total emissions as $E^0 \equiv \sum_i E_i^0$. Further let $H_j^0 \equiv \sum_j P_j \left(\sum_i d_{ij} E_i^0\right)^2$ denote the initial hazard to region j and $H^0 \equiv \sum_j H_j^0$ the total initial hazard. As the regulator has only imperfect information about abatement costs and will substitute $\hat{b}$ for b_i, the effective allocation that the regulator adopts turns out to be

$$A = E^0 \sqrt{\frac{\hat{b} E^0}{2\gamma H^0}} \tag{17}$$

For A to be less than the initial emission level E^0, it must hold that the regulator's weight γ on the health hazard is sufficiently high:

$$\gamma > \frac{\hat{b} E^0}{2H^0} \tag{18}$$

It may be useful to compare (17) to the conventional case of global pollutants where $d_{ij} = \bar{d}$. Defining the total population as $P \equiv \sum_j P$, the regulator allocates

$$A = \frac{1}{\bar{d}} \sqrt{\frac{\hat{b} E^0}{2\gamma P}} \tag{19}$$

permits. This result is only slightly different from conventional results for greenhouse gas permit systems. Here, the non-linear dose-response function gives importance to the number of people exposed to the pollutant, and thus the number of permits decreases with the square root of the population size.

3.6 Ambient Concentration Permit System

While this paper points to the costliness of an ambient concentration permit system, it may be worthwhile exploring some of the properties of such a system. The regulator issues permit allocations A_j for each of the J regions so that $A_j = \sum_i d_{ij} E_i$, where E_i is the actual emission of plant i after abatement. Allocations A_j are distributed to plants as A_{ij} through auction or another suitable method. Each of these markets establishes an equilibrium permit price τ_j. The individual plant now has to participate in all ambient concentration permit markets for which $d_{ij} > 0$. Then the environmental cost function of the plant becomes

$$C_i(\theta_i) = \left\{ [-\ln(1-\theta_i)]b_i + (1-\theta_i) \sum_j \tau_j d_{ij} \right\} z_i q_i - \sum_j \tau_j A_{ij} \tag{20}$$

and thus the optimal abatement effort is $\theta_i = 1 - b_i / \left[\sum_j \tau_j d_{ij}\right]$. The plant's overall abatement effort depends on the permit prices in all J markets, weighted by the attenuation coefficient d_{ij}. This means that markets which are geographically near weigh more heavily than markets which are geographically far. Because permit supply must equal permit demand, permit prices and allocations are linked through

$$A_j = \sum_i d_{ij} E_i = \frac{d_{ij} b_i z_i q_i}{\sum_l \tau_l d_{il}} - \sum_j A_{ij} \tag{21}$$

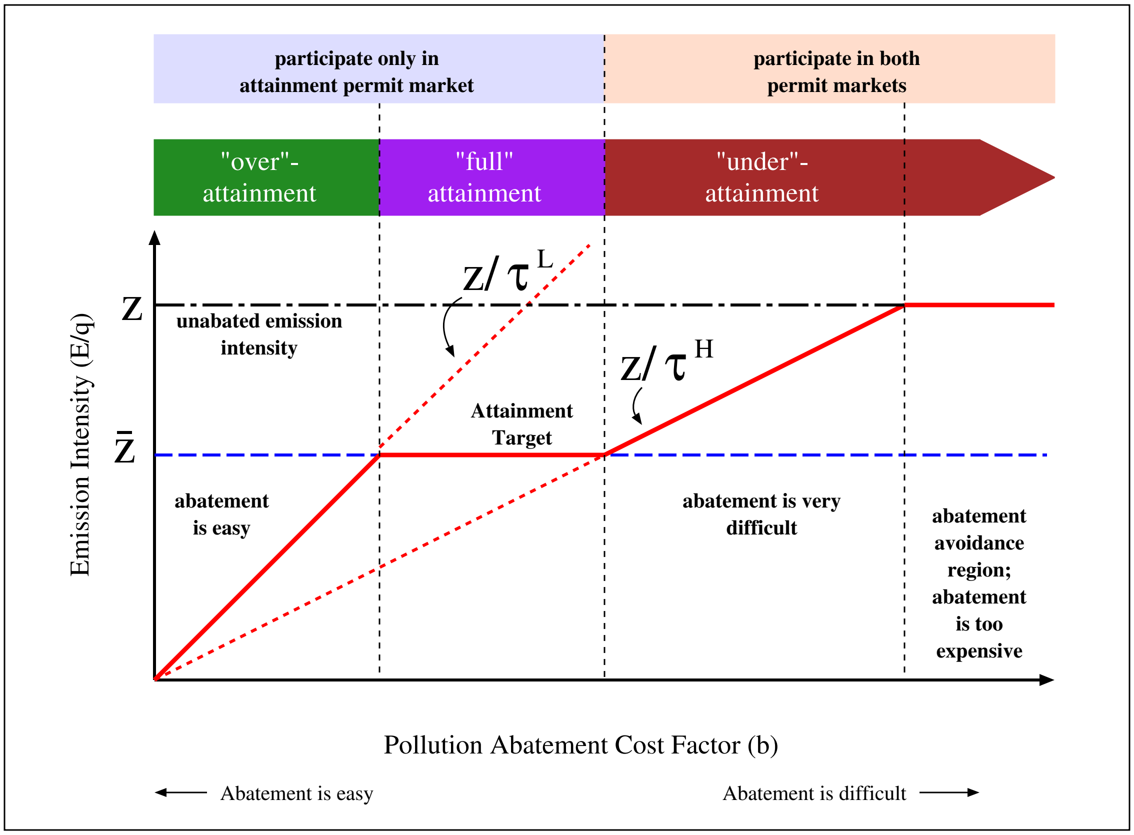
In analogy to (14), the total permit market value is then given by $V \equiv \sum_j \tau_j A_j = \sum_i b_i z_i q_i$. Equation (21) reveals that each permit equilibrium price τ_j depends not only on the corresponding allocation A_j but also on all other permit allocations $A_{l \neq j}$. Because of the intricacy of this cross-dependence it is not possible to provide closed-form solutions to the optimal permit prices τ_j or initial allocations A_j (even in a simple $I = J = 2$ case, or when using a more simplistic quadratic abatement cost function).

3.7 Hybrid Emission Permit System with Plant-Level Attainment Targets

The first hybrid emission permit regime is marked by three distinct features:
(a) plant-specific emission intensity targets $\bar{z}_i$;
(b) a tradeable emission permit market (with equilibrium price τ^L) for emissions below the emission intensity targets, to be known as the "attainment market", and with initial allocation $A^L \equiv \lambda A$;
(c) a tradeable emission permit market (with equilibrium price $\tau^H > \tau^L$) for emissions above the emission intensity target, to be known as the "non-attainment market", with initial allocation $A^H \equiv (1-\lambda)A$.

Figure 2 illustrates the effect of two partitioned emission permit markets on emission intensities E_i/q_i of plants with respect to their abatement cost factor b_i. Plants that find abatement easy are on the left, and plants that find abatement challenging

Figure 2: Emission Intensity, Attainment Target and Market Prices, Effective Abatement Level, and Permit Market Participation



are found on the right. Plants that are "easy abaters" will tend to participate only in the attainment permit market and may be in "over"-attainment in the sense that their emission intensity remains below the emission intensity target $\bar{z}_i$. Plants in the middle will tend to be in "full" attainment and find it optimal to maintain emission intensities right at the attainment target level. Plants that find it very costly to abate pollution will additionally purchase permits in the non-attainment market and may be thought of as being "under"-attainers. A fourth possible state is that a plant may find it too costly to abate at all. At very high levels of b_i, even the non-attainment permit price will be insufficient to induce abatement effort. Alternatively, the regulator may set an attainment target identical to the unabated emission level if the plant is located in a sparsely populated region. Given permit prices τ^L and τ^H, a plant's environmental cost function is given by

$$C(\theta_i) = B_i(\theta_i) + \tau^L \left[\min\{E_i, \bar{E}_i\} - A_i^L\right] + \tau^H \left[\max\{0, E_i - \bar{E}_i\} - A_i^H\right] \tag{22}$$

Depending on whether the plant remains below its emission intensity target $\bar{z}_i$, it either trades only in the lower emission market or in both markets. Cost minimization implies that the optimal abatement effort θ_i^* is given by

$$\zeta_i(\bar{z}_i, \tau^L, \tau^H) \equiv 1 - \theta_i^* = \min\left\{\frac{b_i}{\tau^L}, \max\left\{\frac{\bar{z}_i}{z_i}, \frac{b_i}{\tau^H}\right\}, 1\right\} \tag{23}$$

where for convenience of notation the term ζ_i is introduced as "abatement effort avoidance." Now $E_i = \zeta_i z_i q_i$ and $B_i = \ln(1/\zeta_i) b_i z_i q_i$. The policy maker's loss function is now determined as

$$L(\bar{z}_i, \tau^L, \tau^H) = \sum_i \left[-\ln(\zeta_i)\right] b_i z_i q_i + \gamma \sum_j P_j \left[\sum_i d_{ij} \zeta_i z_i q_i\right]^2 \tag{24}$$

and the optimal solution is determined by the policy maker choosing $\bar{z}_i$ and the markets determining τ^L and τ^H. The regulator's choice of optimal $\bar{z}_i$, given lack of knowledge about the true abatement cost factors b_i, is already given in 7 with $\forall i : b_i = \hat{b}$. The market prices τ^L and τ^H can then be determined by differentiating $L(\bar{z}_i)$ with respect to prices τ^L and τ^H. The solution depends on which plants are participating in which market. All plants participate in the attainment market, no matter how small their emissions, but only a subset of plants participates in the non-attainment market; let Ω^H denote this set. Companies in overcompliance of the attainment target are in set Ω^L, and companies that are neither in Ω^H or Ω^L are in full compliance and meet the attainment target exactly. It must also hold that $A^L = E^L$ and $A^H = E^H$ with

$$\begin{aligned} E^L &= \sum_i \min\left\{\frac{b_i}{\tau^L}, \frac{\bar{z}_i}{z_i}\right\} z_i q_i = \sum_{i \in \Omega^L} (b_i z_i q_i)/\tau^L + \sum_{i \notin \Omega^L} \bar{z}_i q_i & (25) \\ E^H &= \sum_i \max\left\{0, \frac{b_i}{\tau^H} - \frac{\bar{z}_i}{z_i}\right\} z_i q_i = \sum_{i \in \Omega^H} \left[\frac{b_i}{\tau^H} - \frac{\bar{z}_i}{z_i}\right] z_i q_i & (26) \end{aligned}$$

Let $\bar{E}^L \equiv \sum_{i \notin \Omega^L} \bar{z}_i q_i$ denote the amount of attainment permits that plants in "full" or "under"-attainment must purchase, and let $\bar{E}^H \equiv \sum_{i \in \Omega^H} \bar{z}_i q_i$ denote the amount of attainment permits that the "under"-attaining plants alone must purchase. Then it follows that

$$\begin{aligned} \tau^L &= \frac{\sum_{i \in \Omega^L} b_i z_i q_i}{A^L - \bar{E}^L} & (27) \\ \tau^H &= \frac{\sum_{i \in \Omega^H} b_i z_i q_i}{A^H + \bar{E}^H} & (28) \end{aligned}$$

For τ^L to be positive and not too large, the permit allocation A^L for the attainment market must exceed the combined emissions from the plants in "full" attainment or "under"-attainment by a sufficient margin. Solving (24) for the optimal τ^L and τ^H yields

$$\tau^L = \left[\frac{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i \zeta_i z_i q_i\right) \left(\sum_{i \in \Omega^L} d_{ij} b_i z_i q_i\right)}{\sum_{i \in \Omega^L} b_i z_i q_i}\right]^{1/2} \tag{29}$$

and

$$\tau^H = \left[\frac{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i \zeta_i z_i q_i\right) \left(\sum_{i \in \Omega^H} d_{ij} b_i z_i q_i\right)}{\sum_{i \in \Omega^H} b_i z_i q_i}\right]^{1/2} \tag{30}$$

While it is obvious that the permit price τ^H is set only by the participants in the non-attainment market, the permit price τ^L is effectively set only by the plants in "over"-attainment, even though all plants participate in the attainment market. Thus, perhaps surprisingly, τ^L is determined by a group of 'market makers' that may turn out to not very large. Inserting (27) into (29), and inserting (28) into (30) reveals that

$$\tau^L = \left[\frac{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i \zeta_i z_i q_i\right)\left(\sum_{i\in\Omega^H} d_{ij} b_i z_i q_i\right)}{A^L - \bar{E}^L}\right]^{1/3} \tag{31}$$

and

$$\tau^H = \left[\frac{2\gamma \sum_j P_j \left(\sum_i d_{ij} b_i \zeta_i z_i q_i\right)\left(\sum_{i\in\Omega^H} d_{ij} b_i z_i q_i\right)}{A^H + \bar{E}^H}\right]^{1/3} \tag{32}$$

The permit price increases with the inverse third root of the permit allocation. The fact that E^H is in the denominator indicates a ceiling for τ^H, as E^H cannot vanish as long as Ω^H contains at least one plant.

It remains necessary to demonstrate under which conditions either or both markets exist, and if both exist, that $\tau^H > \tau^L$. Conceivably, the regulator could erroneously overallocate non-attainment permits, that is λ is too small. Using (31) and (32), and denoting by K^L and K^H the two hazard summations over j in the numerator, $\tau^H > \tau^L$ if:

$$\lambda > \frac{K^L}{K^L + K^H} + \left[\frac{1}{A}\right]\frac{K^L \bar{E}^H + K^H \bar{E}^L}{K^L + K^H} \tag{33}$$

Two put this into words, the share of attainment permits must be sufficiently large for $\tau^H > \tau^L$, as the two summation terms on the right hand side of (33) are clearly positive.

The regulator is concerned with setting attainment targets z_i and initial permit allocations A^H and A^L. However, the regulator does not know the actual b_i and can only conjecture $\hat{b}$. Thus the regulator will not know precisely which plants will participate in which market. The regulator's expectation is that plants for which $\hat{b}/\tau^H < \bar{z}_i/z_i$ will participate in the non-attainment market, and plants for which $\hat{b}/\tau^L > \bar{z}_i/z_i$ will participate in the attainment market. Algebraically, it is not possible to write down a closed-form solution for A^L and A^H. For example, it can be shown that—given a set Ω^H of non-attainment market participants—the regulator will set

$$A^H = \bar{E}_H - \frac{\hat{b}\left[\sum_{i\in\Omega^H} E_i^0\right]^2}{2\gamma \sum_j P_j \left[\sum_i d_{ij}\zeta_i E_i^0\right]\left[\sum_{i\in\Omega^H} d_{ij} E_i^0\right]} \tag{34}$$

However, which plants end up in set Ω^H depends on the choice of A^H. The more A^H permits are issued, the lower the permit price τ^H becomes, and the more likely it becomes that a plant will find it economical to participate in the non-attainment market. Ultimately, the regulator can obtain the A^H and A^L through non-linear optimization of the objective function (24).

3.8 Hybrid Emission Permit System with Two Hazard Zones

Zonal trading systems have been prposed as a way to overcome the transaction cost problem for nonuniformly-mixed pollutants. However, zones were typically defined as contiguous geographic areas, or as areas of high or low ambient emission concentrations. An important distinction of the hybrid systems proposed here is that they take into account the spatial heterogeneity of population densities. Similar to the previous hybrid emission permit regime, the system with hazard zones is marked by three distinct features:

(a) an assignment of all regions into an attainment (low) hazard zone and a non-attainment (high) hazard zone, along with a determination of each plant's contribution share to each hazard zone;
(b) a tradeable emission permit market (with equilibrium price τ^L) for emission contributions to the attainment hazard zone with initial allocation $A^L \equiv \lambda A$;
(c) a tradeable emission permit market (with equilibrium price $\tau^H > \tau^L$) for emission contributions to the non-attainment hazard zone with initial allocation $A^H \equiv (1-\lambda)A$.

The regulator chooses a zonal hazard threshold ξ and initial permit allocations A^H and A^L for each zone. Based on the zonal hazard threshold, each plant's emissions can be divided into a share s_i of non-attainment emissions and $1 - s_i$ of attainment emissions. Depending on where each plants emissions are deposited, a plant may participate in both markets ($0 < s_i < 1$), only in the attainment market ($s_i = 0$), or only in the non-attainment market ($s_i = 1$). Let $r_j = 1$ identify region j as a non-attainment region, and let $r_j = 0$ identify region j as an attainment region based on initial emission levels. Using the indicator function $\delta(\cdot)$ and initial hazard $H_j^0 = P_j \left[\sum_i d_{ij} E_i^0\right]^2$, $r_j(\xi) = \delta\left(H_j^0 > \xi\right)$. Then a plant's emissions can be decoomposed so that $s_i(\xi) = \sum_j d_{ij} r_j(\xi)$. Choosing the optimal ξ given $\hat{b}$ involves ranking the H_j^0 in descending order and including one region j at a time until the loss function L is minimized.

A plant's optimal abatement effort depends on the permit pricess τ_H and τ^L and the share of emissions it contributes to each hazard zone. Thus plant i's environmental cost function is given by

$$C(\theta_i) = B_i(\theta_i) + \tau^L \left[(1-s_i)E_i(\theta_i) - A_i^L\right] + \tau^H \left[s_i E_i(\theta_i) - A_i^H\right] \tag{35}$$

The plant's optimal abatement effort is then given by

$$\zeta_i \equiv 1 - \theta_i = \min\left\{1, \frac{b_i}{s_i \tau^H + (1-s_i)\tau^L}\right\} \tag{36}$$

The plant's optimal abatement effort depends on its abatement ability (determined by the cost factor b_i) and the weighted average emission permit price, with the weights determined by the fraction of emissions delivered to each of the two hazard zones. Abated emissions are $E_i = \zeta_i z_i q_i$, and the plant's abatement cost is $B_i = \ln(1/\zeta_i) b_i z_i q_i$. Consequently, the policy maker's loss function is given by (24) with zonal threshold ξ replacing the role of attainment targets $\bar{\zeta}_i$.

Which zonal threshold ξ does the regulator choose? All regions can be rank-ordered in terms of their initial hazard H_j^0, which is a function of unabated emissions E_i^0, dispersion factors d_{ij}, and population densities P_j. Choosing a particular ξ implies dividing the regions into two hazard zones at some H_j^0, with sets Ω^L and Ω^H containing the regions j comprising the attainment and non-attainment zones. The regulator chooses ξ so as to minimize the loss function subject to the conjecture $\hat{b}$. The uncertainty about the abatement cost ability of plants will make this choice of ξ suboptimal. As with the previous hybrid permit system, it is not possible to obtain closed-form algebraic solutions for the regulator's choice of hazard threshold ξ of permit allocations A^H and A^L.

4 Simulation

4.1 A Numerical Example

As it is not possible to obtain closed-form solutions for the hybrid emission trading systems, it is very difficult to 'prove' their relative efficiency compared to alternative models. Thus it may be helpful to illustrate the mechanics of the model by considering a simple numerical example with $I = 4$ plants and $J = 16$ regions.[5] Assume the regulator has a preference weight of $\gamma = 1/2000$. Table 1 shows the assumed numerical values for the example. Plants 1 and 2 are efficient abaters. Plants 3 and 4 are relatively inefficient abaters but are close to densely populated area. Without intervention, there are 17,000 units of emissions that generate a hazard-equivalent γH (and thus total loss L) of 2,491 thousand units.

Table 1: Numerical Example Assumptions

i	1	2	3	4
$z_i q_i$	8,000	3,000	2,000	4,000
b_i	25	10	45	50

j	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
P_j	20	50	10	10	100	200	50	10	50	200	500	50	20	50	200	100
D_1	0.5	0.2			0.2	0.1										
D_2					0.1	0.1	0.1		0.1	0.2	0.1		0.1	0.1	0.1	
D_3						0.3	0.1			0.1	0.2	0.1			0.1	0.1
D_4							0.1			0.1	0.4	0.1		0.1	0.2	
R_j	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0

Table 2 shows the results of the simulation for three types of policies: the optimal full-information intervention (setting optimal emission limits $\bar{z}_i$ for each plant directly); the cap-and-trade regime (with single permit price τ and optimal initial permit allocation A); the attainment target (based on expected value $\hat{b}$ of abatement

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[5] The attenuation matrix D makes sense when the 16 regions are viewed as a square, with the first four regions in the first row, and so on.

costs, equivalent to a simple command-and-control policy); and the hybrid trading regime (with dual permit prices τ^L and τ^H. In table 2, the emission levels for each plant are shown as ζ_i, and the total emissions from all plants are $\sum_i E_i$. For example, plant 1 reduces emissions to 46.2% of its original emission level, and plant 2 reduces emissions to 13.3% of its original emission level. Recall that $\zeta_i = 1 - \theta_i$. Thus plant 1′s abatement effort is 0.538, and plant 2's is 0.867. The performance of each policy is indicated by the total loss L, the abatement cost of all plants B, and the equivalent-unit health hazard γH.

Table 2: Numerical Example Simulation Results

	Emission Level					Performance (x1,000)		
Policy	ζ_1	ζ_2	ζ_3	ζ_4	$\sum_i E_i$	L	B	γH
No Intervention	1.000	1.000	1.000	1.000	17,000	2491.0	0.0	2491.0
Optimal Intervention	0.462	0.133	0.368	0.312	6,080	797.9	537.9	260.0
Cap-And-Trade	0.216	0.086	0.388	0.432	4,488	893.4	633.4	260.0
Attainment Target	0.521	0.410	0.273	0.226	6,846	847.9	571.7	276.2
Targets & Trading	0.449	0.180	0.297	0.330	6,051	802.1	542.1	260.0
Zones & Trading	0.470	0.087	0.310	0.344	6,019	802.8	542.8	260.0

Results in table 2 show that the optimal intervention has the lowest overall loss (a and the highest relative efficiency as defined in section 3.2. By comparison, a simple cap-and-trade has a loss that is about 12% larger, whereas the proposed hybrid regime has a loss that is only about 0.5% larger than the optimal performance. All three regimes actually generate about the same health hazard reduction (to 260,000 units), and thus the differences in overall loss are mostly attributable to the relative inefficiency of allocating the emission reductions across plants. (Even though total hazard is almost equal across interventions, the allocation of hazard across regions varies significantly.)

In the numerical example, the cap-and-trade regime generates the health hazard reduction by overshooting on the emission reductions (4,488 units instead of 6,080 units). The cap-and-trade regime is treating emission reductions equally no matter how much health hazard they cause. If the attainment target was implemented as a command-and-control policy, it would also lead to inefficiencies. However, the command-and-control approach fares better than the cap-and-trade approach. The reason is obvious: the cap-and-trade intervention has a single parameter (the permit price) to get the allocation right, whereas the command-and-control approach has J parameters to fine-tune the outcome, albeit still inefficiently. Hybrid trading can improve considerably on the command-and-control approach by adding two more parameters: the attainment and non-attainment permit prices (τ^L and τ^H).

Attainment targets are calculated with the regulator's $\hat{b}$ conjecture (here: the arithmetic average of the b_i's). When comparing the attainment targets with the optimal intervention, it is immediately apparent that plant 2 faces a lax target (0.410) compared to the optimal target (0.133) because the regulator cannot observe that plant 2 has a very low abatement cost factor b_2, and is thus an extremely efficient at abating emissions. By comparison, plant 4 would be targeted too strictly (0.226) than under the optimal intervention (0.312) because it has very poor abatement ability as its abatement cost factor is the highest of the four plants.

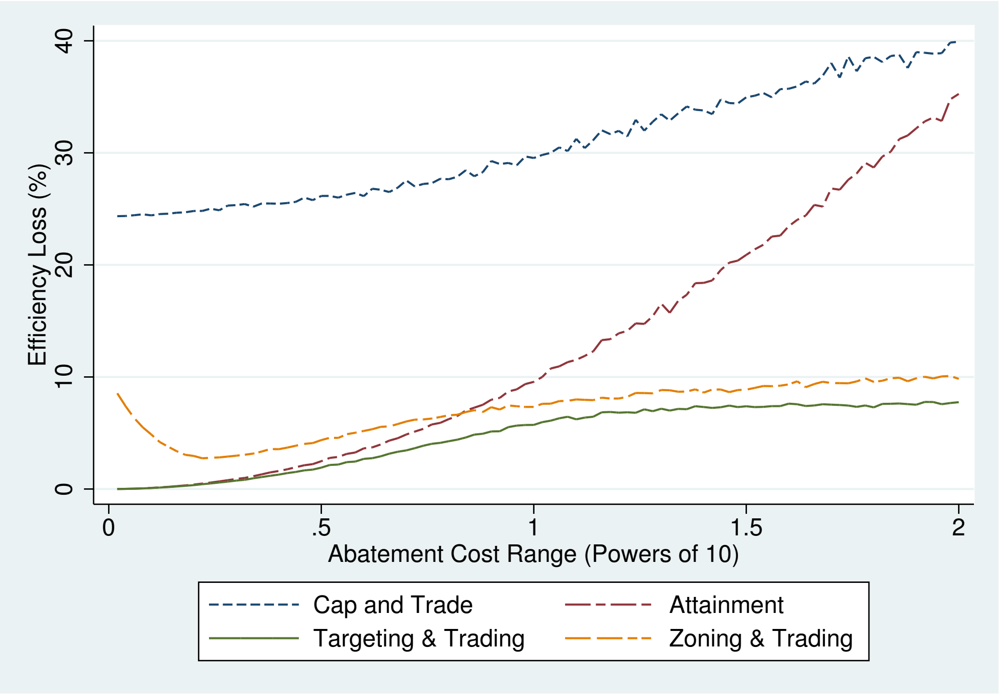
Under the simple cap-and-trade regime, a permit price of 115.85 emerges. For the hybrid trading regime with attainment targets, the two permit prices are 55.63 and 151.33 for the attainment and non-attainment markets, respectively. When comparing the emission levels of the attainment targets and the hybrid trading regime in table 2, all plants participate in the attainment market, but only plants 3 and 4 (the inefficient abaters) trade in the non-attainment market. The total emissions of 6,051 are allocated as 5,583.5 units in the attainment market (A^L) and 467.5 units the non-attainment market (A^H).

Hybrid trading with attainment zones exhibits similar efficiencies as hybrid trading with attainment targets. The results are based on putting the four regions with the highest initial hazard into the non-attainment zone.

4.2 Abatement Cost Range

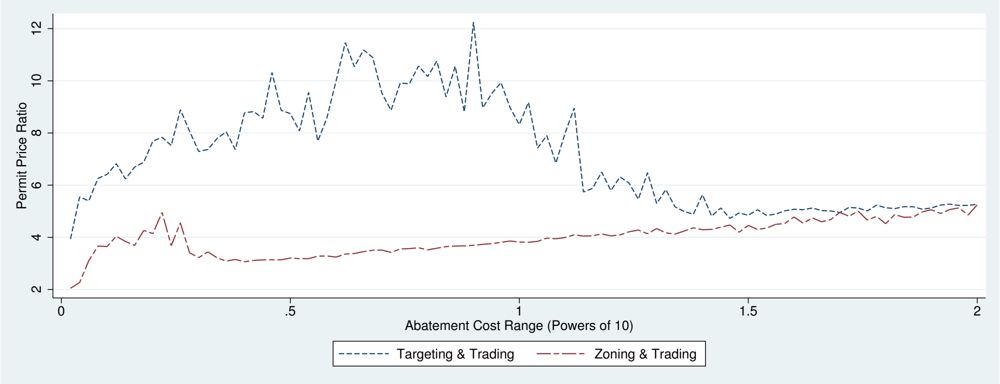
Efficieny gains from permit trading stem from the regulator's lack of knowledge of the precise abatement ability and cost factors of individual plants. Thus it is important to know how the range of abatement cost factors affects efficiency.

Figure 3: Comparative Efficiency Losses of Trading Regimes



To obtain a better understanding of how the range of abatement cost factors affects efficiency, it is useful to construct a simple simulation 'testbed.' Appendix B introduces a simplified model with an equal number of plants and regions and

Figure 4: Price Ratio of Non-Attainment to Attainment Market



each plant only affecting its own region. Plants have equal initial emissions but different abatement ability. Population varies quadratically from low to high in each region. Total emissions and population are normalized to one. This simplification provides for fast calculation of the regime outcomes without relying on general numerical optimization routines. Figure 3 shows the results of varying the abatement cost range over two orders of decadic magnitude. On the right hand side of the chart, abatement costs may span 1:100 between the lowest and highest cost plants.

Conventional cap-and-trade performs poorly throughout this simulation because of its inability to account for the spatial heterogeneity in population. Attainment targets work well when the abatement cost heterogeneity is small. Thus the regulator's error in setting these targets is small. This error increases significantly when the abatement cost range increases. Eventually the attainment targets alone are little better than the cap-and-trade regime. However, the hybrid trading regime with attainment targets is able to improve on the attainment targets without markets significantly. Even while the efficiency losses from attainment targeting increase, efficiency losses from hybrid trading remain relatively small. The increasing error from attainment targeting also provides increasing trading opportunities for the two markets in the hybrid regime.

The hybrid regime with two hazard zones performs slightly less advantageous than the hybrid regime with attainment targets, in particular when there is little variation in abatement ability across plants. Nevertheless, the hybrid regime with zones still outperforms a single-market cap-and-trade regime by a wide margin.

Perhaps it may also be informative to see how the ratio of permit prices changes as the range of abatment cost factors increases. Figure 4 indicates that this price ratio initially increases (from about 4 to 12), but later drops and levels off (to about 5). There is reason to think that a widening abatement cost range would also increase the permit price range. However, the eventual drop in the permit price is a result of the particular distributional choice of b_i's. As the abatement cost range increases, the distribution is increasingly skewed to many low abatement costs and few but very high abatement cost plants. At an abatement cost range of 10^2, the median of the distribution is just 47% of the mean. The very-high cost abaters are pushed into full abatement avoidance, at which point they no longer influence the non-attainment permit price. Figure 4 thus confirms that it is not just the abatement cost range that matters, but also the distribution of plants within that range.

The price ratio for a hybrid regime with two hazard zones is somewhat more compressed when the abatement cost range is small, but at wide abatement cost ranges becomes almost the same as the price ratio for a hybrid regime with attainment targets.

5 Practical Considerations

5.1 Determining Attenuation Factors

Knowledge of attenuation factors d_{ij} is essential for the proposed emission trading system. Perhaps the weakest point in the proposed model is that the attenuation factors may become subject to lobbying efforts by plants and industry, unless they can be measured with some degree of reliability. It is possible to measure pollutant concentrations at receptor locations. However, it is difficult to attribute the pollutant concentrations to individual sources if there are multiple sources close by.

The health hazard from toxins is starting to receive increasing attention from regulators. In April 2007, the government of Alberta announced funding for a study to take blood samples from 30,000 children and pregnant women to analyze them for toxins (herbicides, pesticides and heavy metals). Alberta Health Minister Dave Hancock suggested that testing is particularly necessary in Alberta because of the province's resource-based economy.

Data generated from ambient concentration measurements as well as the accumulation in individuals who have lived for long periods in the same location, should provide the basis for identifying attenuation factors. In addition, spatial modeling of the movement of air pollutants has made significant progress in recent years. For example, as early as 1980 Canada's province of Ontario had developed an extensive Acid Deposition and Oxidant Model (ADOM). In 2004 the province adopted the Community Multi-Scale Air Quality model (CMAQ) developed by the US Environmental Protection Agency to track multiple pollutants simultaneously across regions.

Appendix C discusses some of the econometric challenges of backing out a disperson parameter from measuring ambient concentration measurements.

5.2 Multiple Pollutants

Which toxins should be regulated? Ecologists would probably answer the first question by pointing to pollutants that cause the greatest total health hazard. While this answer may be intuitive, economists would argue slightly differently that regulators should be concerned with achieving a desired reduction of health hazard at the lowest cost. Potentially, if reducing some lesser pollutants is much less costly than reducing the most significant pollutant which is very costly to reduce, focusing on the low hanging fruit may lead to less costly reductions in the total health hazard.

Perhaps an equally important question is whether a regulatory system should cover only single pollutants or multiple pollutants. Pollutants can be both complements and substitutes in production. Some pollutants are joint output, while others can be substitutes for each other by changing the production process. Regulating just one pollutant may cause undesirable substitution effects by shifting production to methods that use the unregulated pollutant. An emission permit system can be designed easily to cover multiple pollutants by assigning fixed toxicity factors to each pollutant by using measures such as the US-EPA's (2004) Risk-Screening Environmental Indicators (RSEI) of Chronic Human Health.

Another important reason to consider a multiple pollutant permit market is that many toxins are only emitted by a small number of plants, and thus single pollutant permit markets would face relatively low liquidity. By covering multiple pollutants, more plants and firms will participate in the market, thus increasing liquidity and efficiency of the market.

A practical downside of covering multiple pollutants is the likelihood that different pollutants attenuate differently over distance. Thus it may be necessary to determine different attenuation factors d_{ij} for each pollutant.

5.3 Bioaccumulation and Biomagnification

Bioaccumulation is the process by which chemical compounds accumulate or build up in an organism at a rate faster than they can be broken down. More concisely, environmental scientists draw a distinction between bioaccumulation and biomagnification. Bioaccumulation occurs within a trophic (food chain) level in an ecosystem and captures the increase in concentration of a substance in an individual's tissues due to ambient exposure to the substance. Biomagnification occurs across trophic levels and captures the increase in concentration of a substance when the substance moves from one trophic level to the next. For biomagnification to occur, a toxin must be long-lived (i.e., does not decay rapidly), mobile (e.g., airborne), soluble in fats, and biologically active (i.e., has an effect on the metabolic activity of living cells).

A drawback of any emission trading system focusing on toxins is the fact that toxins have the tendency to bioaccumulate and biomagnify. For example, if emissions from a smelter in a rural and sparsely populated area expose nearby large herds of milk cows to arsenic, that arsenic may bioaccumulates in these cows and will biomagnify when consumed by city dwellers far away from the smelter. Yet, the health hazard would not be captured by the hazard function (1) because P_j only captures people, but not cows or species at other trophic levels in the ecosystem. Consequently, a better approach is to replace P_j with an appropriately weighted measure of biomass.

5.4 Transboundary Pollution

A further complication arises from the problem that pollutants travel easily across national boundaries. Yap et al. (2005), a study commissioned by the Ontario Ministry of the Environment, concluded that of the estimated $9.6 billion in health and environmental damages from ground-level ozone and fine particulate matter in Ontario in 2003, 55 per cent is attributable to U.S. emissions. However, there are noticeable differences across the province of Ontario, with south-western Ontario experiencing a large proportion of damages attributable to U.S. emissions, and south-central Ontario (including the Greater Toronto Area) experiencing the greatest impact of air pollution originating in Ontario. The progress with modeling air movements of pollutants, along with the sharing of emissions and emission concentration data between neighbouring countries, makes it feasible to determine attenuation factors with some reliability.

5.5 Initial Allocation: Grandfathering or Auctions?

The method of allocating permits does not affect efficiency, except when transaction costs are significant and marginal transaction costs are decreasing in the volume of trades. However, whether permits are grandfathered or auctioned has important distributional effects that also touch upon the political feasibility of the permit system. Grandfathering, which allocates permits to existing polluters based on some formula, is often considered politically less onerous than auctions, which generate government revenue and look more like taxation.

The hybrid permit system proposed in this paper requires two decisions: one each for the attainment and non-attainment market. The duality of markets opens the possibility to consider four options: grandfather both types of permits, auction both types of permits, or combine grandfathering and auction. The option to auction the attainment permits and grandfather the non-attainment permits is perhaps the least attractive: it subsidizes the worst polluters. However, the option to grandfather the attainment permits and auction (all or part of) the non-attainment permits is perhaps the most appealing. Up to the attainment target, firms receive allocations based on past performance, but where emission intensities exceed the attainment target, emission permits must be bought in a permit auction. This means that highly polluting firms will incur a greater financial burden than those that stay below the attainment target.

5.6 Emission Variability and Intertemporal Transfers Through Permit Banking and Borrowing

A stylized fact about toxic emissions is the high variability of releases across years relative to fundamental indicators of operational size, such as plant employment or value added. The evidence is that emissions exhibit great variability, which implies that emissions are not only generated through regular production activity, but are also caused by spills, leaks, and other unforeseen events or accidents. This variability of toxin releases necessitates a closer look at the intertemporal dimension of emissions trading.

A significant advantage of a tradeable permit system that targets emission levels rather than ambient emission concentrations is the ability to allow banking of permits (for use in future years), borrowing of permits (for current use), or both, across time periods. A permit system that is defined in terms of ambient concentrations cannot allow banking or borrowing, because doing so may lead to a possible temporal clustering of emissions. Temporal clustering would lead to "hot spots" of very high peak concentrations, posing a significant health risk. The economic rationale for banking and borrowing is compelling: greater flexibility across time provides for a better allocation of abatement investments over time.

In the proposed double market, a plant that expects to exceed its attainment level temporarily in the current year—perhaps due to a spill—may wish to borrow attainment permits from next year rather than purchase non-attainment permits in the current year. Allowing consolidation of permits over a given time horizon, say two or three years, may contribute to intertemporal efficiency in the presence of high emission variability across years.

Even without banking, intertemporal efficiency can be enhanced by staggering the compliance schedule. As Gangadharan (2000, p. 603) reports for the RECLAIM permit market in Los Angeles, plants were randomly assigned to two compliance cycles (January 1 through December 31 and July 1 through June 30) and are permitted to trade with each other. This overlapping two-cycle system is meant to reduce the likelihood of permit shortages or surpluses at the end of a compliance cycle.

Permit banking may also become attractive when plants anticipate reductions in the number of permits issued in future periods. The economics of permit banking has been explored extensively in Rubin (1996), Cronshaw and Kruse (1996) and Schennach (2000). Through emission banking and borrowing firms can shift their emission stream through time. Banking is generally desirable when standards are becoming stricter over time. However, when standards are constant or easing over time, emission borrowing will increase environmental hazard while lowering firms' costs. Typically, regulators may want to limit the time horizon against which permits can be borrowed. Even though banking is generally desirable, Liski and Montero (2005, 2006) show that market power may distort the outcome, even though these market power effects are mitigated by pro-competitive effects from forward markets for permits. Encouragingly, they find that manipulating a permit banking program appears to be difficult even for large permit stockholders.

5.7 Plant Entry, Plant Exit, and Plant Relocation

The entry and exit of plants poses a slightly greater challenge to a hybrid emission permit trading system than a conventional emission permit trading system because the attainment targets depend on the activity of all other plants, the more so the nearer they are to each other. Entry of a new plant creates a negative externality on surrounding plants because it will lower their attainment targets, and thus potentially increase abatement costs if the plant's emissions are either on or above the attainment target. Plant entry leads to a kind of crowding effect. The more plants locate close to each other, the stricter the attainment targets become. As a result of this effect, a hybrid emission permit system has the beneficial environmental effect of distributing plants more equally across regions. On the other hand, this may also limit potential beneficial economic effects from agglomeration.

Plant exit creates a positive externality for other nearby plants because it will raise their attainment targets, thus reducing abatement costs. At the margin, due to the crowding effect that gets priced through the hybrid permit trading system, one or more plants may find it less costly to pay another plant to either exit or relocate to a less crowded region rather than abate emissions. Induced exits may come about through company mergers and plant consolidation. Induced relocation, on the other hand, is the equivalent of the higher smoke stack policy of the 1960s: spread the hazard more equally rather than reduce emissions.

6 Metallic Toxins in Central Canada

Section 4 described a simple numerical example to illustrate the potential benefits of a hybrid permit trading system. Considering a potential practical application of this hybrid permit trading system may shed further light on some of the key features, benefits, and problems of such a system. Considering such a real-world application comes at the cost of imperfect information. Just like the regulator, the researcher cannot directly observe the abatement cost factors b_i. It is this variation in the b_i's that is the rationale behind an emission permit trading system.

6.1 Data Preview

Metallic toxins account for some of the most significant airborne health hazards. These substances are considered developmental and reproductive toxicants. Using the US-EPA (2004) toxicity scores, table 3 shows the total cumulative emissions of these toxins for the five-year period 2001-2005 across all plants in Canada. As is shown in the table, Central Canada accounts for large fractions of the point sources. Because Ontario and Quebec (which constitute the region of Central Canada) contain Canada's most populated areas along a west-east corridor, it is useful to concentrate on this geographically well-defined area. Emissions are highly concentrated. The top four polluters account for just over half of the entire toxic load, the top 30 polluters account for 90% of the toxic load, the top 53 polluters account for 95% of the toxic load, and the top 150 polluters account for 99% of the toxic load. The single largest emitter is CVRD/Inco's Copper Cliff smelter near Sudbury.[6]

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[6] 'PollutionWatch,' a web site maintained by *Environmental Defence* and the *Canadian Environmental Law Association*, ranked the Copper Cliff smelter first or second across Canada for air releases of various respiratory toxicants.

Table 3: Metallic Toxin Emissions in Canada, 2001-2005

Toxin*	Emission [tons]	Toxicity Score	Toxic Load Canada	Toxic Load ON+QC
Nickel	2,072.4	36,000	74,607	39.7 %
Manganese	1,211.7	36,000	43,622	52.3 %
Chromium	292.1	86,000	25,121	91.7 %
Arsenic	736.3	31,000	22,825	82.6 %
Cadmium	198.0	90,000	17,821	31.2 %
Lead	1,851.4	8,800	16,292	64.7 %
Cobalt	53.2	90,000	4,792	58.9 %
Copper	2,070.5	750	1,553	72.6 %
Selenium	272.6	3,600	981	100.0 %
Antimony	60.7	9,000	546	94.1 %
Zinc	4,574.0	51	233	41.3 %
Mercury	28.4	6,000	170	33.4 %
Total	13,421.3		208,564	55.6 %

* and their compounds

There are a total of 762 plants in Central Canada that emit one or more of the twelve toxic compounds into the air.[7] Table 4 shows the composition of emissions from these plants by industry and pollutant.

6.2 Spatial Heterogeneity

How does a trading system for toxins square with the geographic reality of plant locations? To illustrate the geographic dimension of the proposed emissions trading system, a look at twelve dangerous metallic toxins in Central Canada demonstrates the implications for plants.

Key to modeling the effect of emissions from points sources on receptors at a distance is an understanding of the physical processes that determine attenuation and absorption. In practical terms it requires that plant-specific emissions are translated into surrogate emission concentrations at reception points. Attenuation is the process by which emissions spread spatially in terms of direction, distance, and density. Attenuation of air pollutants is influenced primarily by atmospheric conditions and topography. Absorption is the process by which surrogate emission concentrations at a given location is translated into exposure hazard. Absorption is influenced by factors such as natural decay and vegetation.

A suitable modeling platform is the CIESIN (2005) database of the *Gridded Population of the World*, version 3. This database projects the population of the world into grid squares of 2.5 arc minutes of longitude and latitude. At 45 degrees latitude, a typical grid cell covers about 15 square kilometers. Specifically, the field

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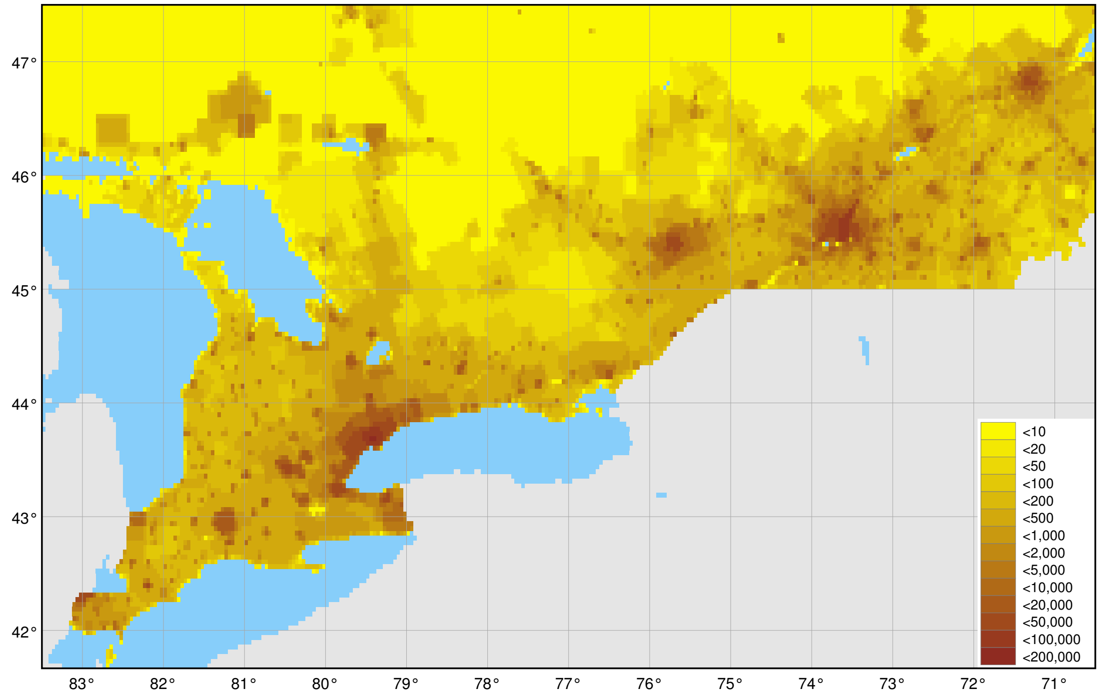
[7] Included in this category are releases through the stack, from storage or handling, from fugitive sources such as leaks from valves, seals and connections, spills and other non-point air releases.

Table 4: Composition of Emissions by Industry and Toxin (Percentage Shares of Emissions in Central Canada)

Industry	Antimony	Arsenic	Cadmium	Chromium	Cobalt	Copper	Lead	Manganese	Mercury	Nickel	Selenium	Zinc
Metal Ore Mining	0.5	45.8	61.4	8.9	43.3	49.1	25.1	2.3	2.8	60.3	42.7	13.4
Electricity Generation, Transmission & Dist.		0.7	0.7	1.8	6.7	0.7	0.4	1.2	25.7	0.8	17.2	1.5
Water, Sewage & Other Systems		<0.1	0.2	<0.1		<0.1	<0.1	<0.1	9.9			<0.1
Textile & Fabric Finishing & Fabric Coating	8.5											
Veneer, Plywood & Engin. Wood Product Mfg.			0.1				<0.1	3.6	0.1			
Pulp, Paper & Paperboard Mills	52.2	1.4	5.0			<0.1	1.0	11.9	3.0			2.5
Petroleum & Coal Products Mfg.		<0.1	0.5		<0.1	<0.1	0.2	0.1	1.0	23.2		1.4
Basic Chemical Mfg.	0.3	<0.1	<0.1	1.5	3.3	0.5	<0.1	<0.1	0.9	<0.1		1.2
Paint, Coating & Adhesive Mfg.				0.2	2.5	<0.1	0.2	<0.1	<0.1			<0.1
Plastic Product Mfg.	1.3	<0.1	0.1	<0.1		<0.1	<0.1		<0.1			<0.1
Clay Product & Refractory Mfg.				1.8								
Cement & Concrete Product Mfg.		0.1	0.7	10.7		0.3	8.7	8.7	10.6	0.1	25.1	5.4
Iron & Steel Mills & Ferro-Alloy Mfg.	<0.1	0.2	1.2	12.8		0.2	2.0	19.7	15.1	0.3	0.2	20.6
Steel Product Mfg. from Purchased Steel		<0.1		0.5	0.2	<0.1	0.2	1.1	0.1	0.4		14.1
Alumina & Aluminum Production & Processing		<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	5.1	0.6	0.3	<0.1	0.4
Non-Ferrous (exc. Al) Production & Processing	<0.1	3.4	14.6	0.7		29.3	21.3	0.6	0.8	0.5	2.5	23.8
Foundries	36.8	48.4	15.0	45.7	2.8	14.0	37.2	16.4	10.5	1.0	12.4	9.2
Forging & Stamping				0.4			<0.1	1.4	<0.1	0.1		<0.1
Coating, Engraving & Heat Treating Act.	<0.1		<0.1	0.2		<0.1	<0.1			<0.1		1.9
Other Fabricated Metal Product Mfg.		<0.1	<0.1	2.0	39.4	1.0	<0.1	0.3	0.4	6.9		<0.1
Agr., Construction & Mining Machinery Mfg.				8.4	1.3	<0.1	<0.1	1.0		5.0		0.2
Ventilation, Heating, AC & Refrig. Equip. Mfg			<0.1				<0.1	5.0	<0.1			<0.1
Electric Lighting Equipment Mfg.							2.2		3.8			
Motor Vehicle Parts Mfg.	<0.1	<0.1	<0.1	2.2	<0.1	3.1	0.3	20.2	<0.1	0.3	<0.1	2.3
Waste Treatment & Disposal		<0.1	0.1	<0.1		<0.1	<0.1	<0.1	13.6	<0.1		0.3

Figure 5: Population by Latitude-Longitude Squares



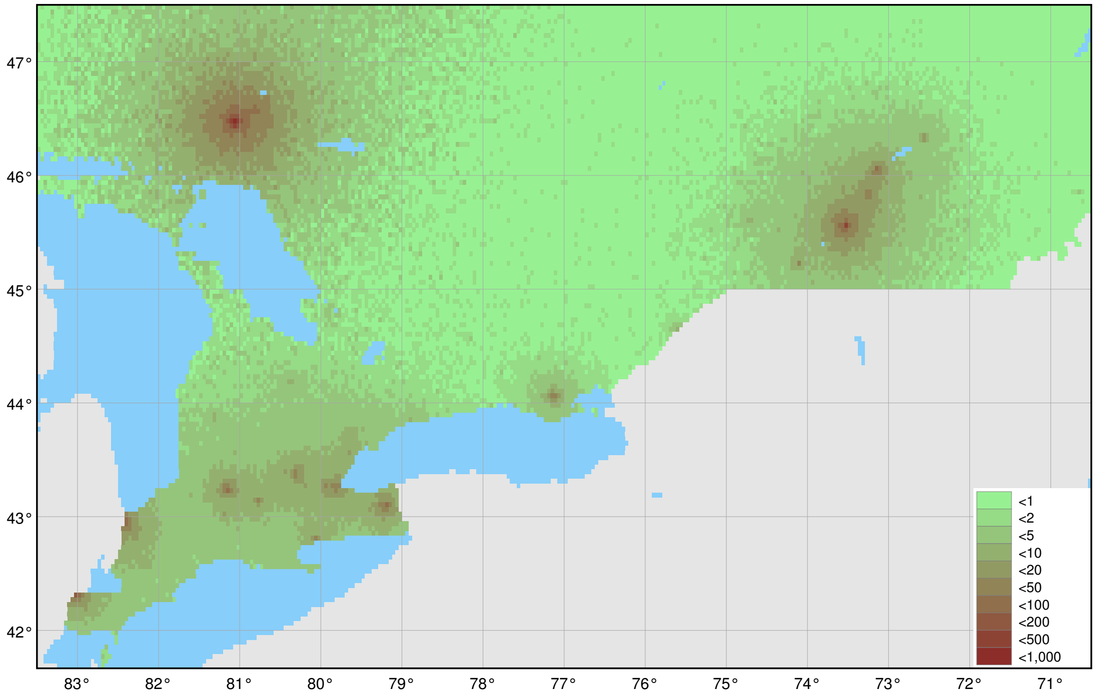
Note: Population figures in absolute numbers based on year 2000 reference data. Source: CIESIN (2005).

between 70°30″ and 83°30″ Western longitude and 41°40″ and 47°30″ Northern latitude covers 312 by 140 grid squares and about 17 million people, roughly half of Canada's population. Most prominently, it covers all major urban areas in Central Canada. Figure 5 shows the population density along the Ontario-Quebec corridor (with major population areas, from west to east, Windsor, Waterloo/Kitchener, Hamilton, Toronto, Kingston, Ottawa, Montreal, and Quebec City). The map is in logarithmic scale, identifying the dense urban areas in red.

Emission dispersion can be modeled by projecting emissions from individual plants into air concentration plumes that decrease in intensity from the point of origin. One particularly simple version of this approach assumes that the plumes decrease exponentially in density and equally in all directions. With suitable knowledge of meteorological conditions such as wind speeds and wind directions it is possible to develop quite realistic air concentration plume projections. Such sophisticated modeling is outside the scope of this paper. Modeling a symmetric radial exponential air plume requires a single parameter r, the mean travel distance of pollution particles. The exact numerical method involving latitudes and longitudes is described in Appendix D.

Figure 6 simulates the emission distribution of toxins released into the air, using actual data from Canada's National Pollutant Release Inventory for the years 2001-2005. The metallic toxins were combined with the toxicity factors described earlier,

Figure 6: Pollution Concentration Plumes by Latitude-Longitude Squares

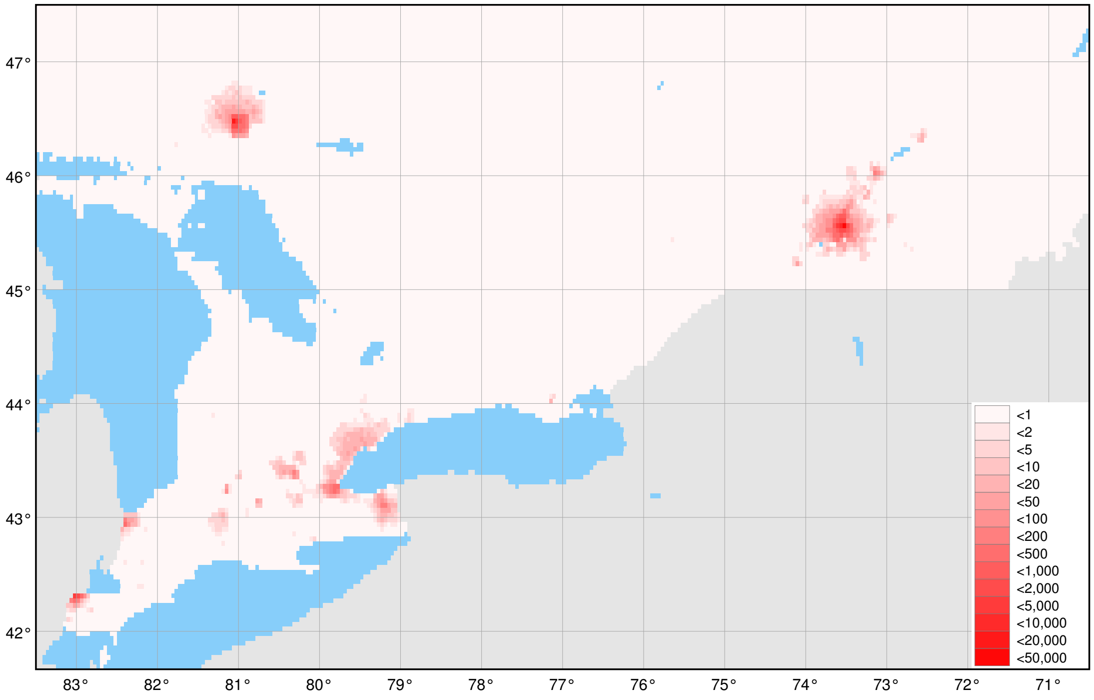


Note: Air pollution concentration plumes are computed using the method described in Appendix D. Numbers are toxicity scores based on an aggregation of twelve metallic toxins using emission data from 2001–2005.

and the mean attenuation distance was assumed (probably quite generously) as 100km. The exact methodology of this simulation is presented in appendix D. Attenuation is assumed to be exponentially decreasing with distance, not accounting for differences in stack heights, wind direction and other relevant factors. The green areas indicate low emission concentrations, and the red areas indicate high emission areas. The emission concentration scale is logarithmic. A small number of plants is responsible for very large emission loads. Very noticeable is the area around Sudbury, where a number of CVRD Inco's smelters are located. A second hotspot is the Montreal area, where numerous metallurgical smelters and mills are located.

Finally, figure 7 combines the population densities and projected emission concentrations into health hazards using the hazard function (1). What is immediately apparent is that the health hazard is highly locally concentrated around major urban areas (the greater Montreal area and the 'golden horseshoe') and hotspots of smelter activity such as Sudbury. On the logarithmic scale of figure 7 virtually all other areas of Ontario and Quebec face very small health hazard due to metallic toxins.

Figure 7: Health Hazard by Latitude-Longitude Squares



Note: Hazard (exposure risk) is calculated using equation (1) and utilizing the population and emission data as shown in figures (5) and (6).

6.3 Hybrid Trading System Simulation

The numerical complexity of a simulation is quite considerable. In Central Canada there are 762 possible participants in an emission trading system and 22,796 populated longitude-latitude squares, forming an attenuation matrix with over 17 million entries. In order to make multiple simulation runs computationally feasible, I constrain the problem and consider only the top 75 polluters (covering 97.0% of the toxic load) and the 3,108 population squares with 500 or more people (covering 89.5% of the population), thus reducing the attenuation matrix to 233,100 entries.

To run a simulation it is necessary to generate some heterogeneity across plants in terms of their pollution abatement ability. This information is as unobservable for the researcher as it is unobservable to the regulator. In the absence of such information it is necessary to adopt a plausible assumption about the distribution of b_i. Concretely, let u_i denote a random draw from a uniform [0,1] distribution, and assign $\tilde{b}_i = 100^{u_i}$. This in turn generates a distribution of b_i with a very sizable range of two orders of decimal magnitude.[8] However, 50% of the plants are within

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[8] It may appear questionable to assume such a wide range of abatement ability across plants. This range is inspired by looking at the actual emission data from these plants. A possible assumption is that pollution abatement cost factors are positively correlated with (sectorally-adjusted) emission intensities: the more emission-intensive plants face greater costs reducing emissions than

Table 5: Simulation Results for Central Canada

	Total Loss		Abatm. Cost		Hazard Cost		Emissions	
	$L = B + \gamma H$		$\sum_i B_i$		$\gamma \sum_j H_j$		$\sum_i E_i$	
Policy	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
No Policy	8,391.8				8,391.8		109.3	
	100%				*100%*		*100%*	
Optimal Policy	1,494.8	864.1	875.2	474.7	619.6	443.7	58.9	6.2
	18%	*58%*		*54%*	*7%*	*72%*	*54%*	*11%*
Cap-and-Trade System	2,934.4	2,300.4	618.4	302.6	2,316.0	2,437.8	46.5	14.9
	35%	*78%*		*49%*	*28%*	*105%*	*42%*	*32%*
Attainment Targets	2,058.7	1,058.5	1,241.0	1,047.6	817.7	98.1	71.0	2.0
	25%	*51%*		*84%*	*10%*	*12%*	*65%*	*3%*
Hybrid Permit System	1,761.0	1,097.9	982.7	615.6	778.3	720.0	48.0	9.3
	21%	*62%*		*63%*	*9%*	*93%*	*44%*	*19%*

Note: Avg.: Average of 100 simulation runs. S.D.: corresponding standard deviation. Percentages in the Avg. column are relative to the 'No Policy' line. Percentages in the S.D. column are relative to the corresponding average. Original costs and emissions are scaled down by 1,000 for greater readability. Emissions are thus in 1,000 tons of Toxicity Equivalency Units [TEU].

Table 6: Permit Prices, Initial Allocations, and Market Participants

Variable	Avg.	S.D.	
Cap-&-Trade Permit Price	29.7	11.9	[$/TEU]
Cap-&-Trade Permit Allocation	46.5	14.9	[1000 TEU]
Attainment Permit Price	16.3	6.4	[$/TEU]
Attainment Permit Allocation	44.8	8.3	[1000 TEU]
Non-Attainment Permit Price	105.4	81.9	[$/TEU]
Non-Attainment Permit Allocation	3.2	3.7	[1000 TEU]
Number of abstaining plants	19.5	4.8	[# of plants]
Number of over-attaining plants	40.2	6.6	[# of plants]
Number of fully-attaining plants	28.2	9.6	[# of plants]
Number of under-attaining plants	6.7	4.9	[# of plants]

Note: TEU: Toxicity Equivalency Unit (tons of emission times toxicity factor). Allocations are in thousands of TEUs. Prices are to be understood in relative terms, not absolute terms, as abatement costs are not known.

the first

Tables 5 and 6 show the results of the simulation. Five regimes are compared: no intervention at all, the optimal intervention given perfect knowledge of the abatement ability of plants, a conventional cap-and-trade regime with a single permit price, command-and-control regulation through attainment targets only, and the hybrid permit system that combines attainment targets with dual attainment and non-attainment markets. A number of 'stylized results' emerge from the analysis:

a) The hybrid trading regime provides a clear improvement over the cap-and-trade regime. Whereas cap-and-trade reduces losses to 35% of the pre-abatement level, the hybrid regime reduces losses to only 21% of the pre-abatement level. By comparison, the optimal intervention reduces losses to 18% of the pre-abatement level.
b) The cap-and-trade regime exhibits the smallest abatement costs, even though emissions are reduced by more than any othe regime. The inability of cap-and-trade to address spatial heterogeneity leads to a reduction of hazard to only 28%, whereas the optimal policy would achieve a reduction to 7% of the original hazard level, and the hybrid trading regime would achieve a reduction to 9% of the original hazad level. Whereas cap-and-trade focuses on emission reductions, the hybrid trading system focuses on hazard reduction.
c) A system that was based entirely on attainment targets (i.e., a command-and-control approach) would be significantly less efficient than the hybrid trading regime, although it would outperform a simple cap-and-trade regime. Attainment targets alone lead to the highest abatement cost of any regime, even though total emissions are reduced the least. Attainment targets without the flexibility of a market instrument to compensate for the regulator's information are relatively inefficient in terms of definition (3).
d) The permit price τ^H for the non-attainment market is about six times larger than the permit price τ^L for the attainment market. Initial allocation of permits are about 14 times larger for the attainment market than the non-attainment market.
e) Whereas all plants participate in the attainment market, only a small number of plants (roughly 7 out of 75) participates in the non-attainment markets. These are typically the plants generating the largest toxic loads closest to urban centres. However, seven plants would generate sufficient market liquidity to make a non-attainment market feasible.
f) A significant number of plants (40 out of 75) will be over-attaining, and thus

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less emission-intensive plants. Concretely, consider plant i in a specific 4-digit NAICS industrial sector s, with n_s plants in this sector. The plant's emission level is $E_{i,s}$ and the employment level, as a measure of scale, is $L_{i,s}$. Thus $\tilde{z}_i = E_{i,s}/L_{i,s}$ is a measure of emission intensity. These numbers are readily available from the Canadian NPRI. Then let $\tilde{z}_{i,s}/(\sum_k^{n_s} \tilde{z}_{k,s}/n_s)$ denotes the ratio of plant i's emission intensity with respect to the average emission intensity of industrial sector s. These numbers indicate a rather wide range of potential $\tilde{b}_i$'s that span orders of magnitude. As there is no way of verifying that these ratios are indeed correlated with abatement costs, simulating a plausible distribution of $\tilde{b}_i$'s through random draws appears to be a more informative approach.

they will become ‘market makers’ for the attainment market.

g) The number of fully-attaining plants (28 out of 75) consists of two groups. These are plants that either achieve an attainment target that is lower than their emission level, but it also includes plants which the regulator exempts from emission reductions because they lie in remote unpopulated areas. There are about 20 out of 75 plants that will abstain from any pollution abatement. These are either under-compliant plants for which pollution abatement is simply too costly, or these are plants that the regulator has exempted from emission reductions.

The simulation results have to be interpreted with great caution as they are based on particular assumptions about the abatement ability and abatement cost function of plants. In addition to defining abatement attainment targets, the regulator's most significant concern is how to split the allowable total emissions into attainment and non-attainment permit allocations. The simulation suggests that the non-attainment market will likely be very small in magnitude, focusing on just a few plants.

The emission reductions suggested by the simulation are relatively large. But even emissions reductions of 10% or 20% would necessarily lead to significant hazard reductions through the hybrid permit system, because these reductions would be focused on the highest-hazard emitters.

7 Conclusion

Unlike emission permit trading systems for carbon dioxide or other common air pollutants that have global or long-range reach, emission permit trading for airborne toxins is made difficult by the fact that the spread of these toxins is geographically confined. Addressing the resulting spatial heterogeneity in emission concentrations is a formidable task for market-based instruments. High transaction costs make it infeasible to operate a large number of regional ambient concentration permit markets. The transaction cost dilemma can be overcome by drastically reducing the number of permit markets. This paper proposes two hybrid emission permit trading systems as feasible solutions to the transaction cost problem. The first proposed system combines attainment targets for emissions (or emission intensities) with permit trading in an attainment and a non-attainment market. The second proposed system combines two hazard zones with permit trading in attainment and non-attainment markets corresponding to the two hazard zones. Such hybrid systems are able to approximate the first-best solution effectively.

In order to increase efficiency and liquidity in the permit market an emission trading system for toxins should cover multiple pollutants emitted by a large numbers of plants, with pollutants aggregated through suitable toxicity scores that capture their adverse health effects.

Focusing on the first of the two proposed hybrid regimes, a simulation of the likely consequences of operating a hybrid emission permit system for metallic toxins in the provinces of Ontario and Quebec, which covers roughly half of the population of Canada, suggests that a relatively small number of plants would participate in the non-attainment market, whereas all plants would participate in the attainment market. Consequently, prices in the two permit markets would differ significantly, by about a factor of 7, and initial allocations vary roughly by a factor of about 13. While this simulation hinges necessarily on a number of rough-and-ready assumptions about the distribution of abatement ability across plants and the disperson of toxins over distance, the results are at least indicative of the potential of a hybrid trading system. What is quite promising is that even when the attainment targets are quite off the mark, the dual markets can restore a great deal of efficiency.

The main advantage of the proposed hybrid trading regimes is their relative simplicity and low transaction cost. Plants only need to trade in one or two markets. Determining individual-plant attainment targets through a transparent rule that is resistant to lobbying and local political interference remains the Achilles heel of the proposed system with attainment targets. While somewhat more efficient than the proposed system with hazard zones, the hazard zone approach may ultimately be administratively easier and thus less costly. Furthermore, in order to set appropriate attainment targets or determine plant's contribution of emissions to hazard zones, the regulator requires knowledge of the disperson of toxins over distance. While much progress has been made in recording emission releases from plants (through mandatory reporting to toxics release inventories), regulators still lack good data on ambient pollutant concentrations across regions and thus plant-to-region attenuation factors. Any type of regulatory intervention that promises to address the spatial heterogeneity in emissions and population, whether by command-and-control or by market instrument, needs to start with addressing this knowledge deficit.

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APPENDIX

A Emission Trading in Canada

While emission permit trading has been successfully used in numerous jurisdictions including most prominently the United States, to date Canada has very limited experience with emission trading systems. This experience consists mostly of analysis and consultations, two voluntary trial programs implemented as public-private partnerships, and private sector trades. The two experimental programs are the Pilot Emission Reduction Trading (PERT) project and the Greenhouse Gas Emission Reduction Trading (GERT) project. These credit systems were launched in 1996 and 1998, respectively. PERT provides tradeable credits to firms in Ontario that reduce emissions by more than required by regulation. Ownership of registered credits can be contractually transferred between parties. PERT covers NOx, VOC, CO_2 and SO_2 emissions. Curiously, the value of these credits stems from the ability to sell the credits as offsets to foreign companies, to the extent that these foreign markets allow offsets. GERT was a similar program involving six other Canadian provinces. It was operated through 2001 and only involved greenhouse gases. In 2000, PERT was supplanted by *Clean Air Canada Inc.*, a non-profit organization, formed by the original private sector members in PERT. Currently, most activity regarding emission permit trading focuses on the implementation of the Kyoto protocol to limit greenhouse gas emissions. No trading system has ever been considered for toxins.

B Simplified Hybrid Emission Trading Model

Consider a simplified version of the hybrid emission trading model with $I = J = n$ regions and plants. There is exactly one plant in each region and population is distributed quadratically $P_j = 6P(j)^2/(n(n+1)(2n+1)) \equiv (j)^2 P^n$ so that $\sum_j P_j = P$. Region 1 has the smallest population and region n has the largest population. Plants are identical in emission levels so that $E_i^0 = E^0/n \equiv E^n$. Plants draw their abatement cost factors b_i from a particular distribution, and the regulator can only observe the average abatement cost factor $\hat{b}$. Emissions are entirely local so that $d_{ij} = 1$ if $i = j$ and $d_{ij} = 0$ if $i \neq j$. The loss function (2) simplifies to

$$L = E^n \sum_i \left[\ln(1/\zeta_i) b_i + \gamma P^n E^n (i\zeta_i)^2\right] \tag{B.1}$$

with ζ_i defined by (23) in the case of using attainment targets, which are considered first here. The full-information optimal regulatory intervention (7) simplifies to

$$\frac{\bar{z}_i}{z_i} = \min\left\{1, \frac{1}{i}\sqrt{\frac{b_i}{2\gamma P^n E^n}}\right\} \tag{B.2}$$

As the regulator conjectures $\hat{b}$, the attainment targets are obtained from the above expression by replacing b_i with $\hat{b}_i$. Because abatement avoidance cannot exceed one, the regulator will set an attainment target equal to the current emission level if $i < \sqrt{\hat{b}/2\gamma P^n E^n}$, that is, for scarcely populated regions.

It is now possible to identify precisely which plants will participate in which market by constructing an 'abatement ladder.' Depending on the set of the participants Ω^H and Ω^L, the optimal permit prices are

$$\tau^H = \sqrt{2\gamma P^n E^n \frac{\sum_{i\in\Omega^H}(ib_i)^2}{\sum_{i\in\Omega^H} b_i}} \tag{B.3}$$

$$\tau^L = \sqrt{2\gamma P^n E^n \frac{\sum_{i\in\Omega^L}(ib_i)^2}{\sum_{i\in\Omega^L} b_i}} \tag{B.4}$$

Market participants can be identified through a simple sequential algorithm. First observe that the permit prices can be arranged in a strictly decreasing order by arranging the plants in a particular order. Note that by adding plant j to an existing list,

$$\frac{\sum_{k\in\Omega}(kb_k)^2}{\sum_{k\in\Omega} b_k} > \frac{(jb_j)^2 + \sum_{k\in\Omega}(kb_k)^2}{b_j + \sum_{k\in\Omega} b_k} \quad \Longrightarrow \quad \frac{\sum_{k\in\Omega}(kb_k)^2}{\sum_{k\in\Omega} b_k} > j^2 b_j \tag{B.5}$$

For the first plant i and second plant j, $i^2 b_i > j^2 b_j$. By ordering plants in descending order of $i^2 b_i$, the permit prices will be decreasing with the inclusion of each next plant. Thus it is possible to traverse this reordered list of plants from top to bottom in decreasing order of τ^H to find the growing set of non-attainment market participants. Likewise, traversing the list from bottom to top in increasing order of τ^L generates a growing set of 'market makers' (over-attainers) in the attainment market. As this traversing procedure increases the list of participants one by one, it is necessary to ensure that $b_i/\tau^H > \bar{z}_i/z_i$ in the non-attainment market and $b_i/\tau^L < \bar{z}_i/z_i$ in the attainment market. For example, by reducing the non-attainment permit price τ^H by widening the list of participating plants, b_i/τ^H increases and may push one or more plants past the $\bar{z}_i/z_i$ threshold. During the traversion it is therefore necessary to validate the participant lists. The sequential traversion is continued until a minimum of L has been found.

This simplified model can be simulated using particular distributional assumptions about the b_i. A key parameter to explore is the range β for the abatement cost factors. Let u denote a random draw from the uniform $[0, 1]$ distribution. Then let

$$b_i = \hat{b}\frac{10^{\beta u}\beta \ln(10)}{10^{\beta} - 1} \tag{B.6}$$

so that the average b_i is equal to $\hat{b}$. Further let $n = 50$, $P = 1$, $E^0 = 1$, and $\gamma = 10^4$. Now vary β from 1/50 to 2 in 1/50 increments, and repeat each draw of b_i's 200 times, generating some 10,000 observations of the performance characteristics of interest.

Note that while the mean of drawing the b_i's is fixed at $\hat{b}$, the median of these draws is $\hat{b}(10^{\beta/2}\beta \ln(10))/(10^{\beta} - 1)$. As β increases to 1 and 2, the median drops to $0.809\hat{b}$ and $0.465\hat{b}$.

Now consider the permit system with two hazard zones. Because each plant's emissions are entirely local, the emission contribution shares s_i are binary and identical to $r_j(\xi)$. Each plant therefore participates either in the non-attainment market or the attainment market, but never in both. Now rank the regions by their initial hazard H_i^0, which here is simply proportional to the population P_i. Then partition the regions sequentially into Ω^H and Ω^L and calculate the corresponding optimal permit prices through (B.3) and (B.4). Then determine the partitioning with the minimal loss L. Implicitly, the partitioning defines the regulator's optimal ξ.

C Estimating Attenuation Coefficients

Establishing the proposed hybrid emissions trading system depends crucially on knowledge of the attenuation coefficients d_{ij}. Ultimately, these need to be determined by measurement of ambient concentrations at receptor locations. With concentrations C_j at locations j and knowledge of emission sources E_i, it is possible to estimate coefficients α, β, and ϱ in the non-linear regression

$$C_j = \alpha + \beta \sum_i (1 - \exp(-D_{ij}/\varrho))E_i + \epsilon_j \tag{C.1}$$

possibly allowing for spatial correlation in the error term ϵ_j. The term α allows for a base ambient concentration that is unrelated to industrial emissions, and $\beta < 1$ allows for the natural decay and absorption. The D_{ij} are physical distances. This model can be refined to allow for wind speeds and directions. The estimated attenuation coefficients are $\hat{d}_{ij} = \hat{\beta}(1 - \exp(-D_{ij}/\hat{\varrho}))$. A significant challenge is that α may vary regionally, and is also subject to capturing transboundary pollution.

D Emission Attenuation Simulation

In this paper, emission attenuation is simulated using a simple single-parameter spatial process defined by r, the mean distance for pollutants to be carried through the air. A given emission load v can be allocated to grid cells or polygons by splitting the load v into $n \geq 10,000$ partial loads of weight v/n, and then distributing these partial loads at impact locations drawn from a suitable attenuation distribution, described below. Partial loads v/n are added up within each grid cell or polygon. This procedure amounts to spatial integration.

Assume that emissions attenuate symmetrically around a given source point. To determine depositions by grid cell or polygon, draw a pair of random numbers (ω, d) comprised of compass angle ω (clockwise from North) and distance d, given average radial dispersion of r. Angle ω is drawn from the uniform distribution $[0°, 360°[$, and distance d is drawn from the exponential distribution with cumulative distribution function $\Omega(d) = 1.0 - \exp(-d/r)$. The exponential distribution function has mean r, the average impact distance. The median impact distance is $\ln(2)r$. In practical terms the distance d can be generated by first drawing z from a uniform $[0, 1[$ distribution and then transforming z through the inverse cumulative distribution function $d = -r \ln(1 - z)$. Given (ω, d) and the location of the emission source (ϕ_0, λ_0) of latitude ϕ_0 and longitude λ_0, the impact location (ϕ_1, λ_1) can be calculated through loxodrome approximation, which is sufficiently accurate for small distances:

$$\begin{aligned}
\phi_1 &= \arcsin\left(\sin(\phi_0)\cos(d/D) + \cos(\phi_0)\sin(d/D)\cos(\omega)\right) \\
\lambda_1 &= \lambda_0 + \arcsin\left(\sin(\omega)\sin(d/D)/\cos(\phi_0)\right)
\end{aligned}$$

where D is the earth radius of 6371km.