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Adaptive Cost-Effective Ambient Charges under Incomplete Information[1]

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Established opinion is that in the face of uncertain information on pollution control costs, environmental agencies cannot set ambient charges that enable the realization of desired concentration levels at multiple receptors in a cost-effective way. Although a trial-and-error procedure could result in attainment of concentration standards this would generally not be cost-effective. This paper, however, proves that environmental agencies can develop charge adjustment procedures that achieve ambient standards at multiple receptors at minimum costs. The procedure is applied to a case study for acidification in the Netherlands. The results show that the iterative procedure approaches the cost-effective emissions fairly quickly.

1. INTRODUCTION

Targets of environmental policy should be met and pollution control costs should not be higher than strictly necessary. If the environment authority has complete information on pollution control costs for every single emission source (firms and households, regions and countries) it is possible to design cost-effective emission (technology) standards for each individual source to meet environmental targets at multiple receptors in the form of ambient standards. However, it is unrealistic to assume that the authority possesses full information on the costs and can allocate emissions at minimum cost by way of central planning. To overcome this problem it has been proposed in the literature to set prices, that is emission charges. Given the price information private sources could calculate their cost-minimizing level of emissions. The difficulty with this policy approach is that it is an ''empty box'' as long as we are not told how the authority can find the right level of charges. In this

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article we set out to demonstrate that it is possible to design a decentralized strategy of pollution control based on ambient charges and interactions between sources and receptors with realistic assumptions on the information and the role of the central agency.

Decentralization in the allocation of scarce resources by way of pricing is the heart of the modern market economy. Each individual chooses his best bundle of available goods with only knowledge of current prices, which are adjusted on the ''market'' according to excess demand. We argue in this article that a system of ambient charges can be designed as a kind of Walrasian market that allocates a scarce environmental resource. The environmental scarcity is defined by the ambient standards at receptor points. By choosing an emission level the individual source ''consumes'' a bundle of goods, the vector of concentrations of pollutants at receptor points, the bundle being defined by the atmospheric transport equations. We define the gap between actual concentration and the target concentration (the ambient standards) at receptors as ''excess pollution function.'' We assume that the agency (authority) is able to monitor the actual levels of this function and adjusts prices (ambient charges) according to these levels at each receptor. Therefore we view environmental qualities at different receptors as different goods, with prices rising and falling with variations in excess pollution. The environmental agency plays the role of a Walrasian auctioneer on the environmental market by monitoring excess pollution and adjusting prices (ambient charges) which, under certain assumptions on the transport of emissions, can be translated into emission charges.

In earlier literature on the subject (Bohm and Russel [3]) it has been maintained that, in the case of multiple receptors, such type of interactive procedures for establishing equilibrium ambient charges (and related emission charges) would not guarantee that the resulting allocation of emission control is cost effective. This seems to be the generally accepted view today and as such it is seen as a conclusion based on the results of earlier studies for simpler cases. Well known among them is the original idea of Baumol and Oates [2] to apply a uniform emission charge to reduce the total emissions of sources to a given target level at minimal total costs. Baumol and Oates proposed the adjustment of the emission charge in successive steps directed by the difference between actual and target emissions. Bohm and Russel [3] suggest that in the general case of multiple ambient standards, and lack of information on total control cost, such an iterative procedure may eventually lead to achievement of the ambient standards, but their main conclusion is that there is no guarantee that this is the cost-effective way of meeting the standards. In this paper we show that Bohm and Russel's conclusion is faulty. It is possible to determine a vector of ambient charges and resulting emission charges to attain ambient standards at minimum costs.

However, even if the ultimate allocation of emissions would minimize total costs of pollution control such a system of ambient and/or emission charges might not be considered practical because it is complex, confusing, and may take a long time to converge. This line of arguing makes a fundamental error in forgetting the artificial nature of the underlying market system. It is possible to separate the procedure in two stages: first a learning phase in which no control measures are taken and a second stage of actual implementation. The agency starts the learning stage by announcing a preliminary set of ambient charges and corresponding emission charges. Sources then state their proposed emission levels from which the

agency can derive the excess concentration at receptor points, adjust prices, announce a new set of charges in a second round, and so on. One can imagine a learning stage organized through a distributed computer network connecting sources and the agency. The local processor at a source stores information on emission reduction cost of the source and computes the best emission level of the source for a given emission tax that has been derived from the set of ambient charges. The central processor of the agency receives the information on emissions from the sources, computes excess pollution, adjusts prices (ambient charges and emission charges), and processes them to the sources. The process is repeated until equilibrium ambient charges are reached. Then the stage is set for implementation: ambient charges and derived emission charges are imposed as prices that must be paid. The procedure copies the Walrasian process of *tâtonnement*: the auctioneer discovers the equilibrium price before agents act and ''false'' emission adjustment, at non-equilibrium prices, can be avoided. In this paper we assume that sources are ''price takers'' and do not give strategic information to influence the charge. For example, they will not exaggerate their level of emission control during the learning stage in order to obtain lower charge levels at the start of the implementation stage. Under which conditions it might be feasible and profitable to give false information in the learning stage and to what extent this could be reduced or eliminated by appropriate penalties is a subject for future research.

The paper is organized in six sections. Section 2 formulates the problem of setting emission standards and ambient and related emission charges under the assumption that the environmental agency has imperfect information on pollution control costs. Section 3 then proceeds to define an adjustment mechanism that enables the agency to discover the cost minimizing vector of ambient charges without knowledge of the costs. It is assumed that the sources are cost minimizers and have perfect information on individual costs. In Section 4 the cost effectiveness of emission standards and ambient charges is discussed for the case where the environmental agency has imperfect information on total cost and individual costs are inherently stochastic. We show that the adjustment mechanism still converges and that ambient charges are both environmentally effective and more cost effective than emission standards. Section 5 applies the theory in an empirical setting to illustrate how the adjustment mechanism functions. Concluding remarks are given in Section 6, which also discusses the institutional setup in a more detailed fashion.

2. DETERMINISTIC POLLUTION CONTROL

Let $i = 1, \ldots, n$ be sources of emission (firms and households, regions or countries) and $j = 1, \ldots, m$ be receptors. Each polluter i emits a single pollutant at the rate x_i. The emission vector $x = (x_1, \ldots, x_n)$ is mapped into concentrations at receptors by a set of transport equations, described by a transfer matrix $H = \{h_{ij}\}$, $i = 1, \ldots, n$, $j = 1, \ldots, m$, where h_{ij} stands for the contribution made by one unit of emission of source i to the concentration of pollutants at point j. Ambient concentrations q_j at the receptor points $Q = (q_1, \ldots, q_m)$ impose con-

straints on emission rates

$$\sum_{i=1}^{n} x_i h_{ij} \le q_j, \qquad j = 1, \ldots, m, \tag{1}$$

$$x_i \ge 0, \qquad i = 1, \ldots, n. \tag{2}$$

The environmental authority's problem is to achieve target concentrations Q at minimum total cost for polluters: that is to choose the vector $x = (x_1, \ldots, x_n)$ to minimize the total cost

$$\sum_{i=1}^{n} f_i(x_i) \tag{3}$$

subject to constraints (1) and (2).

The solution of this problem $x^* = (x_1^*, \ldots, x_n^*)$ defines the cost-effective set of emission levels which can be imposed on sources as emission standards. The implementation of such a policy of direct regulation requires that the regulatory authority has full information on parameters h_{ij}, q_j and on cost functions $f_i(x)$.

By using classical duality results Tietenberg [7, 8] has demonstrated that there exists a vector $\lambda = (\lambda_1, \ldots, \lambda_m)$ of shadow prices at receptors which corresponds with the vector of cost-effective emission standards and can be considered as ambient charges. The simple linear structure of the pollution transport equations also allows the calculation of a vector of emission charges $u = (u_1, u_2, \ldots, u_n)$, which can be written as a function of transfer coefficients and the shadow prices λ_j, $j = 1, \ldots, m$, at the receptors:

$$u_i = h_{i1}\lambda_1 + h_{i2}\lambda_2 + \cdots + h_{im}\lambda_m, \qquad i = 1, \ldots, n. \tag{4}$$

If optimal emission charges $u_i = u_i^*$ associated with optimal $\lambda_j = \lambda_j^*$ are imposed they will induce cost minimizing sources to adjust emissions in such a way that the sum of their control costs plus expenditure on emission charges is minimized

$$f_i(x_i) + u_i x_i = f_i(x_i) + \left(\sum_{j=1}^{m} \lambda_j h_{ij} \right) x_i$$

for $i = 1, \ldots, n$, where $x_i \ge 0$ and $\lambda_j = \lambda_j^*$, $j = 1, \ldots, m$, or $u_i = u_i^*$. It results in the cost-effective emission $x_i^*, i = 1, \ldots, n$. Let us notice that since f_i is a decreasing function of x_i the solution of such subproblem $x_i(\lambda)$ is well defined.

3. ADJUSTMENT MECHANISM

The main question is how the environmental authority can determine the vector of cost-minimizing ambient charges and derived emission charges without knowledge of the cost functions where there is more than one receptor. This section describes an adjustment mechanism that is capable to perform this task through the adaptation of the ambient and resulting emission taxes in successive steps to equilibrium shadow prices. The proposed procedure decomposes the pollution control problem into two types of decision problems. The first choice problem is

that of the environmental authority having to decide on the ambient charges and on how to adjust their level, given its information on the discrepancy between actual and target concentrations. The procedure for adjusting charges is based on non-monotonic optimization techniques which do not require information on the total cost of controlling emissions. We will prove that the environmental authority can actually restrict its task to monitoring the gap between the actual concentration of the pollutant at the receptors and the target concentrations (excess pollution or equivalently excess concentration)

$$\Gamma_j(x) = \sum_{i=1}^{n} x_i h_{ij} - q_j, \qquad j = 1, \ldots, m$$

without bothering about costs.

The second optimization problem is that of individual cost minimizing polluters, each choosing its emission level given the emission charge that is imposed by the environmental agency. The formal description of the adjustment mechanism is the following. Suppose $\lambda^0 = (\lambda_1^0, \ldots, \lambda_m^0)$ is a vector of initial ambient charges on concentrations of a pollutant at the receptor points and let $\lambda^k = (\lambda_1^k, \ldots, \lambda_m^k)$ be the vector of ambient charges at step k of the adjustment process. Each source adjusts its emission level x_i^k, $i = 1, \ldots, n$, by minimizing its total (individual) cost

$$f_i(x_i) + u_i^k x_i$$

at current values of emission charges u_i^k translated from current values of pollution or ambient charges λ_j^k, $j = 1, \ldots, m$, by Eq. (4):

$$u_i^k = \sum_{j=1}^{m} \lambda_j^k h_{ij}, \qquad i = 1, \ldots, n. \tag{5}$$

The agency observes the ambient concentrations generated by the vector x^k; it calculates the excess concentration $\Gamma_j(x(\lambda)) = \sum_{i=1}^{n} x_i^k h_{ij} - q_j$, $j = 1, \ldots, m$, and adjusts the ambient charges in the next step according to

$$\lambda_j^{k+1} = \max\left\{0, \lambda_j^k + \rho_k\left(\sum_{i=1}^{n} x_i^k h_{ij} - q_j\right)\right\}, \tag{6}$$

where $j = 1, \ldots, m$ and $k = 0, 1, \ldots$ and ρ_k is a step size multiplier ($\rho_k > 0$). Therefore, according to Eq. (6) the value $\lambda_j^{k+1} = 0$, if $\lambda_j^k + \rho_k(\sum_{i=1}^{n} x_i^k h_{ij} - q_j) < 0$.

The convergence of $\lambda^k = (\lambda_1^k, \ldots, \lambda_m^k)$, $k \to \infty$, to an equilibrium vector of (cost-effective) ambient charges λ^* is effected by the choice of ρ_k. One might wonder whether it is possible to determine adequate values for the step size multiplier ρ_k such that total cost $\sum_{i=1}^{n} f_i(x_i)$ is decreased by passing from x^k to x^{k+1} since the total cost is unknown to the agency. The sequence λ^k converges to λ^* under a rather broad range of ρ_k, for example, $\rho_k = c/k$ where c is an arbitrarily chosen positive constant, particularly, $\rho_k = 1/k$. As proven in [4], any sequence $\{\rho_k\}$ satisfying the conditions $\rho_k \geq 0$, $\sum_{k=0}^{\infty} \rho_k = \infty$, and $\sum_{k=0}^{\infty} \rho_k^2 < \infty$ leads to convergence. Of course, the choice of a particular sequence $\{\rho_k\}$ affects the rate of convergence and it is important to analyze concrete practical rules.

The charge adjustment procedure (5) and (6) can be interpreted as a kind of "market system." According to this scheme polluters each minimize their cost function $f_i(x_i) + u_i^k x_i$ and thus independently adjust emissions to the current emission taxes u_i^k. The agency learns what the current excess concentrations at receptors $\Gamma(x_i^k)$ are and reacts as a Walrasian auctioneer would. If he observes an "excess demand" for pollution at a certain receptor ($\Gamma_j > 0$) he will raise the price λ_j for users. In the other case the price will be lowered. Prices are a signal for users of the environmental resource to adjust their emissions accordingly.

4. RANDOM COSTS OF INDIVIDUAL SOURCES

An implicit assumption in Section 3 was that the cost function $f_i(x_i)$, $i = 1, \ldots, n$, is not affected by random factors. In this section we drop this assumption. For each source the costs of pollution control depend on a large number of factors. Some of them are of a rather general kind, like weather conditions and prices of inputs; others are more specific, for example, types of fuel and other raw materials used, type and age of existing pollution control equipment, its state of maintenance, quality of operating personnel, and knowledge of available new abatement technology. We shall show that in the face of these additional uncertainties the decentralized strategy of ambient charges generated by the adjustment procedure (5) and (6) results in lower expected total pollution control costs than a centralized policy of setting emission standards.

Suppose $f_i(x_i, \nu_i)$ is the cost function of the source i, where x_i is an emission level and $\nu = (\nu_{i1}, \ldots, \nu_{ir})$ is a random vector representing variables that affect the source costs. In this case the adjustment process (5) and (6) is defined similarly.

Let $\lambda^k = (\lambda_1^k, \ldots, \lambda_m^k)$ be the vector of ambient charges at step $k = 0, 1 \ldots$, and

$$u_i^k = \sum_{j=1}^{m} \lambda_j^k h_{ij}, \qquad i = 1, \ldots, n \tag{7}$$

be current values of resulting emission charges. Each source i adjusts the emission level $x_i = x_i^k$ by minimizing the total cost

$$f_i\left(x_i, \nu_i^k\right) + u_i^k x_i, \tag{8}$$

where ν_i^k is an independent observation of random vector ν_i at step k. Therefore, we assume that each source i is able to observe "local" conditions ν_i when it has to choose its level of emission. Ambient charges are chosen according to Eq. (6). Again, ambient charges converge to an equilibrium (cost-effective) charge with probability 1 when $\rho_k = c/k$ for an arbitrary positive constant c.

There is an important fact concerning the cost effectiveness of the emission standard strategy and the ambient charge policy for the random cost function $f_i(x_i, \nu_i)$. Since the agency cannot know the "local situation" ν_i, a decentralized strategy of ambient charges (and derived emission charges) results in lower expected total costs than a centralized policy of setting emission standards. Let us discuss this in more detail.

First we look at a policy of setting emission standards. In order to minimize control costs the agency has to form expectations on the emission control cost function $f_i(x_i, \nu_i)$. Given the agency expectation $Ef_i(x_i, \nu_i)$ the set of values

$f_i(x_i, \nu_i)$ that minimizes aggregate control costs under the emission standard strategy is found by solving the stochastic optimization problem: minimize

$$F(x) = \sum_{i=1}^{n} Ef_i(x_i, \nu_i) \tag{9}$$

subject to

$$\sum_{i=1}^{n} x_i h_{ij} \le q_j, \qquad j = 1, \ldots, m, \; i = 1, \ldots, n. \tag{10}$$

The result is the set of emission standards x_i^* minimizing the agency's expected cost.

On the other hand, the vector of ambient charges resulting from the procedure (6) maximizes the function (see [4] for details).

$$\begin{aligned}\delta(\lambda) &= \min_{x(\nu)\ge 0} \sum_{i=1}^{n} E\left[f_i(x_i(\nu), \nu_i) + \left(\sum_{j=1}^{m} \lambda_j h_{ij} \right) x_i(\nu) \right] - \sum_{j=1}^{m} \lambda_j q_j \\ &= \sum_{i=1}^{n} E \min_{x_i \ge 0} \left[f_i(x_i, \nu_i) + \left(\sum_{j=1}^{m} \lambda_j h_{ij} \right) x_i \right] - \sum_{i=1}^{m} \lambda_j q_j,\end{aligned}$$

where $x_i(\nu_i)$ denotes the emission level which is chosen on the basis of the observed random vector ν_i. Assume that the function f_i is convex with respect to x_i for any possible ν_i. To avoid technicalities we can also assume that each ν_i has a finite number of possible values. Then it is easy to see that the minimization of $\delta(\lambda)$ is a dual problem of finding an emission vector $x(\nu) = (x_1(\nu), \ldots, x_n(\nu))$ that minimizes the expected cost function

$$F(x(\cdot)) = \sum_{i=1}^{n} Ef_i(x_i(\nu_i), \nu_i) \tag{11}$$

subject to

$$\sum_{i=1}^{n} Ex_i(\nu_i) h_{ij} \le q_j, \qquad j = 1, \ldots, m, \qquad x_i(\nu) \ge 0, \qquad i = 1, \ldots, n. \tag{12}$$

Suppose that $x^*(\cdot)$ is an optimal solution of this problem. Since the vector of decision variables $x(\cdot)$ in Eqs. (11) and (12) depends on actual ν at the sources, the optimal value of the objective function in Eqs. (11) and (12) is smaller than the optimal value of the objective function in Eqs. (9) and (10). Hence

$$F(x^*) \ge F(x^*(\cdot)) = \max_{\lambda \ge 0} \delta(\lambda).$$

In other words, the expected cost of a policy of optimal emission standards is indeed above the expected cost of an optimal ambient charges strategy.

5. A NUMERICAL EXAMPLE

Acidification is one of the major problems in Europe and the Netherlands. Ammonia emissions are a major source of acid rain in the Netherlands. These emissions mainly result from livestock farming and fertilizer use and are generally transported over short distances (50% is deposited within 100 km from the source). This implies that the major sources of ammonia deposition in the Netherlands are in the Netherlands, Belgium, France, Western Germany, Ireland, Luxembourg, and the United Kingdom which contribute to four receptor areas in the Netherlands (grid size 150 $\times$ 150 km). The Netherlands' policy is to reduce acid deposition to 2400 equivalents of acid/hectare in the year 2000 (VROM [9]). After subtracting the expected contribution from sulfur and nitrogen oxides in the year 2000, targets for ammonia deposition can be formulated for each grid.

For the adaptive charge mechanism data are needed on transfer coefficients and costs. Transfer coefficients for ammonia are based on the European Program for Monitoring and Evaluation (Sandnes and Styve [6]). The transfer coefficients for the four Dutch receptors are based on the average meteorology for 1985, 1987, to 1990. The costs of controlling ammonia emissions are based on the RAINS model of IIASA (Alcamo *et al.* [1]). RAINS stands for Regional Acidification INformation and Simulation. RAINS distinguishes the following options for controlling ammonia emissions: low ammonia manure application, ammonia poor stable systems, covering manure storage, cleaning stable air, low nitrogen fodder, and industrial stripping. For each country the potential and costs of their techniques are calculated accounting for country- and technology-specific factors (Klaassen [5]). These options are then combined in national cost functions f_i which rank the options according to their marginal costs and volume of emissions removed.

To simulate the adaptive ambient charge mechanism, a computer program was written. The program simulates the behavior of the environment agency which maximizes, according to Eq. (6), the dual objective function of the pollution control problem on the basis of observed deposition level. Differences between actual and target depositions (excess deposition) lead to changes in ambient (or deposition) charges. These changes are translated in emission charges using the transfer coefficients. The simulation assumes that the agency has imperfect knowledge of costs and perfect knowledge of transfer coefficients. The sources have perfect (deterministic) knowledge of individual costs (as in Section 3.).

Two simulations were carried out:

1. the agency starts with initial deposition charges of zero in all four grids (scenario 1);

2. the agency starts with a deposition charge of 100,000 DM/kton NH_3 that is deposited in grids 3 and 4 and a zero charge in grids 1 and 2 (scenario 2).

The reason for scenario 2 is that the agency knows immediately that without any control the deposition targets at receptors 1 and 2 are already met.

Figures 1 and 2 show the values of both the total (annual) pollution control costs and the Lagrange function as a function of the number of iterations. Figure 1 shows that after 12 iterations the total cost of control plus emission charges (the Lagrange function) converges to around 2.9 billion DM/year (optimal value). Figure 2 clearly shows the impact of starting from an initial deposition charge of 100,000 DM/kton NH_3 deposited at each receptor. In this case only seven

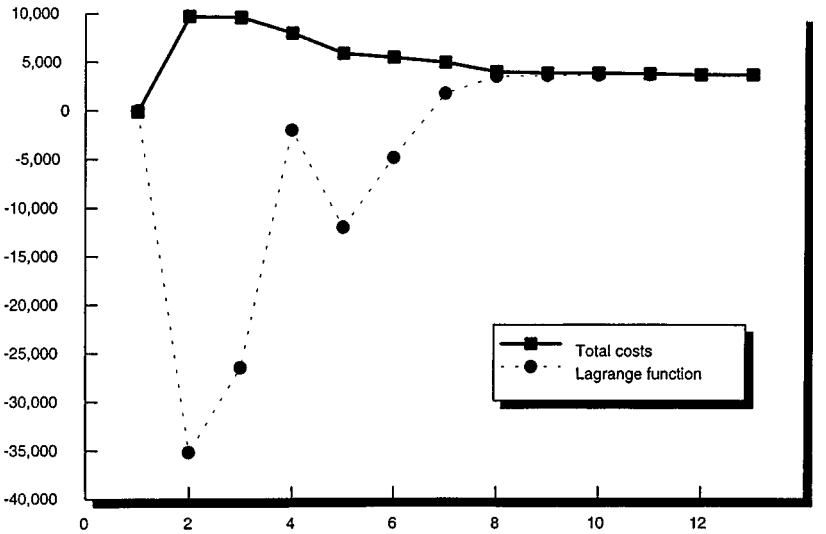

FIG. 1. Total costs and Lagrange function (10^6 DM/year) with zero initial charges (scenario 1).

iterations would be necessary to approach the cost-minimum solution. The number of iterations could be reduced further if the environmental agency would ask the individual sources how they would respond to a certain emission charge before setting the initial charges. If sources would overestimate their emission reductions in order to reduce the charge level, the adaptation process would take longer and, as Fig. 1 clearly indicates, costs would be higher than necessary during the period of adaptation.

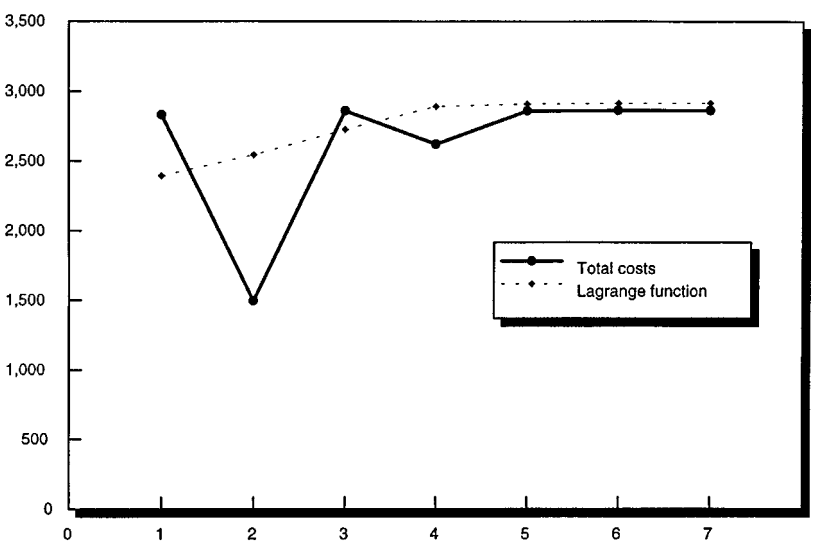

FIG. 2. Total costs and Lagrange function (10^6 DM/year) with positive initial charges (scenario 2).

Obviously, starting from a zero charge would initially (see step 2) lead to very high charges. This is especially so for Belgium and the Netherlands which have large impacts on the deposition at receptors located in the Netherlands. For Belgium the charges would reach 1596×1000 DM/ton NH_3 at step 2 and would then gradually decrease to their final level of 72×1000 DM/ton ammonia controlled. Such overshooting might cause problems without a learning stage. First, during the adaptation period, charges and hence pollution control costs would be higher than necessary. Second, if the fixed cost element of pollution control costs is high, high charges may induce inflexibility since investments already taken are sunk costs. Starting from a deposition charge level of 100,000 DM/kton NH_3 deposited at receptors 3 and 4 reduces the number of iterations to only seven. Moreover, the emission charges would not fluctuate greatly over time. After some (small) overshooting at step 1 and undershooting at step 2, the emission charges in all countries would gradually increase to the level where the deposition constraints are met at minimum costs.

In conclusion, a system of adaptive deposition charges can be formulated that converges to the cost-minimum solution even if the environmental agency has imperfect knowledge on the costs. If some information on possible costs is available to the agency prior to setting the initial charge, the adaptation can proceed faster and lead to less significant fluctuations in costs and emission charge levels than if the agency starts with initial deposition charges equal to zero. Such information could be collected in a learning stage.

At the learning stage the system starts from an arbitrarily chosen vector of ambient charges, which are translated into emission charges u_i^0 and processed to all sources $i = 1, \ldots, n$. Having received the value u_i^0 each source i calculates the emission level x_i^0 and processes it to the environmental agency which, in its turn, calculates the excess pollutions $\Gamma_j(x^0)$ for each receptor $j = 1, \ldots, m$ and produces new charges u_i^1, $i = 1, \ldots, n$, and so on. After calculating optimal values of the ambient charges λ_j^* and derived emission charges u_i^*, these values (as well as the optimal emission values x_i^*) become available to the public. At the implementation stage the agency has the right to adjust further ambient charges if the standards are violated. These adjustments are based on monitoring actual excess pollution at the receptors. The agency may also have the right to verify actual emissions and penalize sources whose actual emission levels exceed those calculated at the learning stage. An important feature of the described artificial market system is its stability to random disturbances in the pollution control costs. In Ermoliev *et al.* [4] it has been shown that this procedure is also stable to uncertainties in the transfer coefficients h_{ij}.

6. CONCLUDING REMARKS

The aim of this paper was to extend the pricing approach of environmental pollution originally proposed by Baumol and Oates to the case of many receptors. We have shown that, contrary to established opinion, equilibrium vectors of ambient and emission charges that are both cost-effective and environmentally effective can be found by using a Walrasian type *tâtonnement* process. Just like the Walrasian auctioneer, who uses information on excess demand at given prices, the environmental agency can use observations of excess pollution levels to adjust

ambient charge levels in a stepwise way, without information on pollution control cost. In the absence of real market signals the artificial market system relies on the ability of a central agency to monitor excess pollution at receptor points, produce market signals (charges), and verify emission levels reported (by sources). Such a system could find the equilibrium (optimal) set of price signals rather quickly by using a network connecting local computers of sources with the central computer of the agency. The central computer stores the information on the transfer matrix, actual concentrations, and ambient standards. The local computers store the information on corresponding cost functions. By using procedure (6), as described in the Introduction, the agency is able to find the appropriate individual emission charges. The procedure consists of a learning stage and an implementation stage. The first stage ends with specifying for each emission source the charges and registering of corresponding planned levels of emissions. At the second stage (implementation) the agency verifies actual levels of emissions and monitors depositions at receptors. At this stage the agency has the right to penalize discrepancies between expected and actual emission levels and adjust ambient and emission charges correspondingly. The agency may repeat the adjustment procedure, consisting of stages 1 and 2, each time when actual emissions are expected to change essentially due to technological shifts, aging of control equipment, and so forth.

Our conclusion is that it makes no real difference for the feasibility of emission charges whether environmental targets are formulated in terms of emission goals or as a set of ambient concentration standards, even if the central agency has no information on control costs of sources. Under both types of environmental policy objectives an iterative procedure of fixing emission charges can be applied as an instrument that is both cost and environmentally effective. It is superior to an emission standard policy, since an agency that has no information on control cost could set standards that are environmentally effective, but cost effectiveness would only be achieved by chance.

APPENDIX: NOMENCLATURE

$x = (x_1, \ldots, x_n)$	n-dimensional emission vector with components $x_1, \ldots, x_n$ at sources $i = 1, \ldots, n$
$x \in X$	the vector x belongs to the set X
$f_i(x_i)$	the pollution reduction cost at source $i = 1, \ldots, n$
$f_i(x_i, \nu_i)$	the random pollution reduction cost for emission level x_i and random variable, ν_i, $i = 1, \ldots, n$
q_j	the level of ambient standard at receptor $j = 1, \ldots, m$
λ_j	the shadow price at receptor $j = 1, \ldots, m$
h_{ij}	deterministic transfer coefficients of emission unit from source i to receptor j
$\|x\| = \sqrt{x_1^2 + \cdots + x_n^2}$	the Euclidean norm of the vector x
$\sum_{i=1}^n x_i = x_1 + \cdots + x_n$	
$(a, b) = \sum_{j=1}^n a_i b_i$	the scalar product of vectors $a = (a_1, \ldots, a_n)$, $b = (b_1, \ldots, b_n)$
$\max\{a, b\}$	the maximum among numbers a, b
$\min\{a, b\}$	the minimum among a, b

$\max_{x \in X} f(x)$	the maximum value of $f(x)$ when x varies in a given set X
$\arg\max_{x \in X} f(x)$	a vector, where the maximum value is attained
$E[\zeta]$	the mathematical expectation of ζ
$E[\zeta \mid A]$	the conditional mathematical expectation of ζ given events A; for any two sets $A, BA \supseteq B(A \subseteq B)$ means that the set $B(A)$ is included into set $A(B)$; for any sequence of vectors $a^1, a^2, \ldots, a^k, \ldots$ the limit point is $a = \lim_{k \to \infty} a^k$ or $a^k \to a$, $k \to \infty$.

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