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Marketable Permits for the Prevention of Environmental Deterioration[1]

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This paper develops a modified system of marketable emission permits that promises both savings in abatement costs to sources and improved environmental quality relative to an initial command-and-control (CAC) outcome. Using a model of TSP emissions for the Baltimore Air Quality Control Region (AQCR), a series of simulation exercises indicates that such a permit system could generate large cost savings while inducing significant reductions in TSP concentrations as compared to the existing CAC regime in Baltimore.

1. INTRODUCTION

A typical approach to environmental management calls for the regulatory authority to determine a set of minimum standards for environmental quality. Under the Clean Air Act Amendments of 1970, for example, the Environmental Protection Agency (EPA) in the United States was directed to establish standards for maximum concentrations of certain "criteria" air pollutants. The attainment of these standards then becomes the objective of some kind of system to regulate the emissions of polluting entities. In the economics literature, there is now a substantial list of studies that explore the design of systems that can achieve such a set of predetermined standards at the least cost (e.g., [11, 3, 12, 5]).

A difficulty with this approach is that such standards, under one interpretation at least, imply a troublesome fiction about the nature of environmental damages: they suggest a kind of "threshold" below which damages are negligible and above which the damages suddenly become unacceptably large [4, pp. 30–43].[2] This "threshold

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[2]Alternatively, from an economic perspective, the standard could be interpreted as the "optimal" level of environmental quality for which the marginal social damages from another unit of emissions equal marginal abatement cost. However, this is not the interpretation that is typically evident at the policy level. In the Clean Air Act, for example, the U.S. Congress has explicitly rejected such an economic tradeoff in the determination of standards; legislators have instead instructed the EPA to set standards for air quality at a level "to protect the public health" (see [4, p. 31]).

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myth" when translated into policy prescriptions yields some disturbing consequences. Since it implies that the damages from environmental degradation are effectively zero until the threshold or standard is reached, it follows that there is little cost associated with introducing polluting activities into previously clean areas so long as pollution levels do not exceed the standard. Or, put more formally, it suggests that our policy problem can be formulated as one in which we attempt to minimize the aggregate cost of pollution abatement subject to the constraint of the attainment of the predetermined levels of air or water quality [11, 5]. When a particular pollution constraint is not binding, the implied cost of additional environmental degradation is zero.

However, such a formulation is unacceptable both in principle and at the policy level. There is little evidence of the existence of such thresholds for most air and water pollutants: some pollution typically yields some damages and somewhat more pollution results in somewhat more damages. At the policy level, the implicit recognition of a continuous damage function is embodied in a variety of measures to maintain or even to improve air and water quality in cases where it is already better than the current standards. As one example, the U.S. Congress has introduced a set of provisions in the 1977 Amendments to the Clean Air Act for the "prevention of significant deterioration" (PSD) in various types of areas where air quality already exceeds the standards. Moreover, under existing command-and-control (CAC) systems, state regulators have imposed relatively strict abatement requirements on sources whose emissions would not otherwise imperil the achievement of existing air or water quality standards.

The purpose of this paper is to describe a system of marketable or transferable discharge permits (TDP) that can effectively both attain the predetermined standards for environmental quality and, at the same time, prevent any deterioration in areas which are already cleaner than the standards. The system is, in fact, disarmingly simple. It calls for redefining the environmental quality standards: the new standard at each point in the region is equal to the predetermined standard established by the environmental authority or the initial level of environmental quality, whichever is the higher. Free trading of permits is then allowed provided that no violation of these *new* air or water quality standards takes place.

Drawing on previous results in the literature [11, 5], we will show that the competitive equilibrium of this new permit system exists and that it satisfies the first-order conditions for the least-cost solution for the attainment of the resulting level of environmental quality. Moreover, we shall find that compared to the initial equilibrium under a command-and-control system, the new competitive equilibrium represents a Pareto improvement for all parties involved, including both environmentalists and polluters. Under this system, not only will sources typically have reduced costs, but environmental quality will, in general, improve (at a minimum, it can never get worse). Even areas that are already clean will tend to become cleaner. In short, the proposed system has the attraction at the policy level of promising benefits both in terms of a cleaner environment and reduced abatement costs.

We also present some empirical estimates of the potential cost savings and air quality improvements based upon a model of particulate emissions (TSP) for the Baltimore Air Quality Control Region (AQCR). We find that potential gains from implementing this system are quite large: air quality improves while aggregate abatement costs are significantly reduced.

We acknowledge at the outset an obvious deficiency of the proposed system: the outcome will not, in general, be Pareto optimal, since the resulting level of environmental quality will not be such that marginal damages equal marginal abatement costs at each location. But this deficiency, of course, characterizes virtually any approach in the absence of explicit damage functions. The system thus promises a Pareto improvement over the initial state (at least in attainment areas), but not a fully Pareto-optimal outcome.

2. A MORE FORMAL STATEMENT OF THE PROBLEM

Let us consider a specific region consisting either of an air shed or system of waterways in which there are m sources of pollution, each of which is fixed in location. Environmental (air or water) quality is defined in terms of pollutant concentrations at each of n "receptor points" in the region; this implies that we can describe environmental quality by a vector $Q = (q_1, q_2, \ldots, q_n)$ whose elements indicate the concentration of the pollutant at each of the receptors. The dispersion of waste emissions from the m sources is described by an $m \times n$ matrix of unit diffusion (or transfer) coefficients:

$$D = \begin{bmatrix} & \vdots & \\ \cdots & d_{ij} & \cdots \\ & \vdots & \end{bmatrix}$$

where d_{ij} indicates the increase in pollutant concentration at receptor j from one unit of emissions of the pollutant by source i.

The environmental authority determines a set of standards that specifies the maximum allowable concentrations at each receptor point: $Q^* = (q_1^*, q_2^*, \ldots, q_n^*)$. For expositional convenience, we shall refer to the Q^* as the "national standards." We note that although the q^* are typically the same for all i, they need not be so. For example, under the Clean Air Act Amendments, EPA has defined a *uniform* minimum air quality standard for certain "criteria" pollutants, but states are free to impose more stringent standards in any region they desire. Under the system we present in this paper, the state environmental authority would do precisely that: redefine more stringent standards for some parts of the region thereby preventing any deterioration of environmental quality once a permit system is implemented. After the standards are redefined, no new emissions or transfers of emissions among sources would be allowed if they result in a violation of the *new* standards at any receptor point.

The policy problem is, therefore, that of attaining the predetermined, "national" set of standards at a minimum of aggregate abatement costs subject to the constraint that air (or water) quality may not deteriorate in areas where the pollutant concentration is already below that allowed by the standard. Suppose that $Q^0 = (q_1^0, q_2^0, \ldots, q_n^0)$ describes the levels of pollutant concentration under the current CAC approach. Then, if e_i is the level of emissions from source i and if $C_i(e_i)$ is its abatement cost function, we are searching for a vector of emissions, $E = (e_1, \ldots, e_m)$, that represents the solution of the following problem:

$$\text{Minimize } \sum_i C_i(e_i)$$

$$\text{s.t.} \quad ED \leq \min(Q^*, Q^0), \quad E \geq 0.$$

The novelty of this formulation of the problem is the inclusion of the Q^0 term in the first constraint. Several papers have explored the solution to the problem where $ED \leq Q^*$ (see, for example, [11, 5]). But, as we have already indicated, the disturbing property of previously proposed TDP systems is that they treat increases in pollutant concentrations as costless to society so long as there are no violations of the national standard. Many empirical studies indicate enormous potential savings in aggregate abatement costs for systems of economic incentives that can approach the least-cost solution as compared to existing command-and-control systems. It is not clear, however, what portion of these cost savings are achieved by allowing increased emissions (and their associated increased pollutant concentrations) at receptor points where the standard is not a binding constraint. In two studies that have addressed this matter, Atkinson and Tietenberg [2] and Atkinson [1], have found that a substantial fraction of the savings in abatement costs resulted from projected increases in emissions in those parts of the region where air quality was better than the national standard. It may thus be that much of the cost savings promised by these systems of transferable permits cannot be realized if the control system no longer regards any existing "shortfall" in pollutant concentrations as a form of "excess capacity" to be exploited at zero cost in the search for abatement cost savings to sources.

From a strictly economic perspective, the introduction of the constraint that air quality not deteriorate beyond current levels is obviously not the appropriate way to address the problem: the decision of whether or not to allow increased emissions should be based on a comparison of marginal damages with marginal abatement costs. However, not only are such calculations extremely difficult, they may not (as in the case of the Clean Air Act in the United States) even be legally admissible. In the absence of these calculations, we shall describe an admittedly second-best approach using economic incentives that promises gains (potentially quite large) in terms both of reduced abatement costs and improved environmental quality.

The system of transferable discharge permits to be considered here is a modification of what elsewhere has been called the "pollution-offset" system [5]. Under this general approach, permits are defined in terms of emissions (e.g., the permit allows the discharge of X pounds of the pollutant, say, per week). However, sources are not allowed to trade permits on a one-to-one basis. More specifically, transfers of TDPs under the pollution-offset scheme are subject to the restriction that the transfer does not result in a violation of the national environmental quality standard at any receptor point. If a proposed transfer encounters a binding pollution constraint at some receptor point, this implies that emissions will be traded at a rate determined by the ratio of the sources' "transfer coefficients" (the d_{ij}'s).[3] For purposes of the analysis here, we will modify the pollution-offset system in two respects:

(1) Free trading of permits will be allowed provided no violation in the *redefined* standards [$\min(Q^*, Q^0)$] occurs as a result of the trade.

[3] This ratio indicates the rate at which emissions from one source can be substituted for emissions from the other source with no change in pollutant concentrations at the applicable receptor point.

(2) For attainment areas (areas where the national standards have been met), there will be an initial distribution of TDPs such that each source will receive the number of permits needed to validate its current level of emissions.

We shall describe the *modified* system simply as the "offset system" (or modified offset system) in the remainder of the paper; the term "pollution-offset" system will refer to the system summarized above and presented in detail in [5].

3. PROPERTIES OF THE OFFSET SYSTEM

In this section, we explore the static properties of the offset system in terms of a convenient diagrammatic framework [10]. First, the analysis develops the least-cost properties of the system: it indicates that the "trading equilibrium" (the outcome at which there are no further gains from exchanges of permits) coincides with the least-cost allocation of permits for the resulting level of environmental quality. Second, we find that for the case where the initial CAC equilibrium has attained the national standards, the equilibrium under the offset system typically results in both an improvement in environmental quality and a reduction in costs to all sources. For the nonattainment case, in contrast, some sources *may* experience an increase in control costs.

For a more rigorous treatment of these matters, we refer the reader to the Appendix where, following Montgomery's seminal paper [11], we appeal to the Montgomery proof to demonstrate the existence of a competitive equilibrium for the offset system and to show that this equilibrium satisfies the conditions for the least-cost solution to the control problem. In addition, we explore further the relationship of the offset system to Montgomery's system of emissions licenses; the discussion serves to clarify and, on one point, to correct Montgomery's treatment.

3.1. The Attainment Case

Figure 1 depicts the case of two sources and two receptor points where the horizontal and vertical axes measure, respectively, the levels of emissions of sources 1 and 2 (i.e., e_1 and e_2). The curves C_1 and C_2 are iso-cost curves for total pollution abatement costs, where a higher curve indicates lower aggregate abatement costs

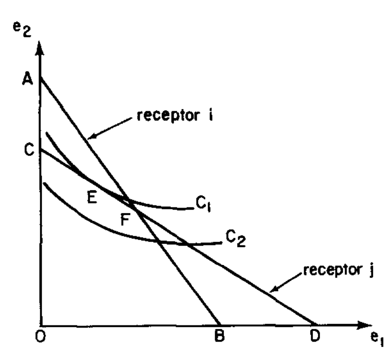

FIG. 1. Pollution-offset system.

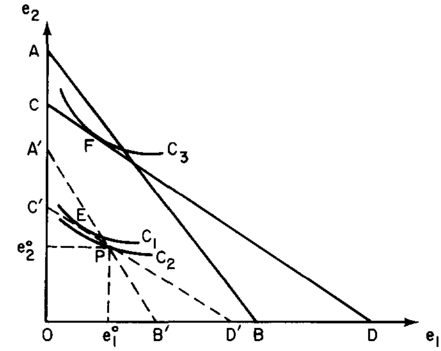

FIG. 2. Modified-offset system: Case I.

($C_1 < C_2$). The line AB represents the pollution constraint associated with receptor i. Points on AB depict combinations of e_1 and e_2 for which $q_i = q^*$; the slope of the line equals the ratio of the transfer coefficients and hence indicates the rate at which emissions from source 2 can substitute for emissions from source 1 with no change in pollutant concentrations at receptor i. Likewise, line CD embodies the pollution constraint for receptor j. The combinations of emissions from the two sources that satisfy the national standards at both receptor points are thus the set of points $OCFB$. We find that the least-cost solution occurs at E, at which point the ratio of the sources' marginal abatement costs equals the ratio of their transfer coefficients. Note further that under the pollution-offset system where sources are free to discharge wastes (if the pollution standard is not a binding constraint) or to trade TDPs (if it does bind), E will also represent the "trading equilibrium" [5]. At any other point in the feasible set, there will be potential gains either from reducing abatement efforts and/or from trading emissions entitlements. The trading equilibrium thus coincides with the least-cost solution under the pollution-offset system.

Suppose, however, that under the prevailing CAC system, the environmental authority has held pollutant concentrations below the national standard at both receptor points, i and j. Point P in Fig. 2 indicates such an outcome. If we now introduce the modified-offset system, sources 1 and 2 will receive transferable discharge permits in the amounts of e_1^0 and e_2^0, respectively. Since the redefined environmental quality standard is now set equal to the prevailing environmental quality, the new constraints on emissions are indicated by the lines $A'B'$ and $C'D'$.[4] The least-cost solution, given these constraints, is E. Moreover, since E can be achieved at lower total abatement cost than P, there exists the potential for mutually profitable trading: source 2 will have an incentive to purchase permits from source 1 in an amount sufficient to move the combination of emissions from P to E. At E, all potential gains-from-trade will have been exhausted.

Further examination of E reveals that, not only have cost savings been achieved by the move from P, but environmental quality has improved. Pollutant concentrations at receptor i are now lower than they were under the CAC equilibrium, while

[4] The lines representing the new constraints have the same slopes as those indicating the standard (equal to the ratio of the transfer coefficients). Their position, however, refers to the initial level of environmental quality which is in excess of the national standard.

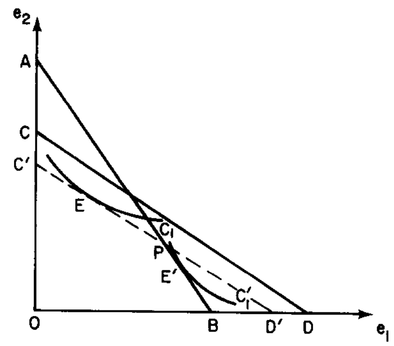

FIG. 3. Modified-offset system: Case II.

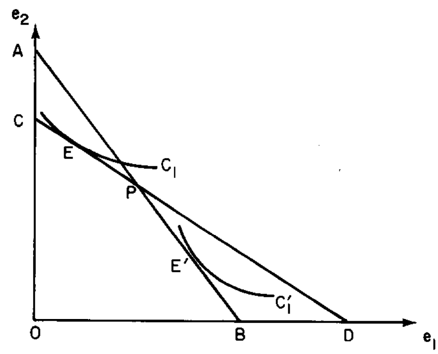

FIG. 4. Modified-offset system: Case III.

concentrations at receptor j are unchanged. Such cost reductions *and* improvements in environmental quality will obviously take place in all cases except that where the tangency with the highest iso-cost curve occurs at P; for this special case, the outcomes under the CAC and offset systems will coincide.[5] We note in passing that under the pollution-offset system, the trading equilibrium in Fig. 2 would be at F; this would allow further savings in abatement costs (relative to E), but at the price of a deterioration in environmental quality up to the national standard.

Figures 3 and 4 depict the other two possible cases for an attainment area and indicate the same general properties of the trading equilibrium as in Fig. 2. In Fig. 3, the initial state, P, under the CAC regime is such that the national standard is itself a binding constraint at one of the receptors. For this case, trading subject to the redefined environmental quality standard implies the constraint $C'PB$, where the segment $C'P$ reflects the redefined portion of the constraint. In Fig. 4, we have the special case in which the initial state occurs precisely at the national standard for

[5]This result depends on the assumption that the initial state under the CAC regime represents a least-cost solution for each source *given* its assigned level of emissions. If, however, the environmental authority had specified a particular abatement technology that was not the least-cost one, the sources typically would not be operating on the iso-cost curves. In this case, some cost savings could be realized under the offset system without any changes in emission levels by simply moving to the least-cost technology.

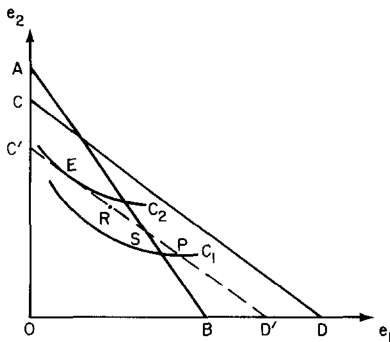

FIG. 5. Nonattainment area: Case I.

both receptor points; in this instance, the standards would require no redefinition, since $q^0 = q^*$ at both receptors. We note that, for both cases (as in Fig. 2), the trading equilibria at E or E' (corresponding respectively to C_1 or C_1') represent both a reduction in abatement costs and an improvement in air or water quality at one of the receptor points.[6] For Fig. 4, incidentally, the outcome under our offset system coincides with that under the pollution-offset scheme.

We thus find that for all three configurations of the initial state under the CAC regime in an attainment area, the introduction of an offset system will typically result in reduced abatement costs and a cleaner environment. For the special case in which the tangency of the iso-cost curve occurs at the initial state, there will be no change: the CAC initial state and the outcome under the offset system will coincide. But in no instances under the offset system can there be a deterioration in environmental quality at any receptor point or an increase in costs for any polluter.

3.2. *The Problem of Nonattainment Areas*

We found in Section 3.1 that if under the CAC regime the environmental authority has achieved the predetermined national standards for air or water quality, then the introduction of the offset system promises a Pareto improvement that will typically improve environmental quality and reduce abatement costs. However, if the initial state is one of nonattainment where the national standards have not yet been everywhere achieved, this dual result can no longer be guaranteed. The offset system still promises to promote attainment of the standards at least cost, but some sources *may* experience increased control costs. Typically, the environmental authority's problem in the nonattainment case is that some parts of the region are in violation of the standard (say, the central business district for air quality), while the environmental quality in the remaining parts of the region is better than the predetermined standard (e.g., the suburbs).

The nature of the problem is apparent in Figs. 5 and 6. Suppose that the initial state under the CAC system is again represented by point P. However, in this

[6] In the multidimensional case involving more than one, say n, receptor points, there can be improved air or water quality at as many as $(n - 1)$ receptors. If, for example, the binding constraint at the trading equilibrium involves a single receptor, then environmental quality may have improved at all the other receptor points in the region.

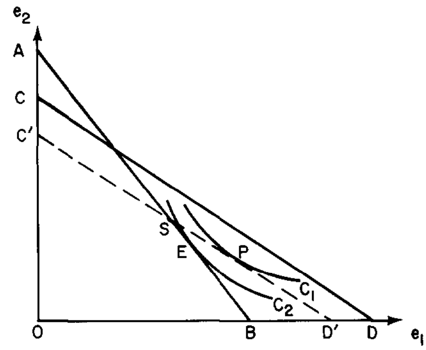

FIG. 6. Nonattainment area: Case II.

instance P is outside the acceptable set of outcomes, for the pollutant concentration at receptor i exceeds the standard indicated by line AB. The pollutant concentration at receptor j, in contrast, is below the maximum permitted level (i.e., P lies inside line CD). The introduction of the offset system implies a new set of environmental standards: to preserve current environmental quality, the standard at receptor j will be tightened as indicated by the line $C'D'$. Line AB will still represent the relevant standard for receptor i, since the pollutant concentration at i is higher than the national standard.

The introduction of the offset system (or any other attempt to reach the standards) will require some contraction in emissions by at least one source to meet the standards. The problem for the environmental authority is to choose some allocation of permits among the sources which will sustain attainment. Unlike the attainment case, these allocations obviously cannot equal current levels of discharges. Instead the authority must select some combination of permits on (or inside) the frontier $C'SB$ to meet the newly defined standards.

Suppose this point is represented by R. There would then exist an incentive for source two to purchase permits from source one until the least-cost solution is reached, at which point all the gains-from-trade would be exhausted (at point E in Fig. 5). Note, moreover, that for this case, total abatement costs actually decline relative to the initial nonattainment point P. For such a case, a Pareto improvement for all sources can be achieved with an appropriate initial allocation of permits. In Fig. 6, in contrast, the trading equilibrium at E entails an increase in total abatement costs relative to P. For cases such as this, some sources (at least one) will necessarily experience higher control costs.

4. SOME EMPIRICAL FINDINGS

To explore the potential differences among a typical CAC regime, a pollution-offset system, and our modified-offset system, we have made use of a computer-based model constructed for an earlier analysis of particulate emissions (TSP) in the Baltimore Air Quality Control Region [9]. The model incorporates control-cost estimates, associated collection efficiencies, and dispersion characteristics for over 400 sources. The control-cost estimates take the form of integer step functions and were estimated using the costing algorithm explained in a series of articles by [13]. In

TABLE I

Annualized Costs to Achieve Air Quality of 98 $\mu g/m^3$ under Three Systems[a]

	Control systems		
	CAC	Modified offset	Pollution offset
Annualized cost	112.9	46.3	27.1

[a]All costs in millions of 1980 dollars.

addition, a careful listing of all CAC requirements was assembled which allowed a simulation of the CAC system presently employed in Baltimore.

The simulation of the existing CAC system produced annualized cost estimates and a vector of air quality readings indicating pollutant concentrations at each receptor throughout the area. Although Baltimore is a nonattainment area for the primary air quality standard for TSP established by the EPA, most of the region had air quality far better than the standard. In general, the central business district (CBD) is the troublesome area (or "hot spot") because of the large number of sources whose emissions contribute to the pollutant concentrations there.

For purposes of comparison with the CAC simulation, the solutions to the following problems (representing the outcomes of the pollution-offset system and the modified-offset system respectively) were estimated

$$\text{Minimize} \sum_i C_i(e_i) \tag{1}$$

$$\text{s.t.} \quad ED \leq Q^*, \quad E \geq 0,$$

$$\text{Minimize} \sum_i C_i(e_i) \tag{2}$$

$$\text{s.t.} \quad ED \leq \min[Q^*, Q^0], \quad E \geq 0,$$

where Q^0 is the air quality vector resulting from the CAC simulation and Q^* is the existing air quality in the central business district (CBD). Note that for this first set of simulation exercises, we assume (contrary to fact) that the existing CAC system has achieved the national standard; we thus equate Q^* with the existing TSP concentration in the CBD of 98 $\mu g/m^3$.

Table I presents the cost estimates associated with each of the three control systems, while Fig. 7 depicts the air quality vector for each case. As Table I indicates, either permit system promises quite large potential cost savings relative to the existing CAC regime: in excess of 50%.[7] From these figures, we get some sense of how much of the cost savings relative to the CAC case come from a more efficient allocation of abatement quotas and how much from the increase in pollution allowed at above-standard sites under the pollution-offset system. For this case, we see that the modified-offset system (which allows no deterioration at any site relative to the CAC outcome) achieves roughly two-thirds of the cost savings under the pollution-offset system. We thus conclude that for this simulation, a more efficient pattern of

[7]For a detailed analysis of the sources of these cost differences, see McGartland [8].

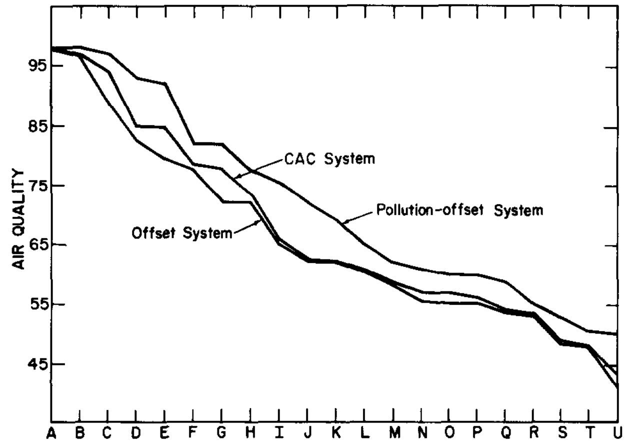

FIG. 7. Air quality under three control systems (receptors ranked in order of pollutant concentrations).

abatement activity accounts for about three-fourths of the cost savings with the remaining quarter attributable to reduced controls and the consequent increase in pollutant concentrations at receptors where the air is cleaner than the national standard under the CAC regime.

As Fig. 7 indicates, however, the further increment in cost savings under the pollution-offset system comes at a discernible "price" in terms of deterioration of air quality at various sites in the Baltimore region. The figure shows the projected TSP concentrations under each of the three systems for 20 representative receptors that were designated as "strategically located" by the Maryland Air Management Administration. Interestingly, the ranking of the receptors is not very sensitive to the choice of regime: the receptor with the worst air quality (A) is the same for all systems, and in all but four instances the ranking of the other receptors is unchanged across the three systems. Examination of Fig. 7 indicates that TSP concentrations at all the receptors (except A for which $q^0 = q^*$) increase significantly under the pollution-offset system from their CAC levels, in some instances by as much as 10 $\mu g/m^3$. In contrast, concentrations under the modified-offset system are less than CAC levels with the largest improvements in air quality occurring at receptors with relatively high levels of pollution. At those same receptors, the differences in air quality between the pollution-offset and modified-offset systems are the most pronounced reaching 10 to 12 $\mu g/m^3$. These results would thus seem to provide some support for the concern over the deterioration in environmental quality that can occur with the adoption of the pollution-offset system.

We previously pointed out that two other studies, Atkinson and Tietenberg [2] and Atkinson [1], have found that a substantial portion of the abatement cost savings from achieving a least-cost solution resulted from projected increases in aggregate emissions. The total emissions associated with each of our three control systems in the first simulation is reported in Table II. As indicated, emissions under the pollution-offset system do increase dramatically relative to the existing CAC system. However, under the modified-offset system, total emissions are not much higher than the emissions associated with the CAC approach—roughly 4%. The reader may be puzzled as to how total emissions can increase yet air quality remain the same or improve at every receptor. Closer inspection of the source-by-source final allocation

TABLE II

Emissions under Three Systems Achieving a Minimum Air Quality of 98 $\mu g/m^3$

	Control system		
	CAC	Modified offset	Pollution offset
Emissions (tons/year)	23,358	24,325	49,392

TABLE III

Annualized Costs Necessary to Achieve the Primary Standard under the Pollution Offset and Modified Offset Systems[a]

	Modified offset	Pollution offset
Annualized cost	76.6	61.4

[a]All figures in millions of 1980 dollars.

of emissions can provide an answer to the question. Some sources' emissions travel relatively far. In fact, a large percentage of these emissions traveling long distances settle on the Chesapeake Bay or Atlantic Ocean. When these emissions increase, the effects on air quality can easily be offset by strategically reducing the emissions of others at a less than one-to-one ratio. Both improved air quality and reduced control costs are thus achieved under the modified-offset system by essentially altering the *pattern* of emissions in such a way as to reduce pollutant concentrations in the region.

In the second set of simulations, we took as the standard for TSP concentrations the EPA-determined primary standard of 85 $\mu g/m^3$.[8] With $Q^* = 85$, there are three receptors in violation of the standard so that the initial CAC regime implies that the Baltimore AQCR is a nonattainment area. Table III and Fig. 8 present the results. For this second case, we find that the differences in costs and in air quality between the pollution-offset and our modified-offset systems are not very large. Closer examination of the resulting distribution of emissions tells us why. As the air quality standard becomes more stringent, sources whose emissions have a relatively large impact on the "problem area" (the CBD) quickly control as much as possible. When the stricter standard is still not reached, sources farther away must adopt tighter controls to help reduce the pollutant concentration at the CBD. When the standard was 98 $\mu g/m^3$, these more distant sources did not have to adopt such strict (and expensive) abatement techniques. As these suburban sources adopt more stringent controls, the surrounding air quality improves even though it already exceeds the standard. In other words, as sources farther away from the problem area adopt stricter controls in an attempt to reduce pollution within the CBD, other areas also experience improved air quality. Therefore, as the predetermined standard is

[8]EPA standards for TSP are generally stated in geometric means. With a standard deviation of roughly 1.5, a primary standard of 75$\mu g/m^3$ expressed as a geometric mean, translates roughly to a standard of 85 $\mu g/m^3$ as an arithmetic mean. See Larsen [6].

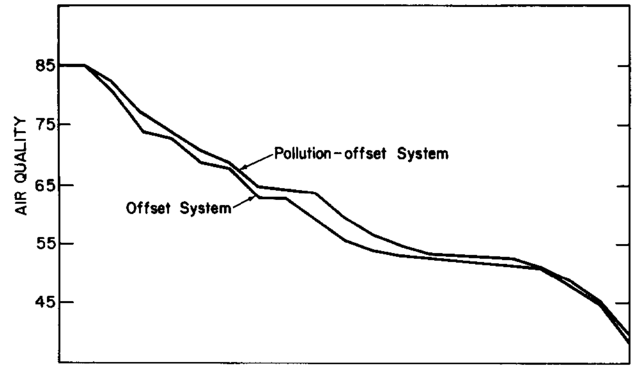

FIG. 8. Air quality under two permit systems.

tightened, the difference between the two systems goes to zero, since they face similar binding constraints. In the limit, if the systems were asked to achieve the lowest pollutant concentration possible, both systems would generate the same outcome: every source would control as much as technically feasible.

Table III indicates that the projected annualized costs are $76.6 million for the modified-offset system versus $61.4 million for the pollution-offset regime. The difference is attributable to two receptors with relatively low pollutant concentrations for which q^0 is a binding constraint under the modified system. We thus find that where the standard requires high levels of control throughout the region, the differences between our two versions of the offset system are much less in terms both of control costs and air quality. In contrast, the potential savings under either system relative to the CAC regime are large: a comparison of Table I and III, for example, indicates that either permit system can achieve the EPA primary standard for TSP concentrations at an aggregate cost far less than that under the *existing* CAC system (which, as yet, has been unsuccessful in achieving the standard.)

5. ON THE DYNAMICS OF PERMIT TRADING

The analysis to this juncture has been wholly in terms of statics; we have compared the equilibrium outcomes under a variety of regulatory systems with respect to certain definitions of allowable pollutant concentrations. We have not, however, explored dynamic issues such as the sequence of trades that leads to the equilibrium. The dynamic properties of most markets are not well understood, but there are some features of the permit market that are of particular note.

We introduce the discussion in terms of a constraint on trades, a "nondegradation condition," that has received some attention in the literature [5]. Recall that under the modified-offset system, trades among sources are subject to the constraint of no violation of the redefined standard (equal to the predetermined, national standard or the initial level of environmental quality, whichever implies less pollution). The nondegradation constraint is a far more stringent condition that applies to *each trade*: it requires that for each trade, environmental quality must not deteriorate at *any* receptor point. (In contrast, the modified-offset system allows increased pollutant concentrations at a receptor so long as the redefined standard is not violated.)

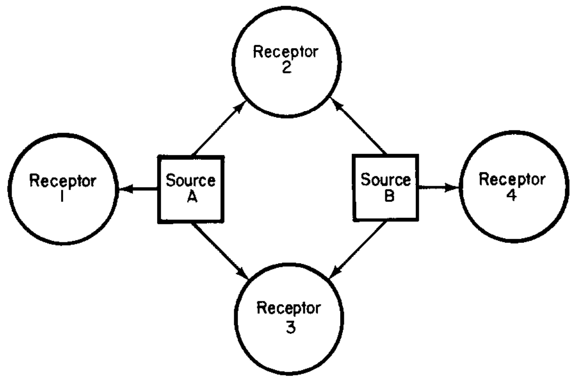

FIG. 9. Trading under a nondegradation constraint.

We wish to emphasize that the nondegradation condition is an extremely restrictive constraint on trades—so restrictive, in fact, that it is likely to paralyze the functioning of the permit market. It is easy to see that a nondegradation condition on individual trades of permits effectively limits trading between two sources solely to cases in which the buyer's emissions affect receptors which are a subset of the receptors affected by the emissions of the seller. Consider, for example, the operation of the modified-offset system in the context of the spatial patterns depicted in Fig. 9. Assume that the air quality at receptor one is better than the redefined standard [i.e., pollutant concentrations are less than $\min(q^0, q^*)$], while these concentrations at the other receptors are equal to the standard. If source A affects receptors 1, 2, and 3 and B affects 2, 3, and 4, A could buy emissions permits from B. Source A would simply buy enough permits to "offset" the effects of his emissions on pollutant concentrations at receptors 2 and 3. Since the pollutant concentration at receptor one is already below the redefined standard, A does not have to acquire any offsets there.

Under a nondegradation condition, however, A and B could not trade. Since air quality deteriorates at receptor one as a result of the trade, the nondegradation constraint would be violated. The nondegradation condition effectively redefines the standard after *every trade*, so that the standard at each receptor is always binding. Thus, if any "excess capacity" is generated by previous trades, it is instantly taken away. As a result, two-party trades are impossible unless it happens that the emissions of the buyer affect only a subset of the receptors that are affected by the seller's discharges.

The moral of this discussion is that it is generally desirable to avoid a nondegradation constraint on trades of permits, for such a constraint is likely to prevent many cost-saving trades. The reader may, however, have noticed that we were careful in the above example to assume that the pollutant concentration at receptor one was below the redefined standard. But that need not be true in which case the nondegradation constraint would effectively apply to the trade in our example. Source A would, in this instance, have to purchase permits from a third source whose emissions affect receptor one, in addition to his purchases from source B. More generally, it is clear that under the modified-offset system, the nondegradation constraint effectively applies to the initial trade. This follows from the introduction of the redefined standard that makes $\min(q^0, q^*)$ a binding constraint at all receptors.

This is admittedly troubling, for it restricts the range of allowable trades at the outset. It is our conjecture, however, that this need not, in general, constitute a serious obstacle to the initiation of permit trading. At the original CAC equilibrium there will typically exist (as in our case of particulate emissions in Baltimore) large potential gains-from-trade, involving a substantial number of sources. The number of permutations among these sources for mutually profitable trades will tend to be relatively large so that it should not be difficult to find buyers whose emissions impinge on only a subset of the receptors affected by the seller (or, alternatively, perhaps two sellers whose discharges encompass all the receptors of relevance to the buyer).[9]

As a few trades are made, excess capacity will quickly be generated so that only a few receptors will remain as binding constraints. For instance, in our Baltimore simulation, we find that at the final equilibria for the standards of 98 and 85 $\mu g/m^3$, there are, respectively, only four and three binding receptors. Were there to be any further trades, some increment to pollutant concentrations would be allowable at all the other (nonbinding) receptors. In contrast, the presence of a nondegradation constraint on every purchase and sale of permits will tend to become a more formidable obstacle to trading as the system moves closer to the least-cost outcome. As the trading process progresses, fewer and fewer potentially profitable exchanges of permits will remain so that it will become increasingly difficult to find combinations of interested buyers and sellers such that a transaction will not result in higher pollutant concentrations at *any* receptor.

Thus, we surmise that the modified-offset system is not likely to encounter the kind of paralysis that will tend to characterize a permit market with a nondegradation constraint in place. More generally, it is difficult to reach specific results on the dynamic properties of the offset system. McGartland [8] offers some discussion of the trading process under the pollution-offset and modified-offset systems. It is clear, for example, that there are cases where the least-cost outcome can involve a fairly complicated transfer of permits among several parties. Whether the multilateral trades implied by such conditions are likely to be realized in the marketplace is not fully clear. As McGartland shows, there can be opportunities for free-rider behavior that will impede the attainment of the desired outcome. It may be that a sequence of bilateral trades can sometimes approach the least-cost solution fairly closely. These issues are hard to analyze in the abstract; they require an explicitly dynamic analysis, preferably using some actual configurations of sources and air sheds and incorporating some reasonable conditions concerning the (for practical purposes) irreversible nature of many types of investment in abatement technology. Important research remains to be done to clarify the dynamic properties of the various forms of permit systems. We must, therefore, conclude on an admittedly

[9]A hypothetical case may help to suggest how trading could get underway. With the existence of substantial gains-from-trade, two sources relatively close to one another could initiate a trade by asking the environmental authority to "simulate" (with an air dispersion model) the effects of possible trades between the two parties. The simulations would identify any areas that would experience violations of the redefined standard along with nearby small area or point sources whose effects on air quality are relatively localized. An area source (e.g., a dirt or gravel road) could be incorporated as a second seller in the trade making a small but important contribution by reducing pollutant concentrations in the area that the buyer affects but the primary seller does not.

cautious note: the modified-offset system has a number of attractive static properties that invite further attention to its potential for improving environmental quality while simultaneously reducing control costs to sources.

6. CONCLUDING REMARKS

The offset system of transferable discharge permits described in this paper has the property that it can attain the predetermined standards for environmental quality and, at the same time, ensure that there is no deterioration in any areas that are cleaner than the standard. And the equilibrium outcome under this system satisfies the first-order conditions for the minimization of aggregate abatement costs for the resulting level of environmental quality (whatever it may be). Moreover, for regions in which the initial state under a command-and-control system already satisfies the standards, the offset equilibrium will typically imply both reduced costs to polluters and further cleanup of the environment. If, instead, the initial state is one of nonattainment of the standards, the reduction in costs to all sources cannot be assured.

Our empirical results suggest that the potential gains-from-trade under a system of pricing incentives are quite large. Although systems that allow increased emissions in those parts of the region where the air or water is cleaner than the standard promise the largest cost savings, substantial savings can still be had while at the same time preventing any deterioration in environmental quality. This feature makes the modified-offset system attractive on both economic and political grounds.

At the same time, we are reluctant to make a completely unqualified case for the modified-offset over the pollution-offset system. Even aside from certain troublesome dynamic issues, the cost in the full economic sense of an absolute ban on any environmental deterioration at any location may be undesirably high. In an area, for example, which has no pollution at present, the adoption of the modified-offset system could amount to a virtual ban on any sort of economic development. Such a ban may be desirable under certain circumstances, but not under others. It may make sense, for instance, to draw some distinctions like those made in the 1977 Amendments of the Clean Air Act between certain areas where no deterioration in air quality is to be allowed and others where some limited increment to pollutant concentrations (still, in total, less than the EPA primary standard) is permissible. In short, one might wish to "modify" our modified-offset system a bit further to allow, in certain circumstances, for the redefinition of the standard to be a little less stringent than the existing level of environmental quality.

APPENDIX

In 1972, Montgomery published a seminal paper [11] on the properties of two alternative forms of marketable permit systems. The Montgomery results have been widely cited in the subsequent literature, but as Krupnick *et al.* [5] show, they have been the subject of some basic misinterpretation. Our purposes in this Appendix are twofold: first, we present a further discussion of Montgomery's emission-license system that serves both to clarify Montgomery's treatment and to correct it on one important point, and second, we then use the Montgomery framework to demonstrate that for our modified-offset system, a competitive equilibrium exists and that this equilibrium satisfies the conditions for the least-cost solution to our control problem.

1. On Montgomery's System of Emission Licenses

Montgomery's emission-license system begins with a distribution of emission permits to each of M sources such that the environmental quality standard is not violated at any receptor point when all permits are fully utilized. Sources are then free to trade permits, but unlike the pollution-offset system where the permits are defined in terms of emissions (properly "weighted" by transfer coefficients), Montgomery's permits confer the right to pollute certain groups of receptors. This distinction is illustrated in Fig. 10.

Consider a transaction where source A buys rights from source B. Further assume that A's emissions influence pollutant concentrations at receptors 1 and 2, while B's emissions affect receptors 1, 2, and 3. Under Montgomery's system, when the transaction is completed, A acquires the right to pollute at receptors 1, 2, *and* 3, even though A's emissions do not affect the pollutant concentration at receptor 3. Montgomery accomplishes this by permanently indexing permits by the dispersion characteristics of the initial holder of permits (in this case B); A thus acquires the right to pollute *all* the areas that B would have polluted if it had continued to hold the permits.

It is easy to show that this property of Montgomery's permits makes the existence of a least-cost equilibrium unlikely under reasonable assumptions. Because his emission-license system does not allow polluters to "break-up" permits so that A would not have to buy the implicit right to pollute at receptor 3, two conditions must be satisfied for the competitive equilibrium to satisfy the least-cost conditions. Montgomery correctly states the first condition: the initial allocation of permits must be such that if all permits are utilized, the pollutant concentrations at every receptor must just equal the standard:

$$E^0 D = Q^*,$$

where E^0 is the vector of emissions implied by the initial allocation of permits. This is, incidentally, a very stringent condition that will not, in general, hold, since for any semipositive D and Q^*, there will not, in general, be a nonnegative solution to E^0.

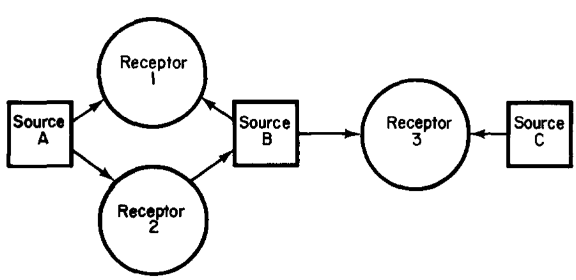

FIG. 10. Trading of emissions licenses.

There is a second constraint that must be satisfied which Montgomery does not treat satisfactorily. Because permits cannot be "broken-up," the final distribution of permits must also satisfy a basic condition. Some notation will help explain the problem. Let X_{ik} be the number of emission licenses originally distributed to source k but now held by source i (in the final equilibrium). With this alternative notation, we can formulate Montgomery's initial condition as

$$\sum_{k=1}^{M} \sum_{i=1}^{M} X_{ik} d_{kj} = q_j^* \qquad j = 1, \ldots, N.$$

In other words, the total amount of pollution at each receptor implied by the initial distribution of permits must be equal to the predetermined standard. (Note that the subscript on the dispersion coefficient denotes the initial holder of the permit.) But, not only must there exist an initial distribution of permits which allows for full utilization of the assimilative capacity of the atmosphere, but also a *final* distribution which allows each polluter to emit the optimal amount of emissions:

$$e_i^* d_{ij} \le \sum_{k=1}^{M} X_{ik} d_{kj} \qquad j = 1, \ldots, N \qquad i = 1, \ldots, M,$$

where e_i^* is the amount of emissions implied by the joint cost-minimization problem.

Although Montgomery attempts to prove that this latter set of conditions is automatically satisfied, there is no guarantee that it will be. Montgomery's Proposition 1 states that X_{ik} will exist such that $\Sigma_k d_{kj} X_{ik} \ge d_{ij} e_i^*$. But Montgomery's proof of this proposition is faulty, since it is easy to show a counterexample where Proposition 1 does not hold. Consider the case of three polluters, A, B, and C, and the two receptors, 1 and 2. Let

$$d_{A1} = 20 \qquad d_{A2} = 0$$
$$d_{B1} = 20 \qquad d_{B2} = 20$$
$$d_{C1} = 0 \qquad d_{C2} = 20$$

with

$$q_1^* = 400 \qquad q_2^* = 400$$
$$1_A^0 = 10$$
$$1_B^0 = 10$$
$$1_C^0 = 10$$

where 1_i^0 is i's initial allocation of permits. Under this allocation, the constraint on the initial distribution of permits is satisfied:

$$d_{A1} 1_A^0 + d_{B1} 1_B^0 + d_{C1} 1_C^0 = q_1^*$$

by substitution

$$20 \cdot 10 + 20 \cdot 10 + 0 \cdot 10 = 400$$

and

$$d_{A2}l_A^0 + d_{B2}l_B^0 + d_{C2}l_C^0 = q_2^*$$

by substitution

$$0 \cdot 10 + 20 \cdot 10 + 20 \cdot 10 = 400.$$

Further assume that the solution to the cost-minimization problem is

$$e_A^{**} = 20 \qquad e_B^{**} = 0 \qquad e_C^{**} = 20.$$

Trading would thus require that A and C buy permits from B. However, in Montgomery's system there is no way to distribute B's *fixed* group of pollution rights. If A buys B's permits to increase its pollution at receptor 1, then A also acquires the right to pollute at receptor 2, even though it is of no use to A.

The nature of the latter set of constraints is straightforward. Again, since these rights cannot be "broken-up," each polluter must collect a portfolio of permits, each of which carries the right to pollute at a number of receptors. For example, one emission permit obtained *from* source k is, in reality, a right to pollute at n receptors equal to $d_{k1}, d_{k2}, \ldots d_{kn}$, respectively. Each source must accumulate a portfolio of these permits from different sources to minimize costs, and at the same time satisfy the above constraints.

Thus, for the existence of an equilibrium which satisfies the first-order conditions of the two joint cost-minimization problems, a semipositive matrix, X, of dimension $M \times M$ must exist which satisfies $N(M + 1)$ constraints: Montgomery's N constraints on the initial distribution of permits plus $M \cdot N$ additional constraints on the *final* distribution when the market is in equilibrium. Presumably Montgomery assumes that these latter conditions will hold, but they are not necessarily satisfied. Note that it is quite possible for Montgomery's initial condition to have a solution, but for the latter constraints to be violated.

Permits under the modified offset and pollution-offset systems effectively allow the breaking-up of rights to pollute at different receptors and, as a consequence, need not satisfy the above conditions on the final distribution of permits. Referring back to the proposed transaction where polluter A buys permits from polluter B, recall that A's emissions do not affect the pollutant concentration at receptor 2 while B's do. Under the offset systems, B is free to include polluter C (who only affects receptor 2) in the bargaining process. Then when B reduces his emissions, A and C can simultaneously increase theirs. The greater degree of flexibility is obvious. In addition, as we demonstrate in the next section, the competitive equilibrium under the modified-offset system exists and satisfies the first-order conditions for the solution to the cost-minimization problem. The constraint to be satisfied under the modified-offset system is similar to Montgomery's; permits must be distributed so that:

$$E^0D = Q^*.$$

Our modified offset system is able to guarantee that this constraint is satisfied, since Q^* is redefined such that the standard at each receptor exactly equals the concentrations allowed under the initial allocation of permits.

2. The Competitive Properties of the Offset System

In this section, we use Montgomery's [11] formal proof to demonstrate that the competitive equilibrium of the offset system exists and that it satisfies the first-order conditions of the joint cost-minimization problem.

Recall that our problem is

$$\text{Minimize} \sum_i C_i(e_i) \tag{A.1}$$

$$\text{s.t.} \qquad ED \le \min\left[Q^*, Q^0\right], \quad E \ge 0.$$

Montgomery [11] has constructed a simple proof that the solution to this problem exists, and we will not repeat it here. We will, however, characterize the polluter's problem. The source wishes to minimize

$$C_i(e_i) + P_i\left(1_i^* - 1_i^0\right) \tag{A.2}$$

$$\text{s.t.} \qquad e_i \le 1_i^*$$

where 1_i^* is the quantity of permits held in equilibrium and 1_i^0 is the quantity initially distributed to source i.

In a truly competitive market, the value of an emission license, P_i, can be represented as the sum of the values of the right to increase the pollutant concentration at each receptor j. For example, when polluter B in Fig. 10 in the Appendix wishes to sell his emission permits, polluter A will pay the value of increasing pollutant concentrations at receptors 1 and 2, and polluter C will pay the competitive price of increasing the pollutant concentration at receptor 3. Therefore, we may write

$$P_i = \sum_j d_{ij} p_j \tag{A.3}$$

where p_j is the value of the right to increase the pollutant concentrations at receptor j by one unit and d_{ij} is the coefficient that translates a unit of emissions from source i into the incremental pollutant concentration at receptor j. Rewriting (A.2) restates the polluter's minimization problem as

$$\text{Minimize } C_i(e_i) + \left[\sum_j d_{ij} p_j\left(1_i^* - 1_i^0\right)\right] \tag{A.4}$$

$$\text{s.t.} \qquad e_i \le 1_i^*.$$

Noting that the term $e_i d_{ij}$ is equal to increased pollutant concentration at receptor j and the fact that an emission right can be "broken-up," we can represent 1_i^* and 1_i^0 as l_{ij}^*/d_{ij} and l_{ij}^0/d_{ij}, $j = 1, 2, \ldots, n$, respectively. Here, l_{ij} refers to the right to increase the pollutant concentration at receptor j by one unit. Therefore, l_{ij} divided by d_{ij} denotes the implied emission right for source i holding 1_{ij}, $j = 1, 2, \ldots, n$.

Rewriting (A.4) restates the polluter's problem as

$$\text{Minimize } C_i(e_i) + \sum_j d_{ij} p_j \left[\left(l_{ij}^* / d_{ij} - l_{ij}^0 / d_{ij} \right) \right] \tag{A.5}$$

$$\text{s.t.} \quad e_i \le l_{ij}^* / d_{ij} \qquad j = 1, \ldots, n.$$

The d_{ij}'s in the objective function cancel and (A.5) becomes

$$\text{Minimize } C_i(e_i) + \sum_j p_j \left[l_{ij}^* - l_{ij}^0 \right]$$

$$\text{s.t.} \quad d_{ij} e_i \le l_{ij}^* \qquad j = 1, \ldots, n.$$

This polluter's problem is identical to the one associated with Montgomery's ambient permit system. Further, the joint cost-minimization problem of the regulator is also the same under each system provided that permits can be initially distributed so that the air quality constraint is binding at every receptor point. Under Montgomery's ambient permit system, we can easily distribute permits so that, if all permits are fully utilized, the pollutant concentrations at every receptor point are just equal to the standard. But as Montgomery and this Appendix show, when emission rights are distributed this is a much more difficult task.

But one of the basic properties of our modified-offset system is that the standards are redefined so that every receptor constitutes a binding constraint if all permits are utilized under the initial allocation. Therefore, our regulator's problem and polluter's problem are identical to those associated with Montgomery's ambient permit system.[10] For this system, he was able to show formally that the equilibrium exists and satisfies the first-order conditions of the joint cost-minimization problem. Since our system is mathematically identical, we can appeal to his proofs to show that the same results hold for the modified-offset system.

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[10] One reviewer noted that the formal equivalence of the regulator's and polluter's problems under the ambient permit and modified offset systems should lead to the conclusion that the implementation of the latter will be fully as difficult as implementing an ambient permit system. This is only partially true. As we show in this Appendix and as in discussed in Krupnick *et al.* [5], within a purely competitive framework with perfect information and zero transactions costs, there are no real barriers to the implementation of either system. However, when we introduce positive transactions and search costs, some very important distinctions arise. As McGartland [7] shows, the offset system may allow buyers and sellers to concentrate on a very few receptor markets, while the ambient permit system requires each polluter to trade many permits simultaneously.

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