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# AIR QUALITY REGULATION IN SPATIAL EQUILIBRIUM MODELS*

by

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ABSTRACT

The purpose of this paper is to present methods for including a wide variety of air pollution regulations within the class of economic equilibrium models where allocation is based on constrained optimization. The first part of the paper discusses current air pollution regulation in the United States and possible future regulation. This is followed by the presentation of a prototype spatial equilibrium model within which a number of regulatory mechanisms are explicitly represented. These include efficient and zoned charges, statically and dynamically efficient permit systems, technological control and hybrid permit/charge systems.

## I. INTRODUCTION

Efficiency is the key issue in environmental regulation today. There are two sides to the regulatory efficiency issue. Efficiency requires that a set of regulations achieve a desired level of environmental protection, while imposing acceptable economic costs on society. Theoretically as well as practically an efficient regulation will be a Pareto superior balancing of these two considerations.

Focusing on the economy's response to pollution regulations, there are a number of policy motivations for better understanding this response. It is important for national energy policy to understand the ultimate constraining effect of particular emission control strategies on domestic energy supply. Another issue is the inflationary impacts of excessively costly regulation. In general, if there are less costly but equally effective mechanisms for

*Comments from Clifford Russell have been appreciated.

achieving environmental quality goals, those approaches should be pursued. From the point of view of the environmentalist, if society tolerates the cost of a suboptimal regulation, then an efficient regulation can achieve even greater environmental quality at the same cost.

The general approach to the determination of the total economy-wide costs of particular environmental regulations has been engineering dominated, focusing on control costs to a specific industry for achieving various levels of emission control.* Some types of regulations (e.g. Prevention of Significant Deterioration regulations) are difficult to analyze in this manner. Even for technologically oriented regulations, an engineering examination can only provide an upper bound on costs of a regulation, missing entirely the market's response to particular regulations. Producers can respond by process substitution, non-uniform control levels among industries, and location change. Consumers can adjust their consumption bundle, reducing demand for products from particularly polluting industries. The dynamic response of the economy to public control of pollution is important and difficult to anticipate.

Having hopefully motivated the reader as to the importance of efficiency in environmental regulation, this paper focuses on a more modest facet of this issue. The problem addressed here is of representing particular types of environmental regulation within applied economic policy models of the equilibrium type. It is common, particularly in energy policy analysis, to represent the economy in space with allocation based on an equilibrium computed by constrained optimization.** The purpose of this paper is to examine the inclusion of existing and potential regulations of pollutant emissions within spatial equilibrium models. For clarity the focus will be on air pollution, particularly from non-reactive pollutants, although many of the concepts are completely transferable to other pollutants and media.

*This discussion is focused on residuals generation, particularly air pollution, rather than the broader issue of environmental protection.

**Many of the US Department of Energy's (US DOE) policy analysis models are of this type (e.g. MEFS, IEES, NCM). Some computable equilibrium models are solved by other methods such as pseudo-cobweb (LEAP) fixed point (Hudson-Jorgenson) and econometric (energy demand) methods (refer to US DOE, 1979). Non-equilibrium methods include system dynamics (FOSSIL2), and engineering based simulation models (Teknekron's Utility Simulation Model). Other non-energy equilibrium models include the Resources for the Future (RFF) Delaware Estuary Model (Spofford, et al. 1976).

## II. REGULATION

### A. Scope of the Air Pollution Problem

There are many different anthropogenic gaseous emissions to the atmosphere, some more significant than others. In the United States, volumetrically, sulfur, nitrogen oxides and particulate matter constitute the major emissions from stationary sources, resulting to a large extent from the combustion of fuels. Mobile sources contribute more to hydrocarbon, carbon monoxide and nitrogen oxides pollution (US EPA, 1974). Focusing on the principal pollutants from industrial sources, there are several classes of deleterious effects, all more or less associated with concentrations of pollutants in the ambient air. At one extreme are the short range pollution problems near a source. Particular meteorological conditions can lead to high local concentration levels that persist for relatively short periods of time. Damage can occur to property, plant and animal life, and human health and welfare. Most ambient air pollution regulation has been oriented to this type of problem. At the other end of the spectrum are the pollutants whose effects occur at long-distances from sources due principally to the slow removal rate from the atmosphere for these pollutants. Carbon dioxide is an example of a pollutant of this type. Somewhat intermediate are the pollution problems associated with continental transport of sulfates and nitrates leading to degradation of visibility (haze) and acid precipitation.

### B. Current US Regulations

The history of air pollution control in the United States is long and complicated (refer to Kneese and Schultze, 1975, for one perspective). Suffice it to say that the 1967 Clean Air Act, amended in 1970, legislated the first significant controls on stationary sources of air pollution. A major component of that legislation was a directive to the newly formed Environmental Protection Agency to set national ambient air quality standards (NAAQS) for various pollutants. These ambient standards were to be the official safe levels of pollutants in the ambient air. The mechanisms for achieving these standards were less well defined. States were to design plans (state implementation plans-SIP's) for federal approval for the control of sources to meet these standards. Although SIP's vary from state-to-state, typical control measures include control technology standards and required uniform percent emission reductions for existing sources. New sources of pollution are to meet emission standards based on technical feasibility regardless of the level of pollution in the vicinity of the new source. New sources are to use "the best adequately demonstrated control technology." Since fuel combustion is often the cause of air emissions, some regulations specify the cleanliness of the fuel used, particularly in the case of coal.

Expanding on the ambient standards mandated in the 1970 legislation, the Clean Air Act Amendments of 1977 specified additional regulations to prevent the significant deterioration (PSD) of air quality in currently clean areas. Specifying procedures for categorizing all areas of the country into one of three air quality classes, the 1977 legislation set forth permissible incremental ambient concentrations for several pollutants. An interesting feature of the 1977 amendments is that new sources must show via meteorological models that they will not violate appropriate ambient pollution limits. Thus for the first time source location and strength are to be governed by ambient concentration limits rather than semi-uniform emission limits. The law further declared "as a national goal the prevention of any future, and the remedying of any existing impairment of visibility in mandatory Class I areas [principally national parks and wilderness areas] which impairment results from manmade air pollution" (US Congress, 1977). Although the EPA appears to be interpreting this as applying (at least initially) only to visibility impairment from visible smoke plumes, sources can contribute to haze formation at substantial distances. Visibility degradation due to haze is directly related to the ambient concentration of fine particulates, particularly species of sulfur and nitrogen (Nochumson et al. 1979).

Thus existing pollution control regulation can be divided into two categories: emission limitations and concentration degradation limitations. Emission limitations are generally in terms of a required control technology for a particular industrial process such as requiring $SO_2$ scrubbers for coal generating stations and as such are conceptually straightforward. In economic terms, such control is merely a legislative restriction on the production possibility set.

Ambient concentration standards are less obviously ambient-type regulations. One can consider the NAAQS primary and secondary standards to be long-term ambient regulations even though the mechanisms for achieving these standards are almost entirely emission based. As ambient concentrations in an area rise to violate NAAQS, the SIP emission limits may be tightened or the EPA's offset policy may come into play under which emissions rights become tradeable. The offset policy can encompass intertemporal allocations through banking whereby a source may reduce emissions at one point in time and hold for later sale the corresponding emission right not being exercised. Depending on the details of implementation of the offset policy, the NAAQS can be viewed as essentially an ambient regulation that when binding efficiently* meets a concentration limit where all sources are considered to contribute in the same manner to the ambient concentration (no meteorological variation).**

Prevention of significant deterioration legislation (PSD) is intended to apply to areas that are not yet in violation of the NAAQS. PSD is implemented by requiring all new sources to show via meteorological modeling that their anticipated emissions will not violate allowed concentration increments. The fact that the source specific relationship between emissions and ambient concentrations enters directly into the regulatory process corrects an inefficiency found in the offset process. PSD as currently implemented however falls short of offsets in terms of dynamic efficiency since the concentration increment is used up in a first come, first served manner with no mechanism for trading in emissions rights should the increment be exhausted.

C. Potential Regulations

There are a number of difficulties with current US regulations for the control of air pollution, having to do with economic efficiency, administrative costs, non-regulated pollution effects and incentive compatibility. A number of alternate regulatory approaches have been proposed to deal with these problems. In fact, the US National Commission on Air Quality is currently investigating alternate control strategies to the Clean Air Act and will report its findings to the US Congress in 1981. Since the regulatory means for controlling air pollution may change, we explore here some of the potential regulations that have been proposed.

*Since the offset policy applies only to nonattainment areas, inefficiencies will occur in time frames in which a region finds itself in attainment prior to becoming a nonattainment areas.

**Tietenberg (1979) and others make the distinction between emissions cost-effectiveness (ECE) and ambient cost effectiveness (ACE). The offsets policy can be a hybrid of the two in the sense that ambient concentrations will govern emission limits but reductions in emissions will not be according to their contribution to the ambient.

A major non-regulated air pollution problem has to do with transport of pollutants considerable distances from their source. Aside from $CO_2$ which is a global problem, the major problems of this type have to do with long-range transport of sulfur compounds and secondarily nitrogen compounds. $SO_2$ decays into sulfates which are removed from the atmosphere relatively slowly which results in their being transport over long distances. A similar problem occurs with nitrates generated from nitrogen oxides. These fine particulates contribute to a reduction in general visibility, an effect whose control is mandated by the Clean Air Act of 1977*. An additional problem occurs when these sulfates and nitrates are washed out of the atmosphere leading to acidic precipitation. It is considered that acid rain is the cause of measured increases in acidity in lakes in Scandanavia and eastern North America with consequent damages, particularly to fisheries. Control of long-range transport is difficult because of the less well known relationship between specific sources and resulting ambient concentrations of sulfates and nitrates which then effect precipitation acidity and visibility.

Another problem with current regulation has to do with cost-effectiveness. Although some of the more innovative recent regulations in the US such as offsets and the bubble concept go a long way towards economic efficiency, regulation is still dominated by technological controls which are not in general set to achieve a given emission level at least cost. It has been shown (e.g. Atkinson and Lewis, 1976) that there are considerable inefficiencies involved in the current approach. Some sources are over-controlled while some may be undercontrolled. A number of alternate regulatory mechanisms have been proposed to correct these cost oriented inefficiencies.

A third difficulty has to do with small sources which are difficult to regulate effectively. In many proposed regulatory schemes, including the current offset policy, administrative costs may not warrant the regulation of small sources, considering their emissions. On the other hand, excluding such sources from market-oriented regulation may lead to difficulty in implementing such regulations. (This applies particularly to marketable ambient permits).

A final problem deals with incentive compatibility. One historic problem that has been encountered in pollution control has been the difficulty in

*The EPA seems to be deemphasizing (at least initially) the control of regional visibility.

bringing sources into compliance with regulation. Some sources have found it easier to spend years in court or Congress fighting a regulation than to obey the regulation. Similarly, in many cases there is no incentive to maintain control equipment or to innovate in pollution control. These difficulties can be blamed on regulation that is poorly designed from an incentives point of view.

In the following few pages we discuss some of the regulatory mechanisms that have been proposed to deal with these difficulties. Since it is not the purpose of this paper to design regulations, we focus on presenting a fairly comprehensive review of proposed mechanisms, deemphasizing a critique of individual mechanisms.

1. Emission Fees. The concept of Pigouvian taxes to control production of a public bad dates back of course to Pigou. Kneese (1962) however is attributed with the modern notion of controlling pollution by the application of a unit fee or tax on emissions. Under such a system, sources will control emissions to the point where marginal control costs equal the fee. If the fee is set to equal marginal social damage, efficient regulation of pollution results. The problems and promises of emission fees have been the subject of debates for nearly two decades (e.g. Rose-Ackerman, 1973). In brief, there seem to be several applied problems with a fee approach. First and perhaps foremost, sources have argued that they would rather not pay once for controls and once for the fee. Further, it is not clear what the proper fee should be, possibly necessitating a politically difficult adjustment process in determining the proper fee. If a fee is used to control ambient concentrations, then the proper fee must vary in space raising both equity and administrative problems. There are also problems with monitoring emissions and possibly legal difficulties with a non-uniform fee.

These problems aside, there have been three principal types of fees that have been proposed to control ambient concentrations: uniform, zoned and source specific fees. Source specific fees can be thought of as optimal since the fee is set to equal the marginal contribution to the ambient from a unit of pollution from the particular source (Tietenberg, 1974). Since the source/receptor relationship is poorly understood in many cases, it may be administratively desirable to apply a uniform fee over a particular geographic zone, partitioning space into several zones (Tietenberg, 1978). The extreme case of this is the uniform fee over all space (a single zone) which is emission-cost-effective but inefficient from an ambient point of view.

To address the problem that an emission tax results in a net transfer of resources from polluters to the government, some have proposed rebating the charge to polluters in such a way as to preserve the incentive aspects of the charge. One proposal, in the context of electricity generation, has been to rebate all fees collected on the basis of power generated. Another possibility may be to design an incentive compatible rebate mechanism in the spirit of Groves and Ledyard's (1977) non-linear pricing scheme.

2. Marketable Permits. The concept of transferable rights to pollute dates back to Crocker (1966) and Dales (1968). Under such a system society vests a limited right to pollute which can be divided and traded among sources. One should distinguish between a right to emit regardless of effects, an undifferentiated discharge permit (UDP), and a right to degrade the ambient pollutant concentration which can be translated into a right to emit certain location dependent amounts of pollution, an ambient differentiated discharge permit (ADP).*

An undifferentiated discharge permit system would involve an initial distribution of permits with sources permitted to buy and sell permits at will with the only restriction that emissions from a source could not exceed permits held by the source. Such a system would clearly equilibrate the marginal costs of control among sources in a region. The offset policy in nonattainment areas is effectively a UDP system.

Since the general goal of pollution control is to avoid exceeding certain ambient concentrations, the UDP system above would be suboptimal under this criteria. To remedy this it has been proposed that the discharge permit be in terms of the contribution to the ambient due to emissions with the relationship between emissions and the ambient defined by a set of official transfer coefficients. While such an approach will inevitably be more complicated than the UDP approach, ambient concentration maxima will be better controlled.

As with emission fees, there can be a highly spatially differentiated permit market with different transfer coefficients for different locations. This

*The terminology is due to Tietenberg (1979).

arrangement might be difficult to administer but would represent an efficient allocation of rights. More approximate but perhaps more implementable is a zoned system where a UDP permit system is considered to operate within a zone with interzone trades occuring according to a ADP system (Russell, 1980).

Some of the potential problems with a marketable permit system involve monopoly aspects of a permit market involving a small number of traders, difficulties in defining ambient transfer coefficients, effects of small sources not involved in the market, market design and the problem of time varying meteorology.

3. Hybrid Systems. Roberts and Spence (1976) have proposed a marketable permit system with fees for emissions above those permitted and subsidies for unused permits. The basic idea behind the procedure is to allow an escape valve if the control cost associated with the permitted emissions has been incorrectly estimated. If costs are lower than expected, the subsidy may encourage greater control. If control costs have been overestimated, the fee can be imposed on those emissions above permitted levels.

In a similar vein, Baumol and Oates (1975) have proposed a non-marketable emissions limitation with fees associated with emissions over that limit. Such a mechanism will equate marginal cost to the fee but involve a smaller transfer of resources from the polluter to the government.

4. Interpollutant Trades. Another form of controlled trading that can be applied involves transferring emissions rights from one pollutant to another. If the marginal social damage function is known (which never is the case), then the marginal rate of substitution of pollutants will be the ratio of their marginal damages. Possibly a more realistic situation is one in which the effects of two pollutants are very similar (the ratio of their marginal damages is unity), such as nitrates and sulfates in acid rain. In such cases, interpollutant trades may be very appropriate.

5. Intermittent Controls. Although prohibited by the Clean Air Act, intermittent controls are usually necessary to achieve efficiency, particularly if pollutant transport is at all time varying. Intermittent control measures include reduced output of goods and bads during particular periods of time, utilization of variable control technology and use of varing quality fuel in the case of fuel combustion. As it becomes more costly to control deleterious effects which depend on meteorological conditions, intermittent controls may become more of an option.

6. Other Technological Options. Although the emphasis here has been on decentralized mechanisms for effecting pollution control, the discussion is not complete without mentioning some alternate technological control options that have been considered. These include additional fuel quality restrictions, tall vs short smoke stack tradeoffs (for dispersion purposes), least emissions dispatching (encourage clean processes, discourage dirty ones) and requiring best retrofit control technology.

## III. REGULATION IN EQUILIBRIUM MODELS

The purpose of this section is to present the representation of several regulatory instruments within equilibrium models. The approach will be to define a prototype economic equilibrium model and then examine the inclusion of the regulatory mechanisms discussed above within the prototype.

### A. Prototype Equilibrium Model

To simplify the problem while retaining the essence of real-world air pollution dynamics, we assume space is partitioned into a grid; points within a grid element are identical for the purposes of this analysis. Sources locate at any one or more of these grid elements. Principally to simplify this presentation, we further assume the existence of one good and one bad and one consumption point. Further assume that sources produce one good and one bad (pollution) jointly according to a single well-behaved cost function. Goods are transported at constant unit cost (eg, per ton-mile) to the single consumption point. Bads are similarly but costlessly transported to the same consumption point, although pollution transport varies through space and time. A real world interpretation of such a model could be electricity production where activity can occur anywhere in space and involves the transport at constant unit cost of a homogeneous good to a consumption point (or points). A more complicated economy would involve a straight-forward extension of this model.

Given these assumptions, we set up a computable equilibrium model based on the maximization of consumer plus producer surplus. As shown by Takayama and Judge (1971), such a maximization results in a competitive equilibrium provided certain conditions are met.* The equivalence between social

*Necessary conditions include integrability of demand functions and negligible cross price and income effects.

optimality (narrowly defined) and a competitive equilibrium is a notion familiar to economists. A problem arises however in simulating an economically inefficient regulation. In such cases the allocation resulting from social surplus maximization may not be the same as a competitive equilibrium. And it is generally the equilibrium which is desired.

A principal inefficiency in air pollution regulation which leads to difficulties in simulation has to do with the intertemporal allocation of emission rights. Whether any foresight is possible in this allocation determines whether the model must be solved intertemporally or can be decomposed into a series of models solved sequentially. There is no problem in examing the extremes of no foresight in any decision or perfect foresight is all decisions. It is the middle ground of foresight in all decisions except those regarding air pollution that raises difficulties. One aspect of this problem is the regulatory tendency to arbitrarily distinguish between new and existing sources, applying different marginal cost criteria to these two categories. In order to treat these two types of economic dynamics, we set up two equilibrium models with capital vintaging (putty-clay) in both cases. One model involves no foresight; the other involves perfect foresight.

There is another element of time involved in air pollution having to do with the time-varying nature of meteorology. Since in general meteorological variations have a much shorter time constant that economic fluctuation (excluding intermittant emission controls), we assume that within an economic time period (such as one or five years), economic activity is fixed but meteorology can vary substantially. Analogously, meteorologic variation is assumed to be the same in one economic time period as another.

Let

$d_t(q)$: inverse demand function for good (q) at consumption point at time t

$c_{it}(g,b)$: total cost of supply of good (g) and bad (b) in a particular supply region i from capital vintage t

$\beta_i$: unit transport cost from region i to consumption point

$g_{it}$: quantity of good supplied in region i from techology vintage t

$q_t$: quantity of good demanded at consumption point

$b_{it}$: quantity of ba[illegible]pplied in region i from technology vintage t

$a_i(\tau)$: transfer coefficient defined as ratio of the ambient concentration of the bad at the consumption point at time $\tau$ to the steady-state strength of sources in supply region i (no accumulation of pollutants). Meteorologic time starts at the beginning of each economic time period.

In the case of dynamic efficiency (ie, decisionmaking with foresight), an equilibrium allocation at time T will obtain by solving

(1a) $$\max D = \sum_{\tau=T}^{\infty} W_\tau (1+\delta)^{T-\tau}$$

(1b) where $$W_\tau = \int_0^{q_\tau} d_\tau(q)dq - \sum_i \sum_{t=0}^{\tau} \left[ c_{it}(g_{it}, b_{it}) - g_{it}\beta_i \right]$$

(1c) subject to $$q_\tau \leq \sum_i \sum_{t=0}^{\tau} g_{it} \qquad \forall \tau$$

(1d) $$b_{it}, g_{it}, q_\tau \geq 0 \qquad \forall t, \tau$$

where $\delta$ is the discount rate.

With no foresight, $\delta \to \infty$, so the model, for any point in time, T, becomes

(2a) $$\max S_T = \int_0^{q} d(q)dq - \sum_i \sum_{t=0}^{T} \left[ c_{it}(g_{it}, b_{it}) - g_{it}\beta_i \right]$$

(2b) subject to $$q \leq \sum_i \sum_{t=0}^{T} g_{it}$$

(2c) $$b_{it}, g_{it}, q \geq 0$$

These two simple models capture the structure of most mathematical programming energy equilibrium models. The more complex models generally contain many more production activities, goods and consumption points. Most assume no foresight (eq. (2)) although some are truly dynamic (eg Manne, 1977).

Ambient pollution concentrations can be calculated directly for a particular time period from the output of the models. If $c_i$ is the total emission rate at a point in economic time (eg for time T, $b_i = \sum_{t=0} b_{it}$), then the pollutant concentration at time · (measured from the beginning of that economic time period) is given by

$$(3) \quad \sum_i a_i(n) b_i$$

Although the notation may be somewhat cumbersome, recall that there are two time scales involved, economic time and meteorologic time.

B. Technology Based Standards

As was discussed earlier a great deal of current air pollution regulation is technology based. New source performance standards specify control technology for new sources. Many state implementation plans similarly require existing sources to undertake specific process changes or adopt particular retrofit control measures. Such regulations are specified fairly precisely in technological terms usually with no utilization of economic adjustment processes. It is for this reason that there is no problem in representing them in equilibrium models (1) or (2). In essence, such regulations represent a restriction of the production possibility set. This restriction can usually be represented explicitly in the model. For example if a regulation states that only a certain maximum emission level per unit output will be tolerated ($\bar{e}$), then the regulation can be represented by requiring.

$$(4) \quad \frac{b_{it}}{g_{it}} \leq \bar{e}$$

Alternately, the restricted production possibility set can be imbedded in the total cost function where legally inadmissable emissions levels are assigned infinite cost.

## C. Emission Fees

There are two questions that arise relative to emission fees that can be addressed by equilibrium models. One piece of information that can be derived from such models is an estimate of the proper fee to apply which will achieve air quality goals. The other use is the simulation of polluter responses to emission fees and the corresponding air quality effects. We discuss both of these questions here for zoned and efficient changes. Since zoned charges are uniform within a zone but vary from zone to zone, the totally uniform charge is a special case of a zoned charge where there is only one zone.

This discussion is oriented towards charges that aim to achieve ambient goals. If the aim is to achieve emission goals only, then the same discussion holds except that the transfer coefficients to convert emissions to ambient concentrations become trivially zero or one.

1. Efficient Charges. Efficient charges are applied non-uniformly in space and time so as to achieve ambient standards at least social cost. To determine the appropriate charges to apply, model (1) can be modified by the addition of a constraint on ambient quality (5c):

$$\text{(5a)} \quad \max D = \sum_{\tau=1}^{\infty} W_\tau (1+\delta)^{T-\tau}$$

$$\text{(5b)} \quad \text{subject to:} \quad q_\tau \le \sum_i \sum_{t=0}^{\tau} g_{it} \qquad \forall \tau$$

$$\text{(5c)} \quad \sum_i a_i(n) \sum_{t=0}^{\tau} b_{it} \le \bar{X}_\tau \qquad \forall n, \tau$$

$$\text{(5d)} \quad b_{it}, g_{it}, q_t \ge 0$$

where $\bar{X}_\tau$ is the regulatory concentration limit and $a_i(n)$ is the transfer coefficient for meteorologic time $n$. The efficient tax at location $i$, technology vintage $t$, at time $\tau$ is given by $\frac{\partial D}{\partial b_{it}}$ at time $\tau$. This can be determined from the shadow prices assoicated with the set of constraints

(5c). Let the right hand side of (5c) be denoted by $\bar{X}_{\tau n}$ even though $\bar{X}_{\tau n}$ are identical for a given $\tau$ over all $n$. Then for a given $\tau$,

$$(6) \quad \frac{\partial D}{\partial b_{it}} = \sum_{n} \left[ \frac{\partial D}{\partial X_{\tau n}} \quad \frac{\partial \bar{X}_{\tau n}}{\partial b_{it}} \right] = \sum_{n} \left[ SP_{\tau n} \quad a_i(n) \right]$$

where $SP_{\tau n}$ is the shadow price associated with the $\tau n$ constraint of set (5c). Note that the efficient tax, given by (6), at a particular location and time point is independent of the technology vintage, an expected result.

Simulating the effect of a tax involves simply modifying the model objective function to include the tax. In model (1), eq. (1b) would be changed to

$$(7) \quad W_\tau = \int_0^{Q_\tau} d(q)dq - \sum_i \sum_{t=0}^{\tau} \left[ c_{it} \, (g_{it}, b_{it}) - g_{it} \, \beta_i - b_{it} \, \lambda_{i\tau} \right]$$

where $\lambda_{i\tau}$ is the emission fee at location $i$ in time period $\tau$.

2. Zoned Charges. As with efficient charges, an equilibrium model can be used to either compute appropriate zoned charges or simulate the effect of a zoned charges system. As used here, a zoned charge is uniform over a zone but may vary from zone to zone. To simplify the notation, we examine these questions in the context of the static model (2).

First, consider the problem of determing the appropriate zoned charges to achieve air quality goals. The difficulty that arises is that a zoned charge is inefficient; it is difficult to determine appropriate charges by solving a model based on efficiency such as (5). There are two ways to proceed in determing the appropriate zoned charges. One way is to simulate the emission effects of a series of charges. Then as a second step, with the relation between a specific set of charges and emission levels known, one can choose a set of charges which achieve desired air quality goals.

A more direct procedure is possible when the marginal cost curves for polluters are continuous. It should be noted that marginal cost curves may not always be continuous in applications. Discontinuities usually arise when process changes are used to reduce emissions. Since the effect of zoned charges is to equate the marginal costs of cleanup within a zone, if model (2) is modified by this requirement then the appropriate zone charge can be determined from the model solution:

$$\text{(8a)}\quad \max S_T = \int_0^q d(q)dq - \sum_i \sum_{t=0}^{T} \left[ c_{it}(g_{it}, b_{it}) - g_{it} f_i \right]$$

$$\text{(8b)}\quad \text{subject to:} \qquad q \le \sum_i \sum_{t=0}^{T} g_{it}$$

$$\text{(8c)}\qquad \sum_i a_j(n) \sum_{t=0}^{T} b_{it} \le \bar{X} \qquad \forall$$

$$\text{(8d)}\qquad \mu_{it} - \frac{\partial c_{it}}{\partial b_{it}} = \lambda_j \qquad \forall\ i,t, \text{ where } i \text{ is in zone } j$$

$$\text{(8e)}\qquad \mu_{it}\, b_{it} = 0 \qquad \forall\ i,t$$

$$\text{(8f)}\qquad b_{it},\ g_{it},\ q, \lambda_j, \mu_{it} \ge 0 \qquad \forall\ i,t,j$$

where $\bar{X}$ is the concentration maximum and $\lambda_j$ is the emission charge for zone j. The use of $\mu_{it}$ is to allow for non-equality of marginal costs within a zone for sources with no production. Equation (8d) can be interpreted by noting that if technology vintage t in region i is reducing $b_{it}$ in an attempt to raise $\frac{\partial c_{it}}{\partial b_{it}}$ to $\lambda_j$, it may at some point choose to cease production activity thus leaving $\lambda_j + \frac{\partial c_{it}}{\partial b_{it}} > 0$. But if $b_{it} = 0$, then $\mu_{it} > 0$ which will preserve the equality of (8d). Thus the solution of model (8) will give the appropriate zoned charges. It should be pointed out that model (8) involves nonlinear constraints which may be a problem in some applications.

As with efficient charges, it is straightforward to simulate the effects of zoned charges. In model (2), eq. (2a) would be modified to

$$(9)\quad \max S_T = \int_0^Q d(q)dq - \sum_i \sum_{t=0}^{T} \left[c_{it}(g_{it}, b_{it}) - g_{it}\,\beta_i - b_{it}\,\lambda_j\right]$$

where i is in zone j and the charge for zone j is $\lambda_j$.

D. Permit Systems

Emission permit systems can be oriented towards controlling aggregate emissions or ambient concentration maxima. Since emission ceilings are conceptually equivalent to ambient concentration ceilings when the transfer coefficients are appropriately defined, we concentrate here on ambient permits. In terms of their regulatory implementation and treatment of time, there are three general types of ambient permit systems: issuance by first-come, first-served with no consideration of of static or dynamic efficiency; issuance by first-come, first-served with static efficiency through tradeable rights; full dynamic efficiency with intertemporal and intersource emission rights trading. In the spirit of the charges discussion above, there is the separate aspect of spatial differentiation. Space can be highly differentiated or zoned in implementing a permit system. We first discuss these three ambient permit systems assuming efficiency in space.

The current prevention of significant deterioration (PSD) regulations fall into the first of these categories. Aside from having to satisfy new source performance standards, new sources can emit at any level as long as the ambient ceiling is not expected to be exceeded. No consideration is given to efficiently allocating remaining airshed resources among sources either before the ceiling is reached or after it is reached. In the second category of permits fall the EPA's offsets policy for non-attainment areas. Although no mechanism is available to anticipate the scarcity of airshed resources when they become fully allocated, emission rights can be traded at any point in time which achieves static efficiency. The third category of permits encompases the offsets policy with banking where intertemporal trades of emission rights can be made to achieve economic efficiency. Under a banking arrangement, sources may undertake overcontrol initially, selling unused rights at a later time. However, neither type of offset comes into play until the ambient ceiling has been reached; thus prior to this point resources are inefficiently managed.

1. Without Offsets. As mentioned above, current PSD regulations fall into this category. They affect new sources only to the extent necessary to assure that PSD increments will not be violated. Since no cost efficiency tradeoffs are permitted among sources, it is difficult to capture this behavior precisely in a mathematical programming model which is based on the equivalence between efficiency and a decentralized equilibrium. Such a mechanism can be simulated in the context of model (2) by assuming that the currently unallocated ambient increment is based on emissions in the previous time period. Thus an equilibrium allocation is obtained by solving

$$\text{(10a)} \quad \max S_T = \int_0^Q d(q)dq - \sum_i \sum_{t=0}^{T} \left[c_{it}(g_{it}, b_{it}) - g_{it} f_i\right]$$

$$\text{(10b)} \quad \text{subject to:} \quad q \le \sum_i \sum_{t=0}^{T} g_{it}$$

$$\text{(10c)} \quad \sum_i a_i(n) b_{iT} \le \bar{X} - X_{T-1}(n) \qquad \forall n$$

$$\text{(10d)} \quad b_{i\tau} \le b_{i\tau,T-1} \qquad \forall \tau < T$$

$$\text{(10e)} \quad b_{i\tau}, g_{i\tau}, q \ge 0$$

where $b_{i\tau,T-1}$ is the value of $b_{i\tau}$ from the previous economic time period, $X_{t-1}(n) = \sum_{t=0}^{T-1} \sum_i a_i(n) b_{it,T-1}$, the concentration from the previous time period, and $\bar{X}$ is the regulatory maximum concentration. More receptors can be handled by using additional constraints of the form of (10c).

2. Static Offsets. In a statically efficient system, rights to emit are fully tradable except that no foresight occurs regarding the relative scarcity of the emission right in the future. Within a model that permits anticipation of future activity, once again there is a difficulty in using a welfare maximization approach to simulate equilibrium. However if no foresight in any markets is assumed then static offsets can be easily simulated. In particular, model (2) would be modified to

$$\text{(11a)} \quad \max S_T = \int_0^q d(q)dq - \sum_i \sum_{t=0}^{T} \left[ c_{it}(g_{it}, b_{it}) - g_{it}\, \beta_i \right]$$

$$\text{(11b)} \quad \text{subject to: } q \leq \sum_i \sum_{t=0}^{T} g_{it}$$

$$\text{(11c)} \quad \sum_i a_i(n) \sum_{t=0}^{T} b_{it} \quad \bar{X}_n \qquad\qquad \forall\ n$$

$$\text{(11d)} \quad b_{it},\ g_{it},\ q \geq 0$$

where $\bar{X}_n$ is the concentration standard at the receptor. More receptors are handled by more constraints of the form of (11c). This model can be used to determine the market price of an ambient permit directly from the shadow prices on (11c). The effective emission permit cost to each source can be derived in a manner analagous to that used to compute efficient fees (eq. 6). Specifically, the market price of a right to emit at point i is given by the negative of

$$\text{(12)} \quad \frac{\partial S_T}{\partial \sum_{t=0}^{T} b_{it}} = \sum_n \left[ \frac{\partial S_T}{\partial \bar{X}_n} \; \frac{\partial \bar{X}_n}{\partial \sum_{t=0}^{T} b_{it}} \right] = \sum_n \left[ SP_n \cdot a_i(n) \right]$$

where $SP_n$ is the shadow price associated with the n constraint of set (11c).

It is often the case that constraint set (11c) may be quite large if for instance n varies over a year in daily increments. If non-linear constraints are admissable, it is possible to reformulate the set of constraints (11c) as a single non-linear constraint or in terms of a penalty function. For instance, consider the function $e^{-n(\bar{X} - X)}$ where $\bar{X}$ is the concentration maximum, X is the concentration, and n is a positive constant. This function will be between 0 and 1 for $0 \leq X \leq \bar{X}$ and very large for $X > \bar{X}$ (depending on the value of n). Thus a constraint of the form

(13) $\sum_{n=1}^{R} \exp(-n(\bar{X} - X_n)) \leq R$ where $X_n = \sum_i a_i(n) b_i$ and $b_i = \sum_{t=0}^{T} b_{it}$

where R is the the number of meteorologic time periods, could replace (approximately) the set of constraints (11c) giving $X_n \leq \bar{X}$ or if $X_n > \bar{X}$, $| X_n - \bar{X} | < \epsilon$, where $\epsilon$ is small and depends on n. Consider the Taylor's series expansion of $e^{-nx}$ about $x = 0$:

$$e^{-nX} = 1 - nX + \frac{n^2X^2}{2!} - \frac{n^3X^3}{3!} + \cdots$$

Approximating (13) using a second order Taylor series gives

$$\sum_{n=1}^{R} \exp(-n(\bar{X} - X_n)) = \sum_{n=1}^{R} \left[1 - n(\bar{X} - X_n) + \frac{n^2(\bar{X} - X_n)^2}{2}\right]$$

$$= R - Rn\bar{X} + n\sum_n X_n + \frac{Rn^2\bar{X}^2}{2} - n^2\bar{X}\sum_n X_n + \frac{n^2}{2}\sum_n X_n^2$$

$$= R - Rn\bar{X} + \frac{Rn^2\bar{X}^2}{2} + n(1 - n\bar{X})\sum_n X_n + \frac{n^2}{2}\sum_n X_n^2$$

This further simplifies since

$$\sum_n X_n = \sum_i b_i r_i \quad \text{where } r_i = \sum_n a_i(n)$$

and $\sum_n X_n^2 = \sum_n \left(\sum_i a_i(n) b_i\right)^2 = \sum_{i,j} \alpha_{ij} b_i b_j \sum_n a_i(n) a_j(n)$

where $\alpha_{ij}$ is the appropriate binominal coefficient. Thus constraint (13) for multiple receptors can be approximated by

(14) $\underset{\sim}{a}'\underset{\sim}{b} + \underset{\sim}{b}'\underset{\sim}{A}\underset{\sim}{b} \leq \underset{\sim}{c}$

where b is the vector of source strengths, a and c are vectors of constants and A is a matrix of constants.

3. Dynamic Offsets. The distinction between dynamically and statically efficient tradeable permits is that the relative scarcity of future air resources are reflected in today's control decisions. Since this is the conventional perception of the economic allocation process in private markets, simulation of this emissions allocation system is straightforward. Model (1) is modified and an equilibrium allocation obtained by solving

$$\text{(15a)} \quad \max D = \sum_{\tau=T}^{\infty} W_{\tau} \, (1+\delta)^{T-\tau}$$

$$\text{(15b)} \quad \text{where } W_{\tau} = \int_{0}^{q_{\tau}} d_{\tau}(q)dq - \sum_{i} \sum_{t=0}^{\tau} \left[ c_{it}(g_{it}, b_{it}) - g_{it} \, \beta_{i} \right]$$

$$\text{(15c)} \quad \text{subject to: } q_{\tau} \leq \sum_{i} \sum_{t=0}^{\tau} g_{it} \qquad \forall \tau$$

$$\text{(15d)} \quad \sum_{i} a_{i}(n) \sum_{t=0}^{\tau} b_{it} \leq \bar{X}_{\tau} \qquad \forall \; n, \tau$$

$$\text{(15e)} \quad b_{it}, \, g_{it}, \, q_{t} \geq 0$$

This model differs slightly from offsets with banking since resources are allocated efficiently even before (15c) is binding. Market prices of ambient permits can be inferred from the shadow prices on constraints (15d) in a manner similar to that for static offsets (eq. 12).

4. Zoned Permits. The final type of pure permit system that will be discussed focuses not on intertemporal aspects of emission rights allocation but the spatial aspects. Akin to zoned emission fees, the zoned permit system allows for trading of emission rights within a zone but bases total allowed zone emissions on the zone's effect on ambient concentrations. Although this is inefficient such a system has many appealing implementation features such as not dealing excessively with meteorological models relating emissions to

the ambient. This is in effect how the NAAQS are implemented through the offsets policy although there is only one zone.

For simplicity, we deal in the context of the static model (2). In a manner analogous to the approach used with zoned emission fees, we simulate an emission zone by requiring the marginal cost of pollution control to be identical for all sources in a zone. This is a proxy for making emission rights totally tranferable and of identical cost within a zone. Thus, allocations under a zoned permit system can be simulated by solving

(16a) $$\max S_T = \int_0^q d(q)dq - \sum_i \sum_{t=0}^{T} \left[ c_{it}(g_{it}, b_{it}) \quad g_{it}\beta_i \right]$$

(16b) subject to: $$q \leq \sum_i \sum_{t=0}^{T} g_{it}$$

(16c) $$\sum_i a_i(n) \sum_{t=0}^{T} b_{it} \leq \bar{X} \qquad \forall\, n$$

(16d) $$\mu_{it} - \frac{\partial c_{it}}{\partial b_{it}} = \lambda_j \qquad \forall\, i,\ t, \text{ where } i \text{ is in zone } j$$

(16e) $$\mu_{it}\ b_{it} = 0 \qquad \forall\, i,\ t$$

(16f) $$b_{it},\ g_{it},\ \lambda_j, \mu_{it},\ q \geq 0 \qquad \forall\, i,t,j$$

where $\bar{X}$ is the permit issuance on ambient concentration increments. The actual quantity of emission rights in zone j will be a function of the distribution of sources within the zone. Specifically the transfer coefficient relating aggregate zone emission to ambient concentration for zone j for time n is given by

$$(17)\quad \hat{a}_j(\eta) = \frac{\sum_{i\epsilon j} a_i(\eta) \sum_{t=0}^{T} b_{it}}{\sum_{i\epsilon j} \sum_{t=0}^{T} b_{it}}$$

Thus to emit one unit of emission in zone j at time $\eta$, $\hat{a}_j(\cdot)$ ambient rights must be purchased. With intermittent controls prohibited so that emission rates are constant, max $\hat{a}_j(\cdot)$ rights must be purchased to emit constantly at the unit rate. In equilibrium, the market price of this right should be $\lambda_j$.

E. Hybrid Permit/Fee Systems

The final regulatory system to be examined is the hybrid system where a permit to emit at a certain level is issued; emissions over the permitted level are penalized with a fee and in some situations, emissions under the permitted level accompanied by a negative fee or subsidy. There are many ways of constructing such a system. We present here a system involving a marketable ambient right accompanied by a fee for emissions above that permitted. It is straight-forward to construct alternate systems involving non-marketable rights, zoned ambient rights, emission rights, and subsidies.

There are several questions that can be asked of an equilibrium model. Given permitted emission rates, what is an appropriate accompanying fee? Given a permit/fee system, what will be emitter responses to such a system? Both of these questions can be examined in the context of model (2). For a desired ambient level of $\bar{X}$, an efficient allocation of emissions is given by (5) with the market price of emission rights given by (6). This price should be the fee rate levied with the permit issuance at some level in the vicinity of $\bar{X}$

On the other hand, suppose ambient permits are issued in the amount of $\bar{X}$ accompanied by a fee $\lambda_i$. Let $\bar{X}_i$ be the permits held for sources in location i. Thus, permitted emissions at location i are $\min_{\eta} \frac{\bar{X}_i}{\alpha_i(\eta)}$. An equilibrium allocation in model (2) is obtained by solving

$$(17a)\quad \max S_T = \int_0^q d(q)dq - \sum_i \sum_{t=0}^{T} \left[ c_{it} \quad (g_{it}, b_{it}) - g_{it} \beta_i - \lambda_i e_i \right]$$

$$\text{(17b) subject to:} \qquad q \le \sum_{i} \sum_{t=0}^{T} g_{it}$$

$$\text{(17c)} \qquad \sum_{i} \bar{X}_i \le \bar{X}$$

$$\text{(17d)} \qquad e_i \ge \sum_{t=0}^{T} b_{it} - \frac{\bar{X}_i}{a_{i(n)}} \qquad \forall\, n$$

$$\text{(17e)} \qquad b_{it},\ g_{it},\ q,\ \bar{X}_i,\ e_i \ge 0$$

Expression (17d) is the amount of emissions in excess of permitted levels, if any. If (17d) is made an equality and $e_i$ allowed to be a free variable, then the model will simulate a fee/subsidy system.

## IV. CONCLUSIONS

This paper is based on the position that allocation of airshed resources is an economic process even though it is often accomplished through quantity signals rather than price signals. Since air quality is a public good, social allocation mechanisms are necessary to achieve anything approaching efficient resource allocation. The purpose of this paper has been to interpret air pollution regulations as allocation mechanisms which are amenable to examination using conventional economic analysis tools. In particular, the focus has been on representing regulation within spatial equilibrium models. Although some compromises have been necessary, in general air quality regulation can be represented in such models. It is hoped that the discussion in this paper will lead to better understanding of the economy's response to pollution control leading to an overall improvement in the allocation of environmental resources.

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