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The Economics of Visibility Protection: On a Clear Day You Can See a Policy

Robert Repetto

THE ECONOMICS OF VISIBILITY PROTECTION: ON A CLEAR DAY YOU CAN SEE A POLICY

ROBERT REPETTO*

BACKGROUND

Oh, say can you see, by the dawn's early light, what so proudly we hailed at the twilight's last gleaming?

Early concerns about air pollution have been augmented recently by the realization that airborne emissions can affect both clarity and range of visibility over a broad area. Brownish smog covering the entire Los Angeles basin, haze obscuring views into and across the Grand Canyon, and a certain flatness in the view of distant Appalachian mountains, are examples of this problem. It is caused mostly by fine particles formed by atmospheric chemistry and gaseous emissions.

Summer visibilities now average 10 to 15 miles along populous coastal regions in the mid-western industrial belt along the Mississippi River and around the Great Lakes. At the other extreme, visual range in the mountain states reaches 70 to 80 miles in summertime, and occasionally approaches the theoretical maximum of 200 miles.[1] While natural conditions account for some of these differences, they are largely the result of man-made pollution.

Since World War II visibility in the United States has declined, except in those metropolitan areas where it had already been low. In the East and Northeast, between early 1950 and early 1970, visual range was reduced by 10 to 40 percent. This is an average of little change in wintertime and reductions of 25 to 60 percent in summer. Over the same period, visibility dropped 10 to 30 percent in the Southwest, due mostly to emissions from smelters and large power stations. In the latter part of the 1970s, air pollution control efforts have largely arrested this alarming trend. Nonetheless, it seems that the question we intone to open our national anthem is no longer purely rhetorical.

Concern over visibility is reflected in the Clean Air Act Amendments of 1977.[2] Prevention of Significant Deterioration sections

*Center for Population Studies, Harvard University, Cambridge, Mass. 02138.

1. U.S. ENVIRONMENTAL PROTECTION AGENCY, PROTECTING VISIBILITY: AN EPA REPORT TO CONGRESS (Sept. 1979 Draft) [hereinafter cited as EPA].
2. Clean Air Act Amendments of 1977, 42 U.S.C. § § 7401-7642 (Supp. II 1978).

(PSD) of the act are intended to 1) protect public health and welfare from air pollution beyond national standards; and 2) preserve, protect, and enhance air quality in special natural areas.[3] National parks, national monuments, and scenic wilderness areas were designated Class I, with strict limits to further degradation of air quality by sulfur and particulate emissions.[4] In the 1977 amendments Congress sought to prevent future and remedy present impairment of visibility in Class I areas from man-made air pollution. Congress directed the Environmental Protection Agency (EPA) to promulgate guiding regulations and require states to incorporate measures which would ensure reasonable progress toward this goal into their state implementation plans (SIPs). These measures include provisions for large stationary sources which impair visibility to install "best available retrofit technology" (BART) to abate emissions.[5]

Recently the EPA identified 156 Class I areas in which good visibility is necessary and must be protected.[6] As a first step to carry out this mandate, EPA proposed regulations requiring each state to analyze the impact and control possibilities of major existing stationary sources and clusters of sources which can be determined to reduce visibility in these protected areas.[7] These analyses could lead to the imposition of BART. When more is known about the long range effects of regional emissions on visibility, these regulations will be broadened. For major new sources, the EPA requires that visibility review be integrated with PSD programs in revised state implementation plans, and each state examine the visibility impact of all major new sources and deny permits to those with adverse impact on protected Class I areas.[8]

This legal and regulatory defense of visibility raises a number of policy issues. First, it is highly selective. It concentrates on a small number of specially designated areas with recognized scenic or aesthetic importance and good air quality. It does not address preservation or improvement of visibility in the rest of the country, even though there is considerable room for improvement. All other regulatory programs indirectly affect visibility levels in the country, but imply ambient concentrations and emission standards that result in continued impairment and, perhaps, deterioration of visibility.

Second, the regulations are designed to preserve high standards of

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3. *Id.* § 160, 42 U.S.C. § 7470.
4. *Id.* § 162(a), 42 U.S.C. § 7472(a).
5. *Id.* § 169(b), 42 U.S.C. § 7491(b).
6. 44 Fed. Reg. 69,122 (1979) (to be codified in 40 C.F.R. §§ 81.400-.437).
7. 45 Fed. Reg. 34,762 (1980) (to be codified in 40 C.F.R. §§ 51.300-.307).
8. 45 Fed. Reg. 34,765 (1980) (to be codified in 40 C.F.R. § 51.307).

visibility in protected areas. New sources are held to the test of *any* adverse effects on designated areas. Analyses have shown that this standard will preclude siting of major new facilities, even those with advanced emissions controls, within a substantial range of protected areas. Single-source models show adverse impacts downwind from sulfur and NO_X sources at distances of 80 to 100 kilometers or further, under some conditions.[9] Therefore a direct conflict exists between visibility protection and siting of new industrial facilities, especially large coal-based power plants and synthetic fuels projects in the West and Southwest.[10] There are many protected Class I areas in these regions, air quality is relatively good, and substantial growth of heavy polluting industry is anticipated.

The broad policy that has emerged is nearly dichotomous: stringent controls, amounting almost to a ban on major pollution sources in high value areas, and no special measures, other than those prescribed by existing control programs, in the rest of the country. This is quite different from the general pattern of environmental policy in the United States, and the pattern of air pollution policy, which tends toward uniform national ambient standards, and uniform national emissions standards for similar facilities. The implicit visibility standards in the Clean Air Act are decidedly nonuniform.

The following section argues that this distinctive feature of visibility protection is grounded in economic logic. Rational environmental protection policy seeks a level of environmental quality that balances the incremental damages from pollution against the incremental costs of abatement, a level which often occurs at a discontinuous threshold of safety or of control costs. This same logic applied to visibility protection is unlikely to produce a defensible uniform standard. Rather, it will imply the kind of visibility "zoning" which present regulations create.

In addition to the selectivity of visibility controls and their stringency in protected areas, the forms taken by state and federal implementing regulations have important economic implications. The EPA has encouraged state agencies to consider innovative enforcement policies to implement PSD regulations for SO_2 and particulates: imposition of emissions taxes or noncompliance fees, or the use of marketable and tradeable emissions permits, for example. States also are encouraged to consider such innovative approaches in drafting specific visibility protection rules.

Even more flexibility exists for PSD regulations for "criteria" pol-

9. EPA, *supra* note 1, at 4-49.

10. Kneese & Williams, *Air Quality Issues and Approaches in the Southwest*, 19 NAT. RES. J. 537 (1979).

lutants other than SO_2 and particulates, especially for emissions of nitrous oxides (NO_X) which affect visibility both in the gaseous NO_2 state and in nitrate aerosol. The Clean Air Act does not prescribe area classifications or fixed ambient limits of deterioration for these "Set II" pollutants, which include photochemical oxidants, if other regulatory approaches are adopted that protect visibility equally well and meet other purposes of the PSD program.[11] One reason for this flexibility is that a larger fraction of the Set II pollutants come from mobile sources, and are more chemically reactive in the atmosphere (making the linkage between source controls and ambient limits more tenuous).

The forms of regulation under discussion include those, such as emissions fees, that control the price of pollution and those, such as quotas and marketable permits, which control the aggregate quantities of pollution in a region. In a static, deterministic, perfectly competitive world, in which the regulatory agency has complete information, these alternatives are equivalent. In the real world, however, the latter approach can impose heavy excess costs, if quantities are miscalculated, while the former can imply heavy excess costs if the prices are miscalculated. The choice between them is a choice between competing risks. A well known analysis[12] shows that if uncertainty is approximately the same regarding the levels of marginal damages and marginal abatement costs at a particular level of pollution, the choice rests on the steepness of the marginal damage and cost functions. If damages rise steeply while costs are relatively flat, price policies would be more risky, because small errors in the control variable would cause large deviations by polluters from the right level of pollution; large excess damages or control costs would result. On the other hand, if marginal damages are approximately unchanged over the relevant range of pollution levels, while marginal abatement costs rise steeply, quantity controls are risky, since an error in setting permissible levels can result in large excess damages or costs.

Visibility regulation involves the following issues: *Where* should visibility be protected?; *how much* should visibility be protected?; and *how* should visibility be protected? The following analysis of the technical and economic aspects of visibility impairment addresses these issues.

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11. Clean Air Act Amendments of 1977 § 166(e), 42 U.S.C. § 7476(e) (Supp. II 1978).

12. Weitzman, *Prices vs. Quantities*, 41 REV. ECON. STUD. 477 (1974); Yohe, *Towards a General Comparison of Price Controls and Quantity Controls Under Uncertainty*, 45 REV. ECON. STUD. 229 (1978).

THE TECHNICAL AND ECONOMIC FOUNDATION OF VISIBILITY DAMAGES

Although visibility is limited by light scattering by air molecules (Rayleigh scattering), absorption by gas (mainly NO_2), and absorption and scattering by aerosols, most man-made impairment of visibility is due to scattering by fine particles in the 0.1 to 1.0 micron size range. These particles are such efficient scatterers that a cloud equivalent to a 1 mm thick sheet of transparent material would scatter 99 percent of incident light, completely obscuring vision.

Ambient particulate concentrations are usually bimodally distributed by size: a fine particle mode at 0.3-0.5 microns, and a coarse mode centered at about three microns. Although fine particle aerosols vary by chemical composition, they typically are dominated by secondarily formed sulfates, nitrates, particulate organics, and ammonium compounds. Sulfate and nitrate aerosols account for over half of actual man-made impairment. Calculated scattering efficiencies per unit mass of fine particles in the atmosphere vary little. There are close relationships, therefore, between fine particle concentrations, scattering coefficients, and visibility.[13]

The nature of this relationship is of fundamental importance. A given addition of fine particles reduces visibility much more in clean air than in dirty air. If visual range is about 200 miles, close to the maximum, pollution by one microgram per cubic meter of fine particles would reduce visibility by about 30 percent; if visual range is 20 miles, typical in populated areas, the same pollution would reduce visibility further by only about three percent. In other words, as pollution increases, marginal effects on visibility *diminish.* This relationship is graphed in Figure 1. A similar relationship exists for the contrast between an object and its background, another aspect of visibility that affects aesthetic enjoyment.

This pattern of strongly declining marginal impact is the opposite of typically assumed, or observed, dose-response and damage functions. With or without a threshold of zero effects, it is usually assumed that marginal damages would rise, or at least, remain constant, as dose increases. A declining marginal damage function for visibility should have important implications for regulatory policy.

The physical response function presented in Figure 1, however, cannot immediately be equated with a damage function because it

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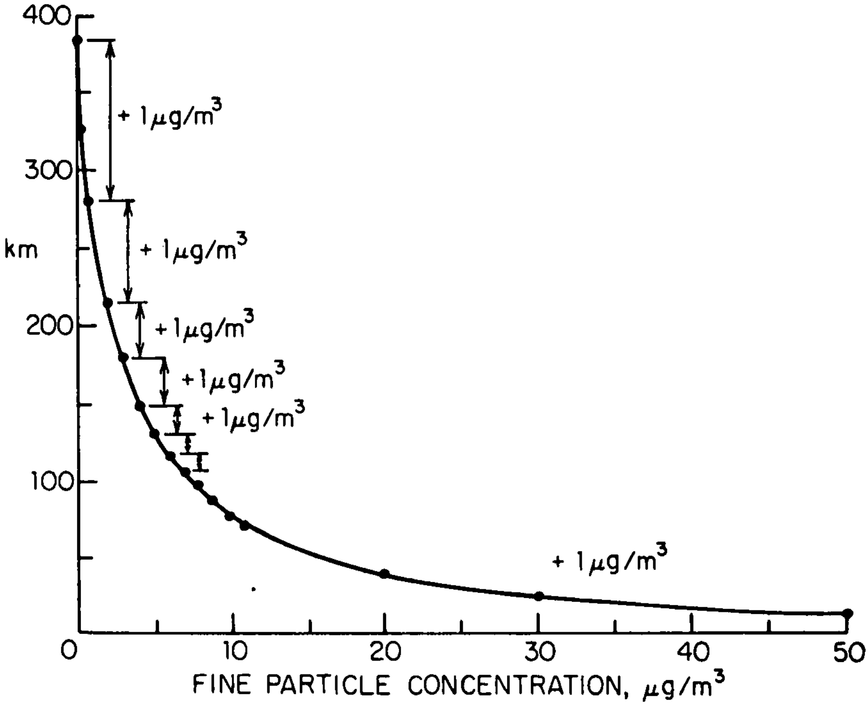
13. Charlton, Waggoner & Thielke, Visibility Protection for Class I Areas: The Technical Basis (Aug. 1978) (report to the Council on Environmental Quality, Washington, D.C.).

FIGURE 1

EFFECTS OF FINE PARTICLE CONCENTRATION ON VISUAL RANGE



SOURCE: U.S. Environmental Protection Agency, *Protecting Visibility: An EPA Report to Congress* (Sept. 1979 Draft).

omits the valuation of visibility loss. It is conceivable that as visual range becomes less and less, each kilometer of range is valued more highly, so that increasing valuation and decreasing physical impact cancel each other out, leaving the shape of the true damage function indeterminate.

Visibility is a classic public good. It would be difficult to provide one person with an unimpaired vista of the Rocky Mountains without making the same view available to everyone. Therefore, valuation attempts have had to contend with the "free rider" problem; potential beneficiaries of visibility protection might misstate their willingness to pay for benefits in order to influence program decisions or avoid program costs. While some efforts have been made to infer air pollution benefits from market behavior, the visibility components of those benefits have not yet been isolated. Attempts to elicit statements of willingness to pay for visibility, using sophisticated polling techniques which test for strategic misstatements, do *not* indicate sharply rising marginal valuation of visibility with diminishing range.[14] In fact, just the opposite seems true. As Table 1 shows, willingness to pay for a given increase in visual range (in this instance 25 miles in southwest Colorado) *diminishes* as visual range declines. While this may not be true for short distances, it makes sense at scenic ranges: the increase in *area* commanded by a given improvement in visual range is proportional to the initial range itself. When these valuation data are combined with the technical relationship between ambient particle concentrations and visibility, it is clear that the damage function for visibility indeed is characterized by diminishing marginal damages. The available data on consumer willingness to pay merely reinforces this conclusion.

EFFICIENT VISIBILITY PROTECTION: THE SIMPLE ONE-REGION PROBLEM

Imagine the problem of a regulatory agency faced with an application for a new power plant or other polluting facility to be built in a relatively unspoiled scenic area. Assume the agency has the entire arsenal of regulatory options described above at its disposal; it can deny or issue a permit, set emissions limits, or impose penalties. Assuming it is motivated to find an efficient solution, which option minimizes total pollution and abatement costs to society? While this is perhaps not the best way the problem could be formulated, because alternative sites and recreational areas are often available, this is prob-

TABLE 1

AVERAGE WILLINGNESS TO PAY (EQUIVALENT SURPLUS) FOR IMPROVEMENTS IN VISIBILITY, BY INITIAL VISUAL RANGE

VISIBILITY RANGE (miles)	AVERAGE WILLINGNESS TO PAY	
	residents ($/mo.)	non residents ($/day)
50-75	4.75	3.00
25-50	3.53	2.53
25-75	6.54-7.58*	4.06

*higher figure after prompting

Source: R. D. Rowe, R. C. d'Arge, and D. S. Brookshire. "An Experiment on the Economic Value of Visibility," 7 *Journal of Environmental Economics and Management* 10 (1980).

14. Rowe, d'Arge & Brookshire, *An Experiment on the Economic Value of Visibility*, 7 J. ENVT'L ECON. & MANAGEMENT 1 (1980).

ably the way the problem usually does arise. In this case, the visibility damage function (Figure 1) implies strong policy guidelines for the regulator. It shows that corner solutions may be efficient, in which the agency pursues one of two extreme courses of action. Perhaps if visibility protection is the only issue the agency should just issue the permit. Perhaps it should allow no emissions and deny the permit. Moreover, even if neither of these extreme solutions is appropriate, economic analysis leads to a strong presumption about what should be done instead.

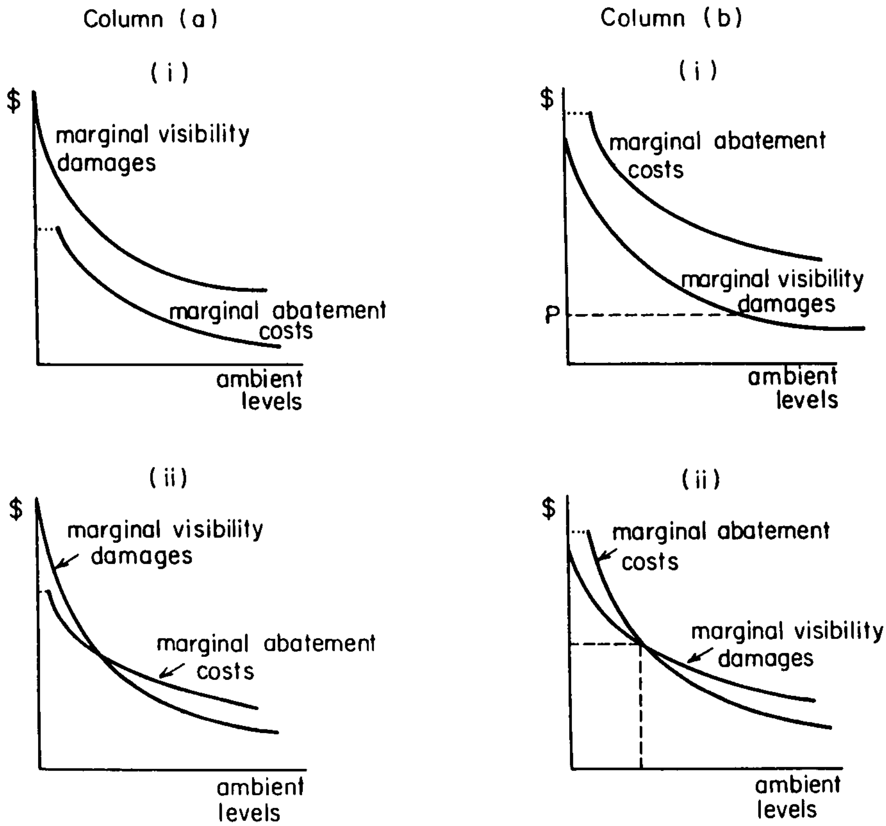
If there is a simple direct relationship between the proposed facility's emissions rate and ambient fine particle concentrations, then both the marginal benefit stream of damages prevented and the marginal costs of abatement increase as emissions and ambient concentrations are curtailed. Successively higher levels of emissions control involve higher unit costs per ton of abatement. At some level of control, costs become prohibitive and it is cheaper to locate the facility elsewhere. Therefore, both marginal benefits and marginal costs rise with increasing abatement. These curves are depicted in Figure 2.

Two alternatives exist. At zero emissions from the facility, either marginal benefits from visibility control exceed marginal costs, or vice versa. These possibilities are represented in columns (a) and (b) of Figure 2. If the marginal benefits from protecting visibility exceed the costs, efficiency requires that a permit should be denied and no emissions be allowed. Society's loss from additional impairment of visibility would exceed the savings in abatement costs. This may be the situation in regions where 1) existing air quality is still very good, so that additional pollution would cause large reductions in visibility, 2) public demand for scenic and aesthetic values are great, and 3) the polluting facilities can be sited elsewhere without great loss. Except that some areas may have valuable mineral deposits, this description fits EPA's mandatory Class I regions. Most have special scenic value, are located in relatively unspoiled areas, and attract many visitors, 280 million man-days in 1978. In areas under National Park Service management, usership is rising rapidly.

The other possibility is that marginal costs of abatement, at zero emissions from the proposed facility, exceed the marginal value of visibility loss. This might occur in regions of little scenic distinction where visibility is already mediocre, and the incremental impact of further emissions would be low. Conceivably, marginal costs could continually exceed marginal damages at higher emissions rates (Figure 2, Column b, i), suggesting that no emissions limits to protect visibility are warranted. Alternatively, abatement could become sufficiently inexpensive in relation to benefits that some level of control

FIGURE 2

POSSIBLE COST: BENEFIT CONFIGURATIONS IN A SINGLE REGION



is justified: falling marginal abatement costs intersect (falling) marginal abatement benefits from above. (See Figure 2, Column b, ii.)

In this last case, efficiency requires that some, but not complete, control over visibility impairment be maintained. Economic analysis provides further guidance about the best mode of regulation in this situation. Near the efficient level of abatement, marginal abatement costs change more rapidly than marginal abatement benefits. In the light of the previous discussion on policies to control pollution quantities and pollution prices, a penalty rate for emissions which impair visibility involves less risk than emissions or ambient limits to achieve the same purpose. The gradient of control costs is steeper than that of damages. Therefore, a penalty rate for emissions, calculated to approximate the value of marginal visibility losses from the proposed facility, runs fewer risks of miscalculation. Should it not be efficient to protect visibility at all, a penalty on emissions set at level p, in Figure 2, column b,i, would not induce any unnecessary emissions control. It would be paid as a dead weight penalty by the source and could be rebated through tax or fiscal adjustments. In this situation, any emission limit to protect visibility would result in over control.

Therefore, a regulatory strategy to protect visibility that would be economically efficient would ban emissions outright in regions where there are exceptional aesthetic values to protect, and where marginal costs of such a ban are probably less than the value of the aesthetic damages being prevented. In other regions, the strategy would tax emissions or establish a penalty rate for emissions based as nearly as possible on the value of visibility gains over ranges of relative constancy in marginal damages.

This scheme is similar to the regulatory policy for visibility that is emerging. Virtual bans on impairment in key areas have been established. Further, Congress and the EPA are urging states to consider innovative regulatory approaches in their SIPs for implementing visibility protection, including emissions fees and noncompliance charges. Finally, Congress has not adopted nationally applicable standards or limits to protect visibility. There is substantial economic logic in this approach.

EFFICIENT VISIBILITY PROTECTION: THE MULTI-REGION CASE

While this simple analysis leads to clear qualitative regulatory guidelines, it is not a completely adequate framework. The valuation of visibility losses in one region is not independent of visibility changes in alternative recreational areas. There is some substitutability between scenic views. Also, the demand for power from a generating station located at point X would depend on the decision whether to locate a station at point Y. There are significant substitution possibilities which influence the magnitude of both visibility damages and abatement costs. Furthermore, the demand for recreation and environmental enjoyment will depend on the level of income, which will be determined by the level of production in the region. The problem is *where* visibility should be protected and *where* production should be located.

This broader problem can be clarified by an analysis of two regions. Each has valuable scenic resources susceptible to visibility damage. Visibility in each region depends on the ambient fine particle concentration, but the *valuation* of any given level of visibility in one region is influenced by the level of visibility in the other, and by the income levels in the two regions. Higher income implies higher valuation of visibility. A lower visibility level in one region implies a higher visibility value in the other. Given available abatement technologies, the level of ambient pollution in each region depends on the level of income and output in that region. Output generated in one region substitutes perfectly for output generated in the other.

The regulatory problem is to choose the level of visibility in each region or, equivalently, given the abatement possibilities, to choose levels of production and corresponding ambient concentrations in each region. The efficient solution is one which maximizes total welfare, including both the value of visibility in each region and the value of output. In the two-region case it is even more likely that an efficient solution will concentrate output in one region and preserve unimpaired visibility in the more scenic region. This can be demonstrated by graphical analysis similar to that for the single region. A mathematical derivation is presented in the Appendix.

Assume, initially, that abatement possibilities are the same in both regions, in the sense that the amount of income sacrificed to reduce ambient concentrations is the same in both regions at all concentrations. These abatement possibilities are depicted in Figure 3 as the marginal cost curve, which rises with successive reductions in pollution.

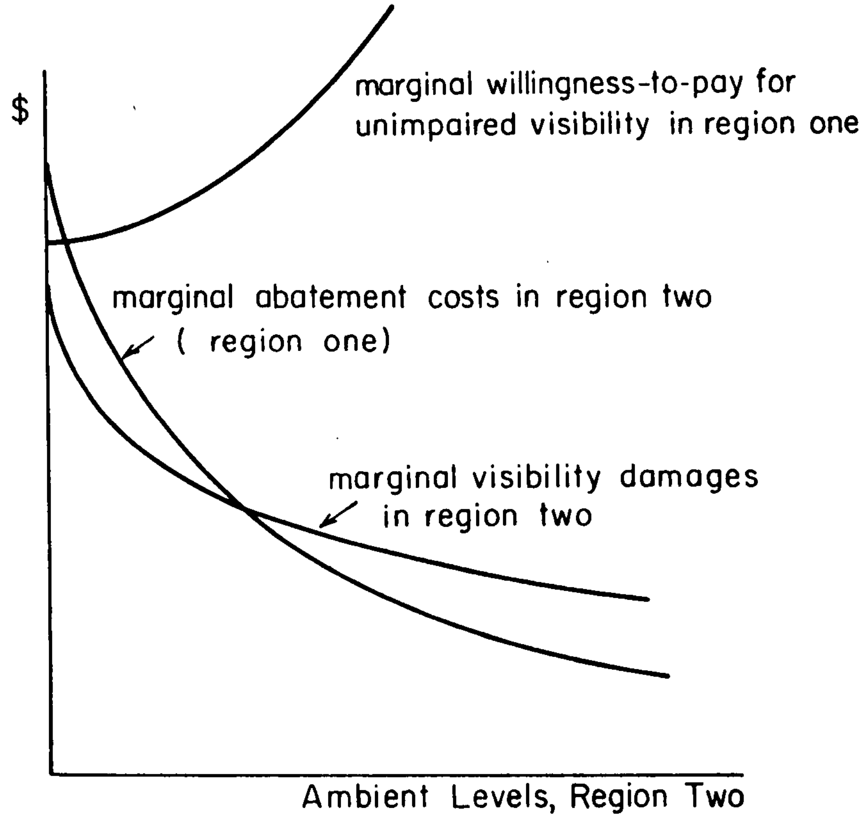
Figure 3 shows pollution levels in region two, indexed by ambient concentrations. Marginal visibility damages are defined as willingness to give up a dollar of income to improve visibility incrementally in region two. This curve declines with increasing pollution levels.

Superimposed on this graph is an additional function representing marginal willingness to pay for visibility *in region one* (when visibility is still unimpaired there), *as a function of the level of ambient concentrations in region two.* This is shown as a rising function of ambient concentrations in region two for two reasons. First, since visibilities in the two regions are substitutes, pollution increases in region two make visibility more valuable in region one. Second, more income generated in region two makes the demand for scenic values and the valuation of unimpaired visibility greater in region one. It is also clear from Figure 3 that region one is, by definition, more scenic; at zero pollution levels in both regions, there is greater willingness to pay for visibility in region one.

To make the analysis meaningful, the marginal cost of abatement when pollution is zero in both regions exceeds the marginal value of visibility. The efficient solution can be understood easily by considering the initial location of production. Production would be located in the less scenic region, because the net gain in welfare, the gain in in-

FIGURE 3

BENEFITS AND COSTS OF VISIBILITY PROTECTION IN THE TWO-REGION CASE WITH EQUAL ABATEMENT COSTS IN BOTH REGIONS



come less the loss of visibility values, would be maximized. This dictates location of the next production facility there also, because the pollution from initial production raises the marginal value of visibility in the more scenic region and lowers it where the first unit was sited. The net gain in welfare is maximized if the second unit is also located in region two. Production is expanded in region two until marginal abatement costs fall to the level of marginal visibility damages, or, if there are other kinds of pollution effects at higher concentrations, until they fall to the level of overall marginal pollution damages.

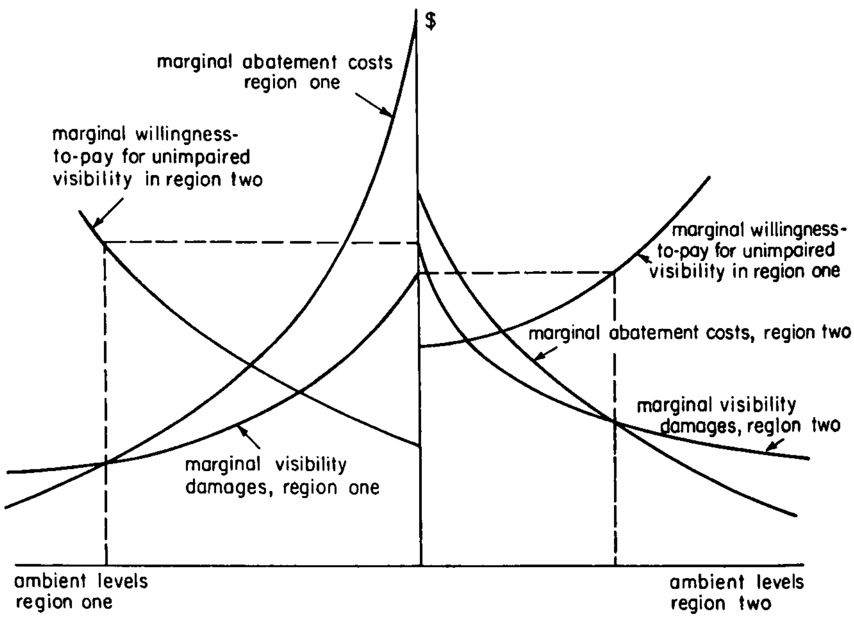
It is inevitable, in this framework, that a form of zoning will be the efficient regulatory solution. Production in one region increases ambient concentrations and lowers visibility levels; and this raises the value of good visibility in the other region. Production facilities will be concentrated in one region, while visibility will be preserved in the other. Consideration of the substitution possibilities between regions reinforces economic arguments for a limited and dichotomous regulatory policy to protect visibility.

Specialization between regions will *not* necessarily arise as the efficient pattern if the more scenic region also happens to be the more productive, in the sense that more income can be generated per unit increase in ambient concentrations. Otherwise, the marginal gains from interfering with visibility in the pristine region will always be less than the value of expanding production activities that pollute the other. This condition might arise for one of three reasons: better dispersal of emissions due to favorable meteorological conditions, exceptionally rich resources in the scenic region, or specialization for less polluting kinds of production in the scenic region. Many scenic regions have chosen to limit their economic development to industries that generate a high level of income per unit of emission.

Figure 4 describes an efficient solution to the problem, with visi-

FIGURE 4

EFFICIENT ABATEMENT IN TWO REGIONS WITH ABATEMENT COSTS HIGHER IN THE MORE SCENIC REGION



bility impaired to some extent in both regions. Ambient concentrations in regions one and two are graphed along the horizontal axis back-to-back. Marginal abatement cost curves are drawn so that more income can be produced per unit of pollution in scenic region one. The marginal valuation of unimpaired visibility in each region as a function of ambient concentrations in the other are drawn such that, at zero pollution in both, losses in visibility are more valuable in region one. In both regions, marginal abatement costs intersect the relevant marginal damage functions from above. Even though visibility losses are greater, it is efficient in this example to begin production in the more scenic region. These gains are rapidly exhausted, however. At the same time, development in the more scenic region does not lead to rapidly rising valuation of visibility benefits in the less scenic region, so production is also expanded there.

In summary, a multiregional analysis in which there can be substitutions in demand between production locations strengthens the previous conclusion. Typically, it is efficient if polluting activities are concentrated in the less scenic region and the more scenic region is left unspoiled. Exceptions will occur only if scenic regions are unusually productive in heavily polluting activities, or have unusually high abatement costs. In addition, efficiency losses are probably reduced if visibility impairment in nonpristine areas is regulated through pricing mechanisms such as emission taxes and noncompliance penalties, rather than through quantitative emission and ambient limits. There is, therefore, an economic rationale for the visibility policy that is evolving from the Clean Air Act.

APPENDIX

Mathematical Formulation of the Two-Region Problem

As indicated in the text, the search for an efficient regulatory outcome is equivalent to the search for a pattern of production and pollution which maximizes potential social welfare (W). Welfare is determined by the levels of visibility (V) in each region, dependent on ambient pollution concentrations (A), and the income level (Y), which can be produced in either location. Thus, visual quality in region one partially substitutes for visibility in region two, while incomes produced in the two regions are perfect substitutes. The allocation problem is to choose ambient concentrations in the regions which maximize

1) $$W = W\,[V_1\,(A_1), V_2\,(A_2), Y_1\,(A_1) + Y_2\,(A_2)] = \max_{A_1, A_2}$$

Welfare rises at a decreasing rate with income, and at an increasing rate with visibility over the relevant range of pollution. The entire set of qualitative relationships underlying 1) and reflecting the physical and economic characteristic properties discussed in the text is as follows:

$$2)\ W_{V_1}, W_{V_2}, W_Y > 0\quad W_{V_1V_1}, W_{V_2V_2} > 0,\ W_{YY} < 0,\ W_{v_1, v_2}, W_{v_2 v_1} < 0,$$

$$W_{V_1Y}, W_{V_2Y} > 0$$

$$V_{1A_1}, V_{2A_2} < 0,\ V_{1A_1A_1}, V_{2A_2A_2} > 0$$

$$Y_{1A_1}, Y_{2A_2} > 0,\ Y_{1A_1A_1}, Y_{2A_2A_2} < 0$$

The first-order conditions to maximize the welfare function are:

$$3)\ W_{V_1} \cdot V_{1A_1} + W_y \cdot Y_{1A_1} = 0 \text{ or } \left(\frac{W_{V_1}}{W_Y}\right) V_{1A_1} = Y_{1A_1}$$

$$W_{V_2} \cdot V_{2A_2} + W_Y \cdot Y_{2A_2} = 0 \text{ or } \left(\frac{W_{V_2}}{W_{Y_2}}\right) V_{2A_2} = Y_2A_2$$

where the second version parallels the marginal visibility damage and marginal abatement cost functions graphed in the text. The left hand functions, $\left(\frac{W_{V_1}}{W_Y}\right) \cdot V_{1A_1}$ and $\left(\frac{W_{V_2}}{W_Y}\right) \cdot V_{2A_2}$, are the marginal willingness-to-pay functions for small changes in ambient pollution levels which impair visibility. The right hand functions represent reduction in abatement costs, including loss of production, from small increases in ambient concentrations.

For these equations to correspond to a welfare maximization, a further set of second-order conditions must be fulfilled. It is these which the nonconvex damage function threatens to violate. The second-order conditions are:

$$4)\ W_{A_{11}} = W_{V_1V_1} \cdot V_{1A_1A_1} + W_{YY} \cdot Y_{A_1A_1} < 0$$

$$W_{A_{22}} = W_{V_2V_2} \cdot V_{2A_2A_2} + W_{YY} \cdot Y_{A_2A_2} < 0$$

However, $W_{A_{ii}}$ are not necessarily negative. Since the marginal damage function is decreasing with higher pollution levels and falling visibility ranges, as indicated by $W_{V_1V_1} V_{1A_1A_1}, W_{V_2V_2} V_{2A_2A_2} > 0$, the second-order conditions will generally not hold. If W_{VV} and V_{AA} are positive they cannot be met, since W_{YY} and Y_{AA} are both negative. If W_{VV} is negative, then the condition can hold only if the marginal abatement costs are falling more rapidly than marginal visibility losses as ambient levels rise.