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The Effects and Efficiencies of Different Pollution Standards

JON D. HARFORD* AND GORDON KARP**

I. Introduction

A number of authors have devoted serious effort to proving that the tax approach to controlling pollution externalities under conditions of perfect competition is superior to a standards approach. Baumol and Oates (1975), Buchanan and Tullock (1975), and Maler (1974) all indicate that using pollution standards to attain Pareto efficiency is futile unless the output of the polluting industry is also controlled in a firm-specific way. Even when market imperfections exist, the tax approach has many virtues that could make it preferable to a standards approach to a pollution problem.[1]

Be that as it may, the U.S. Environmental Protection Agency is committed to the standards approach. Therefore, it is of theoretical and practical interest to consider what the nature of "relatively efficient" standards are in contrast to the relatively inefficient ones. Our concern will be to compare the efficiency of the firm's choice of input combinations when faced with different types of pollution standards. We will not concern ourselves with the determination of the relatively efficient level of such standards.[2]

Many authors have assumed that the pollution standard consists of an absolute limitation of the amount of pollutant a firm or industry can emit.[3] An examination of some actual pollution standards indicates that they are virtually always relative standards, i.e., the limitation on pollution is made relative to some variable which reflects the scale of operations of the firm. In many cases, standards are essentially maximum pollution to output ratios. However, there are examples in which the allowed level of pollution is made proportional to the level of some input. Furthermore, since the legislation authorizing effluent standards for water pollutants is replete with requirements for the EPA to determine the "best practicable technology" or the "best available technology" for pollution control,

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*Associate Professor, Cleveland State University, 1983 East 24th Street, Cleveland, Ohio 44115.

**Graduate Student, SUNY, Albany.

[1] The tax approach automatically ensures that pollution is always eliminated at least cost as long as firms know their own costs of pollution control, whereas achievement of this goal by a standards approach requires that the Pollution Control Authority know the pollution reduction cost schedules of all firms. Additionally, pollution taxes can be used as substitutes for taxes on consumption, and labor and capital income, which generally cause inefficiencies.

[2] In this regard, Harford and Ogura (1981) have examined the efficiency condition for a pollution to output ratio standard under conditions of perfect competition. Appropriately arranged this condition is

$$MC = MD/(1 - ((MD)w\epsilon/P)), \qquad \text{(i)}$$

where MC is the marginal cost of pollution reduction, MD is the marginal damage of pollution, "w" is the ratio of pollution to output, P is the price of output, and ϵ is the (positive) elasticity of demand for the output. The practical implications of this result are that the marginal cost of pollution reduction should exceed the marginal damage of pollution as those concepts are conveniently measured, and that the optimal pollution standard depends upon the elasticity of demand for the output of the polluting industry.

[3] For example, the use of the concept of an absolute pollution standard for purposes of analyses has been done by Kneese and Bower (1968), and Harford (1978).

one may also suspect that standards are sometimes being set implicitly in the form of a required amount of pollution control capital per unit of output or per unit of an input. These types of standards do not exhaust the types that can or do exist, but this list illustrates that the term "standard" has been applied to a variety of types of pollution controls. Since these controls do not all have the same effect on resource allocation, it is worthwhile to consider how they differ in their effect on the choices of the firm and on efficiency.

In order to examine the effects of different types of standards we must have a model of production and pollution generation. However, several models might be suggested. A model of production and pollution often used consists of treating pollution as an input into production. This approach has the virtue of convenience, but fails to allow an explicit role for the treatment of pollution and any associated inputs into pollution treatment. An alternative approach is to treat pollution as a by-product of the production process. Here, pollution may either be a by-product of output itself, or a by-product of a "dirty" input. In either of these cases, one may assume that there exists a pollution generation function which is a positive function of the cause of pollution (output or input) and a negative function of a pollution treatment input(s). This approach allows consideration of pollution capital requirement types of standards, something not possible in a model which treats pollution simply as an input. Accordingly, we explicitly examine several of the types of pollution standards we have mentioned in the context of two models: a pollution as input model (Model I), a pollution as a by-product of a "dirty" input model (Model II). We also briefly discuss the nature of results in the context of the model in which pollution is a by-product of output.

Throughout our discussion we shall assume that firms minimize costs subject to output and pollution standard constraints. Our discussion of the efficiency of various standards will be based upon the presumption that, for given levels of output and pollution, it is efficient for the firm to have minimum input costs. This is the basis for our conclusion that pollution to output standards are generally superior to other types of standards regardless of the model of production and pollution generation used. We wish to concede, however, that if the costs of monitoring are greater for a pollution to output standard than for some other standard, then the superiority of the output ratio standard may not remain. It is of interest to note that high monitoring costs can be due to the difficulty of measuring output as well as pollution, since both quantities must be measured to determine if an output-ratio pollution standard is being complied with.

In the next section, we offer some examples to support our contention that there are many actual standards that are different from the pollution to output ratio kind. In section III we use the model of pollution-as-an-input to compare absolute pollution standards with a pollution to output standard before comparing the latter with a pollution to input ratio standard within the same model. In section IV compare pollution to output, pollution to input, pollution capital to output, and pollution capital to input standards in a model in which pollution is a by-product of a dirty input. In section V we discuss some evidence regarding the empirical importance of the different types of inefficiency that may result from poorly set standards. A final section touches on the pollution as by-product of output model, and discusses some of the implications of the analytical results.

II. Types of Actual Standards

An examination of federal water pollution standards indicates that a number of different methods are employed. A casual examination of water pollution standards in a number of industries indicates that a standard set in terms of the weight of pollutant relative to the weight of output is a very common approach. In so far as weight is a good measure of the quantity of output and pollutant, this type of standard can be termed an output-ratio standard. For the pulp paper industry, for example, one finds that the allowed biochemical oxygen demand and total settleable solids are in terms of kilograms of pollutant per thousand kilograms of product.[4]

However, when output cannot be meaningfully measured in terms of pounds, other approaches are used. In the case of photographic point sources, where film processing is the basic activity, the standards consist of allowed amounts (in kilograms) of silver and cyanides per square meter of photographic material processed. Although this approach may approximate a pollution to output standard, one could argue that different types of photographic outputs are being lumped together without proper weighting as to value. The difficulty of defining something that approximates an output ratio standard becomes more severe in an industry such as hospitals. Here the allowed levels of biochemical oxygen demand and the weight of total settleable solids are proportional to the number of occupied hospital beds.[5] Clearly, one could argue that hospital beds are merely an input into the production of a complex output called hospital care. In this case, the difficulty of defining and monitoring hospital *output* caused the EPA to resort to an input ratio standard.

Air pollution standards also offer some interesting deviations from an output-ratio type of standard. Baumol and Oates (1979, pp. 342–3) report standards for the allowed level of sulfur dioxide from power plants burning fossil fuels that tie the level of pollutant to the amount used of the particular fuel, not the output measure of electricity actually generated. Since this is a case where the pollution is a by-product of the use of the "dirty" input, fossil fuel, the EPA may feel it is appropriate to set the standard this way. However, there would seem to be no great difficulty in using an output-ratio standard in this case.

Lastly, emission standards for automobiles offer an interesting case. These standards allow specific amounts of hydrocarbons, nitrous oxides, and carbon monoxide for each mile driven.[6] If an automobile were a standardized product and every car were driven the same number of miles with the same number of passengers, then these standards would no doubt be of the output-ratio type. However, none of those suppositions hold, and the existing automobile emission standards must be considered something different from output-ratio standards. A more accurate description of the appropriate output (rather than automobile-miles) would be quality adjusted passenger miles, where the quality of each passenger's ride depends on such things as comfort and safety. In this case true output ratio standard would set allowed amounts of pollutants per quality adjusted passenger mile.

Of course, such a standard would be extremely difficult to create and monitor, since it requires large amounts of information about car use and knowledge of many of its attributes. Nevertheless, the foregoing discussion could lend support to a proposal to allow more pollutants per mile for autos that can carry more passengers if it is believed that greater capacity is correlated with a greater average number of passengers. The present form of automobile pollution standards might be described as an input ratio standard, where the auto is considered an input into the production of quality adjusted passenger miles. On the other hand, the use of catalytic converters

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[4] Volume 40, Code of Federal Regulations, Section 430.

[5] For photographic processing, the source is Volume 40, Code of Federal Regulations, Section 459. For hospitals, Ibid., Section 460.

[6] The history and exact nature of the automobile pollution standards are discussed by E. P. Seskin in Chapter 3 of Portney (1978).

in conjunction with unleaded gasoline is virtually a technical mandate from the viewpoint of the automobile purchaser, so that an interpretation based upon required levels of pollution control inputs is not totally without basis.

These examples indicate that actual standards do vary in type. In the following sections we show, all other things being the same, that no type of standard is superior to the output ratio type and that most are less efficient.

III. Standards with Pollution as a Production Input

Throughout our formal discussion, we shall assume that the welfare of society depends directly only upon the quantities of output and pollution produced by the firm. This implies that welfare is maximized if firms minimize their input costs subject to output and pollution constraints, assuming that input prices are determined in perfectly competitive markets. The desirability of attaining minimum input costs subject to the constraints is independent of the state of competition in the output market, although other government regulations could create biases that would change our conclusion.[7]

To begin our analysis, let us assume that output (Q) is produced in a process involving capital (K), labor (L), and pollution (z) as inputs. Mathematically, we assume,

$$Q = F(K,L,z). \tag{1}$$

This is the production and pollution relationship we shall call Model I.

The firm is assumed to face the price r for capital and price v for labor. The costs of the firm are defined to be

$$C = rK + vL. \tag{2}$$

Suppose the firm faces an absolute pollution standard in which the level of pollution used in production cannot exceed the value z_o. If the firm minimizes its costs for a given output subject to the constraint on pollution, one obtains the familiar condition

$$v/r = F_L/F_K. \tag{3}$$

For purposes of comparison, suppose now that the firm is faced with a standard that makes the allowed level of pollution proportional to the output of the firm. In mathematical terms, the Pollution Control Authority (PCA) imposes the constraint

$$z = wQ, \tag{4}$$

where w represents the constraint output ratio standard.

If one substitutes (wQ) for z in the production function and again determines the cost minimizing conditions for K and L, an equation of the same form as (3) obtains. The only difference in the capital to labor ratio that could occur is due to differences in the constrained value of output or pollution, and even this would not matter for some production functions. Thus, for given output and pollution levels, exactly the same input usage occurs with an absolute standard as with a pollution to output ratio standard. Both standards are therefore relatively efficient under restrictive assumptions.

However, there is a difference of some significance between the two standards. The absolute standard tends to create diseconomies of scale in the production process. This proposition is fairly straightforward. If $F(K,L,z)$ exhibits constant returns to scale, then the constraint $z = z_o$ yields a production function in which only capital and labor can be varied. Clearly, doubling capital and labor alone will not double output as long as isoquants are convex. Thus the production function would exhibit decreasing returns to scale in the inputs the firm could vary.

The output ratio standard, on the other hand, will not cause diseconomies of scale where none existed before. If the production function has constant returns to scale, then doubling all inputs will double output. Since pollution is one of the inputs, the ratio of pollution to output will not be changed by changes in the scale of production. In terms of the cost functions, this implies that a pollution to output standard will not change the output level at which a U-shaped average cost curve is at its minimum, although it will presumably shift the curve up above the level it would have in the absence of any pollution standard.[8]

However, there is a tendency for an output ratio standard to exaggerate whatever economies or diseconomies of scale exist in the original unconstrained (homothetic) production function. If output more than doubles when all inputs are doubled, the pollution to output ratio will fall. Since the allowed ratio of pollution to output is presumed to be fixed, doubling capital and labor will allow the firm to more than double pollution. Since pollution has no private cost, the firm's unit cost falls relatively more rapidly than otherwise. Just the opposite effect occurs when diseconomies of scale exist. Pollution is not allowed to increase as rapidly as other inputs because output increases less than proportionately with all inputs.

The PCA may decide to impose a pollution standard limiting the ratio of pollution to the input of labor instead of limiting the pollution to output ratio. In this case, the firm would face the constraint,

$$z = yL \tag{5}$$

where y is a constant. If the firm minimizes its costs subject to an output constraint and the pollution to labor ratio, one finds that the capital to labor ratio is determined by the equation indicated in Table I for the "y" standard. This equation indicates that the ratio of input prices for labor and capital will equal the ratio of the marginal products of labor and capital plus a term equalling the ratio of the marginal products of pollution and capital multiplied by the allowed ratio of pollution to labor. For given levels of output and pollution, diminishing marginal productivity of each factor implies that the cost minimizing capital to labor ratio is lower for a firm facing the pollution to labor standard (y), than for one facing the pollution to output standard (w). The intuitive reason for this result is that greater use of labor under the input ratio standard allows a bonus of a larger allowance of the free input of pollution, an effect absent under the pollution to output standard.

Given our framework, it must be true that the pollution to labor standard is relatively inefficient. However, since the attraction of an input ratio standard may be lower monitoring costs, one would like to know the extent of the input efficiency that is created. This is an empirical question, but some feel for the possibilities can be gleaned from an example. Accordingly, we have calculated the cost function under both types of ratio standards under the assumption that the production function is of the Cobb-Douglas form and exhibits constant returns to scale. Holding out-

TABLE I
(MODEL I)[a]

Standard	Cost Minimizing Condition
$w = (z/Q)$	$(v/r) = (F_L/F_K)$
$y = (z/L)$	$(v/r) = (F_L/F_K) + (F_z y)/F_K$

[a] All symbols are defined in the text.

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[7] It is well known that rate of return regulation tends to create a capital using bias in the firm's input decisions. Under these circumstances, a pollution standard that created an incentive to use relatively more non-capital inputs might be preferable to one which was neutral.

[8] In an uncertain world, the PCA might find that an absolute standard had some advantages over a relative standard. This is the case when uncertainty over pollution damages, stemming from uncertainty regarding total pollution levels, will lower expected welfare more than uncertainty over pollution control costs.

put and pollution constant, calculations reveal that the cost of the distortion created by an input ratio standard is greater the larger the exponent on the pollution input, and the smaller is the exponent on the input to which the allowed level of pollution is tied (labor in this case). Thus, at least for the Cobb-Douglas case, if one uses an input ratio standard under the circumstances of Model I, it is better to tie the allowed level of pollution to an input which represents a relatively large fraction of total costs, all else the same.[9]

IV. Pollution as a By-Product of a "Dirty" Input

We now wish to explore a second model of pollution generation (Model II), where pollution is a by-product of a dirty input. This model might be considered more realistic than the previous one in as much as it describes the many situations in which the burning of a fossil fuel to produce heat, electricity, or power for the operation of a machine leads to pollutants which can be directly related to the use of the fuel.

To avoid confusion with the previous model we define the production relationship of Model II as

$$Q = G(K_1, E), \tag{6}$$

where K_1 is *production capital* and E is the fuel or *dirty input*. Pollution is, accordingly, a positive function of fuel and a negative function of K_2, pollution control capital. This function and our assumptions regarding it can be summarized mathematically,

$$z = H(E, K_2), \tag{7}$$

$$H_E > 0;\ H_{K_2} < 0;\ H_{K_2K_2} > 0;$$
$$H_{EE} > 0 \text{ for } K_2 > 0. \tag{8}$$

For a given output the firm's objective is to minimize its costs, subject to the pollution control constraint, the pollution generation function, and the production function.

Retaining the symbols v for the price of the non-capital input and r for the price of capital, and eliminating Lagrange multipliers, the necessary condition for satisfying the firm's objective function under various types of standards are listed in Table II. For the pollution to output-ratio standard (w), the ratio of input prices will be set equal to the ratio of the marginal products of fuel and production capital plus the ratio of the "marginal pollution products" of fuel and pollution control capital. As the last line of Table II indicates, a lack of any pollution standard implies $K_2 = 0$, the ratio of the marginal products of fuel and capital are equated to the ratio of the input prices. With declining marginal productivity of fuel and capital, the fact that fuel is a dirty input ($H_E > 0$) implies that relatively less fuel should be used in an efficient situation than would be chosen in the absence of a standard. The greater use of pollution control capital is an additional necessary adjustment to the "dirtiness" of fuel, and not usually a perfect substitute for the reduction in the fuel to production capital ratio.

When the pollution standard is in the form of an allowed ratio of pollution to fuel ($y_2 = (z/E)$) the ratio of input prices equals an expression which differs from the "w" standard by the subtraction of a term equal to the ratio of the pollution-fuel standard to the marginal pollution product of control capital. (See the second line of Table II.)

TABLE II[b]
(MODEL II)

Standard	Cost Minimizing Condition
$w = (z/Q)$	$(v/r) = (G_E/G_{K_1}) + (H_E/H_{K_2})$
$y_2 = (z/E)$	$(v/r) = (G_E/G_{K_1}) + (H_E - y_2)/H_{K_2}$
$e = (K_2/E)$	$(v/r) = (G_E/G_{K_1}) + (H_E - y_2)/H_{K_2}$
$u = (K_2/Q)$	$(v/r) = (G_E/G_{K_1})$
none ($K_2 = 0$)	$(v/r) = (G_E/G_{K_1})$

[b]All symbols are defined in the text.

Since there are three inputs, comparisons of the input choices of the firm under the w and y_2 standards are potentially ambiguous. However, holding output and total pollution constant, it is known that

$$dK_1/dE = -(G_E/G_{K_1}) < 0, \text{ and} \tag{9a}$$

$$dK_2/dE = -(H_E/H_{K_2}) > 0. \tag{9b}$$

It follows that an increase in fuel for a given output and pollution implies a decrease in production capital and an increase in pollution capital. Furthermore, any production function with negatively sloped isoquants which are convex to the origin, and a pollution generation function with convex isopollution curves ($d^2K_2/dE^2 > 0$), implies that $E^{w*} < E^{Y*}$, where the superscripts denote the chosen values of fuel under the "w" and "y" standards, respectively, with output and pollution held constant.[10] Accordingly, production capital will be greater and pollution capital will be smaller under the output ratio standard than under an input ratio standard that yields the same pollution for a given output. Obviously, allowing pollution to increase with increases in the use of the "dirty" input of fuel creates less disincentive to use fuel than a pollution to output ratio standard.

Suppose, for reasons relating to monitoring costs, that the PCA decides to deal with the pollution problem by requiring certain amounts of pollution control capital. Two conceivable ways of doing this are to set a required ratio of pollution control capital to output or to fix the ratio of pollution control capital to the amount of the "dirty" input. Addressing the latter first, assume that the firm faces the constraint

$$e = K_2/E, \tag{10}$$

where e is constant.

By substitution, we find that

$$z = H(E, eE), \text{ or } z/E = H(E, eE)/E \tag{11}$$

Given the substitutions used in (11), if the pollution to fuel ratio is a constant, then the use of a pollution capital to fuel ratio is equivalent to the use of a pollution to fuel ratio standard. Therefore, if the pollution

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[9]Mathematically, the specific production function is

$$Q = K^{\alpha}L^{\beta}z^{\mu}, \tag{ii}$$

where $\alpha + \beta + \mu = 1$.

By expressing the cost function of the firm under the input ratio standard as $C(y)$, and the cost function under the output ratio standard as $C(w)$, and further assuming that total pollution is the same for both standards ($yL = wQ$), one can show that

$$C^{yw} = C(y)/C(w)$$
$$= (\beta/(\beta + \mu))^{\beta/(\alpha+\beta)}(1/(\alpha + \beta)). \tag{iii}$$

As extreme examples, $C^{yw} = 1.667$ for $\alpha = .1$, $\beta = .1$; and $C^{yw} = 1.001$ for $\alpha = .1$, $\beta = .8$.

[10]To prove $E^{y*} > E^{w*}$, we first introduce the superscripts w and y on all concepts related to the respective standards. From the first order conditions in Table II, we know that

$$(G^y_E/G^y_{K_1}) - (G^w_E/G^w_{K_1})$$
$$= (H^y_E/H^y_{K_2}) - (H^w_E/H^w_{K_2}) - (y/H^y_{K_2}). \tag{iv}$$

Due to our assumptions, we also know that (E^{w*}, K_2^{w*}) and (E^{y*}, K_2^{y*}) are on the same isopollution curve. We assume further that the production isoquants are convex and that $d^2K_2/dE^2 > 0$ for the function $K_2(E)$ representing an isopollution curve.

Contrary to our hypothesis, let us assume that $K_2^{y*} \leqq K_2^{w*}$. It follows that $E^{y*} < E^{w*}$, and from this that $K_1^{w*} \leqq K_1^{y*}$. From convex isoquants it follows that

$$(G^w_E/\mathrm{G}^w_{K_1}) - (G^y_E/G^y_K) \leqq 0 \tag{v}$$

Since $-y/H^y_K > 0$, we have the further implication that

$$-(H^y_E/H^y_{K_2}) > -(H^w_E/H^w_{K_2}) \tag{vi}$$

Inequality (vi) implies that the slope of the isopollution curve is larger for the y standard. Given that we assume $d^2K_2/dE^2 > 0$, this implies that $K_2^{y*} > K_2^{w*}$, contrary to our initial assumption. This last result indicates that $K_2^{y*} > K_2^{w*}$ and $E^{y*} > E^{w*}$ are the correct conditions.

generation function exhibits constant returns to scale, when e and y_2 are appropriately set they will have precisely the same effect on the firm's input choices and on efficiency. This result is indicated in Table II by the identical cost minimizing conditions for both standards.

If the pollution generation function exhibits increasing returns to scale in the sense that doubling pollution capital and fuel leads to *less* than twice as much pollution, then, assuming that the y_2 and e controls yield the same costs, output, and pollution for the average firm, firms of above average output and input use will need relatively less pollution capital to satisfy the input ratio type of standard than the pollution capital to input standard. Conversely, firms with below average output and use of inputs will be in the opposite position. However, as a practical matter, there are usually several inputs into pollution reduction, and imitation of the effects of a production input ratio standard by the use of pollution control input standards would require a separate standard for every input into the pollution control process. This would tend to destroy whatever advantage such standards might have in not requiring a measure of pollution.

Consider now the input choices of a firm facing a standard which determines how much pollution control capital the firm must employ in proportion to the level of output. Specifically, the firm is assumed to face the constraint

$$u = (K_2/Q), \qquad (12)$$

where u is a constant. If the firm pursues cost minimization for given output under this constraint, as indicated in Table II, the ratio of the input prices will ultimately equal the ratio of the marginal products of the two production inputs.

The level of pollution is determined by the firm's choice of the level of fuel and the pollution capital required to satisfy the pollution capital to output constraint. Clearly, the firm over-utilizes the fuel input in this situation. In this respect, the firm's choice of fuel and production capital is no different from a situation in which there are no standards. However, the required pollution capital does reduce pollution below the level existing without any standard by the amount

$$z_e = H(E_0, 0) - H(E_0, uQ_0), \qquad (13)$$

where E_0 represents the use of fuel in producing output Q_0 in the absence of any standards.

V. Empirical Significance of Model II

Empirical estimates of the cost of relatively inefficient forms of pollution standards for the steel industry of the Chicago-Gary region have been made by Thomas (1980). Although details of the Thomas approach differ from those of our Model II, he does base his analysis on a model of production which includes a "dirty" fuel input and a separate function to describe the level of pollution as function of fuel use and pollution control inputs. His production and pollution generation functions were based upon assumptions regarding specific functional forms and empirically based estimates of the relevant parameters. His analysis examines how costly it is for a firm to attain a given pollution control level when faced with different types of standards.

Thomas examined the relative costs of a prototype firm of attaining a 90 percent reduction in particulate levels under different types of standards. Using a direct limitation on the amount of pollution as the "efficient" baseline, it was found that a standard requiring specific amounts of pollution control inputs cost 30 percent more. Furthermore, a standard based on relating the allowed amount of pollution to the amount of fuel used in production (a standard which has actually been

in effect in Illinois) cost 40 percent more than the simple limitation on total pollution. If these figures are representative, it is clear that the distortion in input usage caused by other than output-ratio or absolute standards can be the source of significant inefficiencies.

Although Thomas' paper indicates that inefficiency related to input use can be significant, one may wonder whether the inefficiency created by standards that fail to equate the marginal cost of pollution reduction across different polluters is more serious.[11] Baumol and Oates (1979; 266–67) discuss a study by Bingham and Miedema (1974), performed for the U.S. Environmental Protection Agency, which compared the costs of pollution control associated with emission charges and standards for a given reduction in sulfur emissions in the cities of St. Louis and Cleveland. The cited study found that the existing program of standards would cost approximately 50 percent more than the emission tax approach to achieve the same level of pollution control in the two cities.

Baumol and Oates attribute the extra costs of standards to the variation in the marginal costs of pollution control across firms, a problem that should be absent with the tax. However, any emissions tax would also tend to eliminate inefficiency due to distorted input use that would occur with other than output-ratio standards. Although the Bingham-Miedema study may involve only the interfirm misallocation of pollution control, the increased efficiency provided by a pollution tax can flow partly from the elimination of intra-firm (input) inefficiency. In any case, a comparison of the Thomas estimates with those of Bingham and Miedema indicates that the potential for inefficiency from distorted input use is not necessarily small compared to that stemming from interfirm differences in marginal control cost.

One would expect an interaction between the two potential sources of inefficiency in standard setting. Although space precludes presenting the supporting derivations, the marginal cost of pollution reduction via the use of changes in an output-ratio standard has a different functional form than the marginal cost of pollution reduction achieved by the use of changes in an input-ratio standard. Specifically, it can be shown that for cost minimizing firms with Model II technology, the marginal cost of pollution control under output-ratio and input-ratio standards will be, respectively,[12]

$$-C_z(w) = r/H_{K_2}; \qquad (14a)$$

$$-C_z(y) = r/(H_{K_2}(1 + \theta)), \qquad (14b)$$

where

$$\theta \equiv (\partial E^*/\partial y)(y/E^*). \qquad (14c)$$

Conceivably, there could be interfirm differences in marginal cost of pollution control that would be caused by differences in the type of standard they faced rather than by any difference in the underlying technology of pollution control or the "stringency" of the standard. In such a case, overall efficiency is likely to be improved more by changing the *type* of standard that one of the firms faces than by adjusting the stringency of either firm's standard. However, further implications of a mixed system of standard "types" will have to be addressed another time.

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[11] Harford (1982) has shown that equating the marginal costs of pollution control across firms when standards are being set is not generally efficient when the composition of output can be affected by the stringency of a (pollution to output) ratio standard.

[12] The derivation of equations (14a, b) proceeds by the method of totally differentiating the cost function and substituting appropriately from the first order conditions and from the totally differentiated production and pollution generation functions. Details will be provided upon request.

VI. Other Models and Conclusions

Specifications for Model III would depart from Model II by making pollution generation a function of *output* and pollution control capital. Using such a model, the cost minimizing conditions for the firm under output-ratio and input-ratio standards indicate that the firm would use inefficiently large amounts of the input to which the use of pollution is tied. Thus, the inefficiency of input-ratio standards is not tied to the specific nature of Model II. The results with Model III do differ from Model II, however. Requiring pollution capital to be in proportion to an input does not produce the same results as an output-ratio standard. Conversely, requiring pollution capital in proportion to output can (in principle) mimic the effects of an output-ratio standard within Model III.

The fundamental contention of this paper is that an output-ratio standard is generally more efficient, *ceteris paribus*, than other forms of standards due because it does not distort input use. Even an output-ratio standard can be highly inefficient if the allocation of pollution reduction across firms is inefficient. In this regard, it may be noted that a standard requiring all firms to reduce pollution by a given percentage would be relatively efficient with regard to a firm's input usage, although it might be highly inefficient from the viewpoint of allocating pollution control responsibility among firms. We have noted that the input inefficiency caused by input-ratio standards may not be small in comparison with the interfirm misallocation of pollution control efforts.

The difficulty of monitoring an output-ratio standard relative to some other standard may be the reason why it is not used by a pollution control agency. An ironic aspect of this is that it may be the difficulty of measuring output as much as pollution which disallows the output-ratio standard. If one could measure the differences in monitoring and/or measurement costs between standards, then a cost-benefit analysis could be performed to identify which standards are most appropriate.

Finally, we note that proper measurement of the costs of pollution control depends on which standard is used with which model. If pollution is a by-product of output (Model III) and an output-ratio standard is used, then the costs of pollution control can be accurately measured by the cost of pollution control inputs. But if an input-ratio standard is used, we must add the increased costs associated with the inefficient choice of production inputs to the direct cost of pollution control inputs in order to determine the total costs of pollution control. If pollution is a by-product of a production input (Model II), then both output ratio and input ratio standards will affect the choice of production inputs for a given output. This implies that the total costs of pollution control will be the sum of the cost of pollution control inputs and the increase in the cost of production inputs for a given output.

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