Sources of Emission Changes:
A Joint Production Perspective of Existing Decomposition Models

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ABSTRACT

This study investigates previous models that analyze the relative importance of factors associated with changes in emissions of air pollutants. Specifying a model of the joint production of good and bad outputs allows us to analyze changes in production of the bad output associated with the bad output not being freely disposable, changes in technical efficiency, technical change, input growth, and changes in the mix of good and bad outputs. The less restrictive specification of the joint production technology allows a more accurate depiction of the relative importance of the factors associated with changes in production of the bad output. It is determined that when pollution abatement activities other than fuel switching exist, previous models of the factors associated with changes in emissions produce biased results.

I. Introduction

The passage of environmental legislation in the United States prompted studies of both the effects of environmental regulations on economic growth (see Jaffe, Peterson, Portney, and Stavins, 1995) and the factors associated with changes in emissions of pollutants. One measure of the effectiveness of environmental regulations is observing changes in emissions of pollutants generated by a producer. However, factors other than environmental regulations influence the production of emissions. For example, an expanding industry produces more emissions if it produces emissions and its marketed good output in fixed proportions. As a result, simply observing changes in emissions does not accurately measure regulatory intensity.

Although previous decomposition models analyze the relative importance of the factors associated with changes in emissions in a manner similar to growth accounting models that determine the sources of change in the production of marketed output, there has been no explicit consideration of the underlying production technology. By specifying a model of the joint production of the good output (i.e., the marketed output) and the bad output (i.e., emissions), this study analyzes the implicit assumptions underlying previous decomposition models.

Models employed in previous studies assumed the only available pollution abatement activities consist of substituting among energy inputs (e.g., substituting low for high sulfur coal or substituting natural gas for coal) or substituting non-energy inputs for energy inputs. Unlike previous decomposition models, this study explicitly models the technology in which good and bad outputs are jointly produced and pollution abatement activities in addition to those involving energy inputs exist. As a result, the technology specified in this study permits a more accurate picture of changes in production of the bad output resulting from changes in the amount of the bad output produced per unit of the good output (i.e., emission intensity or output mix) by the technology. Specifying the joint production of good and bad outputs allows an analysis of changes in production of the bad output associated with technical change, changes in technical efficiency and regulatory intensity, and input growth of an industry. The joint production model also allows us to determine the reduced production of the bad output when a producer is not allowed to freely dispose of it.

This study provides a framework for assessing previous decomposition models of the factors associated with changes in production of the bad output. The remainder of this study is organized in the following manner. Section II discusses the theoretical basis of the decomposition models used by previous studies to investigate the factors associated with changes in production of the bad output. Section III specifies a joint production decomposition model and Section IV uses the joint production model to analyze previous decomposition models. Finally, Section V summarizes the study and discusses its implications for future research.

II. Previous Decomposition Models

This section compares and contrasts two frameworks currently used to estimate the relative importance of the factors associated with changes in the emissions of pollutants.[1] Although the two approaches have evolved independently, they have many features in common. First, the time series decomposition (TSD) model is discussed and then linked to the structural decomposition analysis (SDA) model.[2]

When determining the relative importance of the factors associated with changes in emissions, the TSD model starts with the following identity relating emissions to factors associated with the production of emissions (see Lin and Chang 1996, p. 3):

$$Q_{hjt} = U_{hijt} \times M_{ijt} \times I_{jt} \times S_{jt} \times G_t \qquad (1)$$

where

Q_{hjt} = quantity of pollutant h from total energy consumed by industry j in year t

U_{hijt} = pollution coefficient of pollutant h from fuel type i consumed by industry j in year t

M_{ijt} = share of fuel type i consumed by industry j in year t (the percentage of BTUs used by industry j which are accounted of by fuel type i

I_{jt} = energy intensity of industry j in year t (BTUs per dollar of output of industry j)

S_{jt} = share of total output of economy produced by industry j in year t

G_t = output of economy (GDP in year t)

Using a simple average Divisia index, Lin and Chang derived an expression for the change in emissions being determined by changes in the factors listed in equation (1) (see Ang, 1999, for a review of the literature).

A variation of the TSD model can be found when CGE models are used to decompose the importance of factors associated with changes in emissions (see Stutt and Anderson 2000). Stutt and Anderson (2000) use a Laspeyres approach when decomposing the factors associated with changes in carbon, nitrogen, and sulfur emissions. While TSD models use historical data to investigate the factors associated with changes in emissions, the CGE decomposition models compare the factors associated with changes in emissions between a base case and a counter-factual simulation.

When the SDA model is used to investigate the factors associated with changes in emissions, they are incorporated into a open, static input-output model (see Rose, 1999, for a review of the literature). The following discussion of the SDA model follows Lee (1990) and Lee and Schluter (1993). Equation (2) specifies the traditional input-output relationship regarding the uses of the gross output of each industry where

$$q_i = FD_i + W_i + EX_i - IM_i \tag{2}$$

q_i = gross output of industry i

FD_i = domestic final demand of industry i

W_i = intermediate input demand of output of industry i

EX_i = exports of industry i

IM_i = imports of industry i

Equation (2) can be rewritten in matrix form as:

$$q = Y\bar{y} + Aq + E\bar{e} - M(Y\bar{y} + Aq) \tag{3}$$

where q is the vector of gross output, Y is the vector of the composition of domestic final demand by industry, $\bar{y}$ is a scalar of the level of domestic final demand (consumption + investment + government spending), and A is the input-output coefficient matrix. Intermediate input demand, W, (i.e., Aq). E is the vector of the composition of exports by industry, $\bar{e}$ is a scalar of the level of exports, and M is a diagonal matrix whose elements are the ratio of imports to total domestic demand (intermediate input demand plus domestic final demand).[3] Imports are used to satisfy both domestic final demand $(MY\bar{y})$ and intermediate input demand (MAq).

Equation (3) can be rewritten as equation (4) which shows that the total (gross) output for each industry of the economy is equal to the amount of output consumed at home (intermediate inputs and domestic final demand supplied by domestic production) plus the amount of exports:[4]

$$q = (I - M)(Aq + Y\bar{y}) + E\bar{e} \tag{4}$$

where I is the identity matrix.

The vector of gross output required to produce a matrix of domestic final demand and exports is obtained by solving equation (4) for q:

$$q = [I - \mu A]^{-1}\,(\mu Y\bar{y} + E\bar{e}) \tag{5}$$

where $\mu = I - M$ is the diagonal matrix of domestic content (supply) ratios and μA represents the domestic input-output matrix. A change in imports affects gross output through changes in the domestic content ratios, μ. The vector of industry output in equation (5) is equal to the product of two of the components of equation (1) (see Meyer and Stahmer, 1989, for the initial statement of this link) :

$$q = [I - \mu A]^{-1}\,(\mu Y\bar{y} + E\bar{e}) = S_j \times G \tag{5'}$$

The next phase in investigating the factors associated with emissions is formally introducing emissions into the SDA model. Emissions of air pollutants are produced by processes and fuel combustion. It is assumed that process emissions are related to output through a vector of emission factors (emissions from processes per unit of good output produced), ω_p. Fuel combustion emissions are the product of fuel emission factors, the energy intensity of an industry, and the combination of fuels consumed by an industry, $\omega_F N_I F$. Substituting equation (5') into equation (1) and allowing emissions to be linked to both fuel combustion and gross output yields the following expression relating emissions to factors associated with the production of emissions:[5]

$$(6) \qquad \varepsilon = (\omega_p + \omega_F N_I F)q = (\omega_p + \omega_F N_I F)[I - \mu A]^{-1}(\mu Y\bar{y} + E\bar{e})$$

where

ε = a matrix of emissions by industry

ω_p = process emission factor

ω_F = fuel combustion emission factors (i.e., emission per Btu for each type of fuel)

N_I = energy intensity of an industry (i.e., total fuel consumed for heat and energy, in terms of Btu, per dollar of output in each industry)

F = industry fuel combination (i.e., percentage contribution of each fuel type to the fuel usage, in terms of Btu, for each industry)

Following Lee (1990) and Lee and Schluter (1993), taking the total derivative of equation (6) yields the following expression:

$$\begin{aligned}(7) \quad d\varepsilon = {} & (\omega_p + \omega_F N_I F)[I - \mu A]^{-1}(\partial\mu Y\bar{y} + \mu\partial Y\bar{y} + \mu Y\partial\bar{y} + \partial E\bar{e} + E\partial\bar{e}) \\ & + (\omega_p + \omega_F N_I F)\partial[I - \mu A]^{-1}(\mu Y\bar{y} + \partial E\bar{e}) \\ & + (\partial\omega_p + \partial\omega_F N_I F + \omega_F \partial N_I F + \omega_F N_I \partial F)[I - \mu A]^{-1}(\mu Y\bar{y} + \partial E\bar{e})\end{aligned}$$

The derivative of [I - μA]$^{-1}$ can be written as (see Lee and Schluter 1993, p. 667):

$$
\begin{aligned}
(8)\qquad \partial[I - \mu A]^{-1} &= -[I - \mu A]^{-1}(-\mu\partial A - \partial\mu A)[I - \mu A]^{-1} \\
&= [I - \mu A]^{-1}(\mu\partial A + \partial\mu A)[I - \mu A]^{-1}
\end{aligned}
$$

Substituting equation 8 into equation 7 yields

$$
\begin{aligned}
(9)\quad d\varepsilon = {} & (\omega_p + \omega_F N_I F)[I - \mu A]^{-1}(\partial\mu Y\overline{y} + \mu\partial Y\overline{y} + \mu Y\partial\overline{y} + \partial E\overline{e} + E\partial\overline{e}) \\
& + (\omega_p + \omega_F N_I F)[I - \mu A]^{-1}(\mu\partial A + \partial\mu A)[I - \mu A]^{-1}(\mu Y\overline{y} + \partial E\overline{e}) \\
& + (\partial\omega_p + \partial\omega_F N_I F + \omega_F \partial N_I F + \omega_F N_I \partial F)[I - \mu A]^{-1}(\mu Y\overline{y} + \partial E\overline{e})
\end{aligned}
$$

The terms can be rearranged and ten factors associated with changes in emissions are identified. These factors are derived in Appendix A, which is available from the authors on request.[6]

Changes in emissions associated with fuel consumption, changes in energy intensity, and changes in the proportion of fuels consumed are estimated by both the TSD and SDA models. In addition, both models measure the direct emission changes associated with changes in emissions per unit of fuel consumed.

The SDA model, equation (6), differs from the TSD model, equation (1), in two respects. First, equation (6) includes emissions produced by processes (e.g., particulate matter emissions from grain milling operations). If all emissions are produced by fuel combustion (i.e., ω_p is zero), then equation (6) is identical to equation (1). Second, the $S_j \times G$ term in equation (1) is equivalent to the vector of industry output, q, in equation (5). In equation (6), structural changes in the economy - the "S_j" term in equation (1) - are captured by changes in μ, A, Y and E.

Hence, the use of an input-output table by the SDA model (equation 6) permits a more detailed analysis of the factors associated with changes in emissions. One way to derive expressions based on equation (6) that are comparable to the effect of changes in GDP (G in equation (1)) on emissions, is to assume the percentage changes in $\overline{y}$ and $\overline{e}$ are identical to the percentage change in GDP, and μ, A, Y and E are constant. In this case, the TSD model (equation 1) estimates emission changes associated with changes in the GDP of an economy without structural change.

The SDA and TSD models both require data on emissions, energy consumption, and the proportion of fuels consumed by an industry; however, there are differences. In addition to information about emissions and energy consumption, an SDA model requires input-output coefficients and final demand vectors. As a result, SDA models analyze data from years in which benchmark input-output tables are compiled. In addition to information about emissions of pollutants and energy consumption, TSD models only require data on GDP and industry output. As a result, TSD models are implemented using annual data.

Two studies have used the TSD method and five studies have used the SDA method to calculate the relative importance of the factors associated with emission changes when pollution abatement activities in addition to those involving energy inputs exist.[7] Lin and Chang (1996) and Selden, Forrest, and Lockhart (1999) represent the two applications of the TSD model. Of the five SDA studies, Wier (1998, 1999) and deHann (2000) specified complete SDA models. Neither Leontief and Ford (1972) nor Meyer and Stahmer (1989) specified a complete SDA model. In addition to the studies surveyed in this section, both methodologies have been used to analyze the factors associated with changes in CO_2 emissions (see Ang, 1999, and Rose, 1999, for reviews of these studies).[8]

III. A Joint Production Model of Emission Changes

Two perspectives on incorporating emissions into production models have emerged in the literature. One view holds emissions are inputs, while the other view maintains they are bad outputs. If emissions are viewed as inputs, they serve as a proxy for use of the environment by a producer.[9] From this perspective, an increase (decrease) in the quantity of a pollutant emitted represents an increased (decreased) use of the purification services provided by the environment. In this case, each unit of pollutant emitted is assumed to use the same quantity of purification services regardless of where or when the emissions are produced. If this assumption is invalid, it is necessary to determine the quantity of purification services used by each unit of emissions. It would then be necessary to adjust the quantity of emissions by their use of environmental purification services. In order to avoid this difficulty, this study models emissions as bad outputs.

The joint production model specified in this section is a variation of growth accounting models used to calculate total factor productivity. Instead of estimating the relative importance of the factors associated with changes in the production of the good output, we investigate the relative importance of the factors associated with changes in the production of the bad output. To accomplish this, we specify production technologies, which model the joint production of good and bad outputs, based on two sets of assumptions - strong and weak disposability of the bad outputs. The strong disposability technology, which we will refer to as the unregulated technology, assumes the producer may freely dispose of the bad outputs it produces. If regulations exists throughout the period for which data are available, the strong disposability technology actually represents the least regulated technology. The weak disposbility technology, which we will refer to as the regulated technology, assumes the producer may *not* freely dispose of it bad outputs.

In this study, a "technology" refers to the set of processes available to a producer. Each process represents a fixed relationship, among inputs, the good output, and the bad output. Linear combinations of these processes can be employed by the producer.[10] The unregulated technology is formally specified as:

$$(10) \quad P^u(x) = \{(y^g, y^b): \begin{array}{ll} \sum_{k=1}^{K} z_k y^g_{km} \geq y^g_m & m = 1,\ldots,G \\ \sum_{k=1}^{K} z_k y^b_{ki} \leq y^b_i & i = 1,\ldots,B \\ \sum_{k=1}^{K} z_k x_{kn} \leq x_n & n = 1,\ldots,N \\ z_k \geq 0 & k = 1,\ldots,K\} \end{array}$$

and the regulated technology is:

$$
\begin{aligned}
(10)\quad P^{u}(x) = \{(y^{g}, y^{b}):\ & \sum_{k=1}^{K} z_k y_{km}^{g} \geq y_m^{g} \quad m = 1,\ldots,G \\
& \sum_{k=1}^{K} z_k y_{ki}^{b} = y_i^{b} \quad i = 1,\ldots,B \\
& \sum_{k=1}^{K} z_k x_{kn} \leq x_n \quad n = 1,\ldots,N \\
& z_k \geq 0 \quad k = 1,\ldots,K\}
\end{aligned}
$$

The characteristics of the regulated technology specified in this study include (1) increasing marginal abatement costs (for the regulated technology when there is more than one process) and (2) null-jointness (i.e., zero emissions only occur when none of the good output is produced).

The first constraint of (10) and (11) represents the constraint imposed on the good output. There is a separate constraint for each of the G good outputs of producer kN. The right-hand side of the constraint represents the actual production of the good outputs for producer kN.

The left-hand side represents the production of the good output of the theoretical efficient producer. The “greater than or equal to” sign imposes the restriction that the production of good outputs by the theoretical producer must be greater than or equal to the observed production of the good output of producer kN.

The second constraint of (10) and (11) represents the constraint imposed on the bad output. There is a separate constraint for each of the B bad outputs produced by producer kN. The equality sign associated with the constraint on the bad outputs imposes weak disposability on the bad outputs. The right-hand side of the constraint represents the observed generation of the bad outputs of producer kN. The left-hand side represents the level of the bad output generated by the theoretical efficient producer. The difference between the regulated and unregulated technologies are the constraints associated with bad outputs. The "equal to" sign imposes the assumption of weak disposability on the bad outputs. For the unregulated technology, the constraint is written as "less than or equal to."

The third constraint of (10) and (11) represents the constraint imposed on input use. There is a separate constraint for each of the N inputs employed by a producer. The right-hand side of the constraint represents the observed input use of producer kN. The left-hand side represents the inputs employed by the theoretical efficient producer. The inequality sign means the theoretical producer cannot employ more inputs than producer kN.

A non-negativity constraint is imposed on the z_k in (10 and (11). The z_k are the weights assigned to each of the available production processes when constructing the production frontier. Since the summation of the intensity parameters (i.e., the z_k) is not constrained, *constant returns to scale* is assumed for the technology.[11]

In addition to the regulated (equation 11) and unregulated (equation 10) technologies, which are based on observed inputs and outputs, there is also a hypothetical unregulated technology that would evolve in the absence of pollution abatement activities. This hypothetical technology would include levels of inputs that would have existed in the absence of environmental regulations. The allocation of R&D resources between pollution abatement activities and the production of the good output is the principal source of the decline in production of the good output by the observed unregulated technology relative to the hypothetical unregulated technology (see DeBoo, 1993).[12] The absence of pollution abatement activities associated with the hypothetical technology causes increased production of the good and bad outputs relative to what is produced by technologies developed after the imposition of environmental regulations. The difference in production of the bad outputs by the hypothetical and observed unregulated technologies constitutes the reduction in production of the bad output associated with environmental regulations that is unobserved (i.e., invisible) from the perspective of existing processes. Since this study does not specify the hypothetical unregulated technology, it does not estimate the invisible decrease in the production of the bad output.

Using a joint production framework, Färe and Grosskopf (1983) specified an output-based radial measure of technical efficiency using data envelopment analysis (DEA) that constrained a producer to the observed output mix. Hence, production occurs along the process ray passing through the observed production of good and bad outputs (i.e., the good and bad outputs are treated in a symmetric manner).[13] This study adopts the Färe and Grosskopf (1983) definition of technical efficiency which is the maximum proportional expansion of the good and bad outputs.

Although it is preferable to specify a decomposition procedure using a moving period reference technology, in order to simplify the discussion we assume the initial period represents the fixed reference technology (i.e., the Laspeyres method). As a result, in order to measure the change in production of bad outputs, we specify two different distance functions. The first output-based distance function is defined as:

$$(12) \quad D_o^t(x^t, y^t, b^t) = \inf\{\theta : (x^t, y^t/\theta, b^t/\theta) \in S^t\}$$

This distance function measures the reciprocal of the maximum expansion, θ, in the observed production of the good (y^t) output and bad (b^t) output with the technology (S^t), and inputs (x^t) available in period t. When $D_o^t(x^t, y^t, b^t) < 1$, the observation is technically inefficient, and $D_o^t(x^t, y^t, b^t) = 1$ indicates the observation is technically efficient. A similar expression can be derived for $D_o^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$.

In addition, a mixed period output distance function is defined as

$$(13) \quad D_o^{t+1}(x^{t+1}, y^t, b^t) = \inf\{\theta : (x^{t+1}, y^t/\theta, b^t/\theta) \in S^t\}$$

This distance function measures the reciprocal of the maximum change, θ, in the good and bad outputs required to make the inputs employed in period t+1 and the output mix of period t (i.e., (x^{t+1}, y^t, b^t)) feasible in relation to the technology available in period t+1.

Maximizing the expansion of the bad output, b^t, while maintaining a constant mix of bad to good outputs (i.e., b^t / y^t) is equivalent to maximizing expansion of the bad output, b^t, and good output, y^t. Since in any period the output mix is assumed to be fixed, an “emission production function” can be written with the bad output as the sole output. Obviously, the goal of production activities is not to produce bad outputs, which are the undesirable byproducts of producing the good output. However, an emission production function is a means of linking the joint production model with previous models that analyzed the relative importance of factors associated with changes in the production of bad outputs.

The remainder of this section is in two parts. First, we develop a model of the change in production of the bad output associated with its lack of free disposability. Existing decomposition models do not calculate this factor associated with changes in production of the bad output. Second, we use the joint production model to investigate the factors associated with changes in the observed production of the bad output.

The maximum production of the bad output in period t by the unregulated technology is determined by the state of the technology, the observed mix of good and bad outputs (R^t), and the available inputs, X^t. Therefore, the unregulated emission production function can be written as:[14]

$$(14)\quad B_u^t = f_u(X^t, R^t, t)$$

where B_u^t is the quantity of the bad output produced.

When production of the bad output is regulated, the maximum production of the bad output in period t is determined by the regulated technology, available inputs, and the observed output mix. The regulated emission production function can be written as

$$(15)\quad B_r^t = f_r(X^t, R^t, t)$$

where B_r^t is the quantity of the bad output produced and the observed output mix serves as the proxy for the intensity of environmental regulations.

In period t, the ratio of production of the bad output in unregulated and regulated environments is:

$$(16)\quad EMISSION^t = \frac{B_u^t}{B_r^t} = \frac{f_u(X^t, R^t, t)}{f_r(X^t, R^t, t)}$$

Hence, the decreased production of the bad output associated with its lack of free disposability is 1 - EMISSION^t. Since existing production processes are likely to include pollution abatement activities, B_u^t is less than the true unregulated production of the bad output. As a result, (16) understates the decline in production of the bad output associated with its lack of free disposability. Since a similar relationship exists for period t+1, the change in production of the bad output between periods t and t+1 resulting from its lack of free disposability is:

$$(17)\quad \Delta EMISSION_t^{t+1} = \frac{B_u^{t+1} / B_r^{t+1}}{B_u^t / B_r^t} = \frac{f_u(X^{t+1}, R^{t+1}, t+1) / f_r(X^{t+1}, R^{t+1}, t+1)}{f_u(X^t, R^t, t) / f_r(X^t, R^t, t)}$$

$$= \frac{B_u^{t+1} / B_u^t}{B_r^{t+1} / B_r^t} = \frac{f_u(X^{t+1}, R^{t+1}, t+1) / f_u(X^t, R^t, t)}{f_r(X^{t+1}, R^{t+1}, t+1) / f_r(X^t, R^t, t)}$$

The change in production of the bad output due to its lack of free disposability (i.e., changes in the distance between the unregulated and regulated frontiers) shown in (17) results from technical change, input growth, and changes in the output mix.[15]

In order to link the emission production functions and the distance functions, it is useful to express the distance function in terms of the production of the bad output and the regulated emission production function for period t:

$$
\begin{aligned}
(18)\quad & D_{or}^{t}(x^{t}, y^{t}, b^{t}) \\
& = \inf\left\{\theta : (b^{t}/\theta) \in P_{r}^{t}(x^{t})\right\} \\
& = \inf\left\{\theta : (b^{t}/\theta) \leq f_{r}(X^{t}, R^{t}, t))\right\} \\
& = \inf\left\{\theta : (b^{t}/f_{r}(X^{t}, R^{t}, t)) \leq \theta\right\} \\
& = b^{t}/f_{r}(X^{t}, R^{t}, t)
\end{aligned}
$$

Equation (18) links the distance function that models the joint production of the good and bad outputs with the production function that models the bad output as the sole output (i.e., equation 1). The value of the distance function in equation (18) is the ratio of the observed production of the bad output, b^t, to the maximum production of the bad output with the inputs, regulatory intensity, and regulated technology of period t, $f_r(X^t, R^t, t)$. Similar relationships can be derived for $D_{or}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$, $D_{ou}^{t}(x^{t}, y^{t}, b^{t})$, $D_{ou}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$.

Equation (18) can be rewritten as:

$$(19)\quad f_{r}(X^{t}, R^{t}, t) = \frac{b^{t}}{D_{or}^{t}(x^{t}, y^{t}, b^{t})}$$

Next, equation (19) and $f_u(X^t, R^t, t)$ are substituted into (16). EMISSION^t is now defined in terms of two distance functions:

$$(20)\quad \Delta EMISSION^{t} = \frac{b^{t}/D_{ou}^{t}(x^{t}, 1, b^{t})}{b^{t}/D_{or}^{t}(x^{t}, 1, b^{t})}$$

Next, equation (19), $f_u(X^t, R^t, t)$, $f_r(X^{t+1}, R^{t+1}, t+1)$, and $f_u(X^{t+1}, R^{t+1}, t+1)$ are substituted into (17). $\Delta\mathrm{EMISSION}_t^{t+1}$ is now defined in terms of four distance functions:

$$(21)\quad \Delta EMISSION_t^{t+1} = \frac{D_{or}^{t+1}(x^{t+1},1,b^{t+1}) / D_{ou}^{t+1}(x^{t+1},1,b^{t+1})}{D_{or}^{t}(x^{t},1,b^{t}) / D_{ou}^{t}(x^{t},1,b^{t})} = \frac{D_{ou}^{t}(x^{t},1,b^{t}) / D_{ou}^{t+1}(x^{t+1},1,b^{t+1})}{D_{or}^{t}(x^{t},1,b^{t}) / D_{or}^{t+1}(x^{t+1},1,b^{t+1})}$$

Existing decomposition models focus on observed changes in the quantity of the bad output produced in periods t and t+1. The observed production of bad outputs in periods t and t+1 is either on the regulated frontier, if the producer is efficient, or inside the regulated frontier, if the producer is inefficient. Since B^t equals the ratio of the observed production of the good output to its maximum expansion (b^t / θ^t), the change in the observed production of bad outputs can be expressed as:

$$(22)\quad \Delta EMIT_t^{t+1} = \frac{b^{t+1}}{b^t} = \frac{f_r(A^{t+1}, X^{t+1}, R^{t+1}) \times \theta^{t+1}}{f_r(A^{t}, X^{t}, R^{t}) \times \theta^{t}}$$

where the technical efficiencies for periods t and t+1 are θ^t and θ^{t+1}. θ^t represents the proportional expansion of all outputs (good and bad) required to project observation b^t from inside the production frontier to the regulated frontier (B_r^t) in period t. θ^{t+1} represents a similar relationship for period t+1. When $\theta^t < 1$, the observation is technically inefficient, while $\theta^t = 1$ indicates the observation is technically efficient. Existing decomposition models assume producers are technically efficient in both periods (i.e., θ^t and θ^{t+1} are unity).

The change in production of the bad output associated with its lack of free disposability and the change in observed production of the bad output are illustrated in Figure 1 and Figure 2. In Figure 1, the regulated (0ABCDE) and unregulated (0FBCDE) frontiers represent the combinations of good and bad outputs that can be produced by the input vector and technology available in period t. The observed level of production (0a) associated with process P^t, is projected to the regulated and unregulated frontiers. The reduced production of the bad output resulting from technical inefficiency is 0a/0b. The reduced production of the bad output resulting from it not being freely disposable in period t, $EMISSION^t$, is determined by the ratio (0bN/0b).

The downward sloping segment of the frontiers - CD - represents observations that can simultaneously increase production of the good output and reduce production of the bad output. Clearly, this represents a counter-intuitive result. There are two possible explanations for why this might be observed. First, observation D may represent an older technology than the other observations used to construct the frontier. While the model assumes a frontier is constructed with observations with access to similar technologies, this is not always the case. Second, observation D may represent an outlier due to measurement error.

Figure 2 extends Figure 1 by depicting the regulated and unregulated frontiers in periods t and t+1. The regulated frontier (0GHIJKL) and the unregulated frontier (0MJKL) represent the combinations of good and bad outputs produced by the inputs and technology available in period t+1. 0i is the observed level of production in period t+1. Figure 2 illustrates the case when the process used in period t+1, P_{t+1}, produces less of the bad output per unit of good output than P_t. The reduced production of the bad output resulting from technical inefficiency in period t+1 is $\theta^{t+1} = 0i/0j$ (i.e., $D_{or}^{t+1}(x^{t+1}, y^{t+1}, b^{t+1})$). The ratio of the distance between the unregulated and regulated frontiers in period t+1 (0jN/0j) represents the reduced production of the bad output resulting from its regulation in period t+1.

In terms of the production frontiers depicted in Figure 2, the change in production of the bad output due to environmental regulations, equation (21), can be written as:

$$(23)\quad \Delta EMISSION_t^{t+1} = \frac{\left(\dfrac{0i/0j}{0i/0j'}\right)}{\left(\dfrac{0a/0b}{0a/0b'}\right)} = \frac{(0j'/0j)}{(0b'/0b)} = \frac{(0j'/0b')}{(0j/0b)}$$

If $\Delta EMISSION_t^{t+1}$ exceeds unity, this indicates an increase in the reduced production of bad outputs between periods t and t+1 due to the bad output being regulated. A value of less than unity signifies a decrease and a value of unity indicates no change in the reduced production of bad outputs between periods t and t+1 associated with its regulation.

The change in the observed production of emissions between periods t and t+1 (equation 22) is:

$$(24)\quad \Delta EMIT_t^{t+1} = \frac{0i}{0a}$$

If $\Delta EMIT_t^{t+1}$ exceeds unity, the observed production of the bad output increased between periods t and t+1. A value of less than unity signifies a decrease in production of the bad output, and a value of unity indicates no change in production of the bad output between periods t and t+1.

Changes in the observed production of the bad output between periods t and t+1 are associated with shifts in and movements along the regulated production frontiers. Technical change and input growth shift the frontiers, while a change in the output mix appears as a movement along the frontiers. Finally, a change in technical efficiency manifests itself as a change in the distance between an observation and the regulated frontier.

All factors have unambiguous effects on changes in production of the bad output. A shift by a producer to a process that produces fewer (more) bad outputs per unit of the good output results in decreasing (increasing) production of the bad output. An increase (decrease) in the quantity of inputs results in an increase (decrease) in production of the bad output. Likewise, technical improvement (deterioration) is associated with increases (decreases) in production of the bad output. Finally, an increase in technical efficiency increases the production of the bad output, and conversely, a decrease in technical efficiency reduces production of the bad output. After accounting for changes in technical efficiency, the remaining factors are associated with changes in production of the bad output between period t (0b) and period t+1 (0j).

If there is no technical inefficiency, the combined change in production of the bad output resulting from technical change and input growth is equivalence to the change in output component of previous decomposition models. In addition, the change in production of the bad output associated with the output mix component of the regulated technology corresponds to the emission intensity component of previous decomposition models.[16]

IV. TSD AND SDA Decomposition Models: A Joint Production Perspective

While Rose and Cassler (1996, pp. 50-53) examined the link between neoclassical production theory and SDA models when there are only good outputs, there has been no comparable effort to link the SDA and TSD models with joint production models. Having outlined a model of the joint production of good and bad outputs, we now proceed to investigate the assumptions underlying the TSD and SDA models used to analyze the relative importance of factors associated with changes in production of the bad output. The joint production model allows us to illustrate biases in the results of previous TSD and SDA decomposition models that result from assumptions imbedded in the production technology specified in those models.

In Figure 3, as was the case for Figure 1 and Figure 2, 0a represents the observed production of the good and bad outputs in period t and 0i represents the observed production in period t+1. The TSD and SDA decomposition techniques assume 0a and 0i represent the maximum production of the good output in periods t and t+1, respectively. As a result, the TSD and SDA models assume the regulated production possibilities frontiers are 0aN in period t, and 0idP in period t+1. Hence, when TSD and SDA models estimate the production of the bad output in period t+1 with the output mix of period t, P_t, the radial projection through observation "a" stops at point "d". Point "d", which is the intersection of P_t and the quantity of the good output produced in period t+1 (observation "i"), represents the production of the good output in period t+1 that maintains the output mix, P_t, of period t. As a result, the TSD and SDA models conclude increased production of the good output results in additional production of the bad output and the reduced production of the bad output per unit of the good output results in decreased production of the bad output.

The change in production of the bad output associated with changes in production of the good output (the difference between 0d and 0i) can be stated as:

(25) $e_t (Y_{t+1} - Y_t) = ad$

where e_t represents the observed output mix produced in period t. $(Y_{t+1} - Y_t)$ represents the change in production of the good output. The distance function $D_{or}^{t+1*}(x^{t+1}, y^t, b^t)$ represents the ratio 0a/0d (the asterisk indicates the distance function associated with the production frontier assumed by existing decomposition models). This can be rewritten as $0d = (1/ D_{or}^{t+1*}(x^{t+1}, y^t, b^t)) \times 0a$.

The change in production of the bad output associated with changes in the output mix of an industry (the difference between 0a and 0d) can be stated as:

(26) $(E_{t+1} - Y_{t+1}e_t) = id$

where E_{t+1} represents the observed production of the bad output in period t+1 and $Y_{t+1}e_t$ represents the quantity of bad output that would be produced in period t+1 if the output mix of period t remained in effect in period t+1.[17] The distance function $D_{or}^{t+1*}(x^{t+1}, y^{t+1}, b^{t+1})$ represents the ratio 0i/0i.

According to equation (1), production of the bad output is the product of a industry's output mix (U × M × I) and production of the good output (S × G). The TSD and SDA models assume changes in a industry's output mix are associated with changes in energy intensity of its production, fuel switching, and changes in the emission intensity of individual fuels.

TSD and SDA models only allow pollution abatement activities involving substituting among energy inputs (e.g., substituting low for high sulfur coal or substituting natural gas for coal) or substituting non-energy inputs for energy inputs. As a result, the TSD and SDA models do not allow input vector **x** to produce more of the good output even when switching to a process that emits more of the bad output per unit of the good output.

The joint production model offers an alternative perspective of the sources associated with changes in production of the bad output. By superimposing the actual regulated frontiers (see Figure 2) on the regulated frontiers assumed by the TSD and SDA models (see Figure 3), Figure 4 allows a comparison of the conclusions derived by the joint production model and the TSD and SDA models. As was the case in Figure 2, 0a and 0i represent technically inefficient observations. Hence, the 0a/0b and 0i/0j represent the extent of technical inefficiency in periods t and t+1. Point "e", which lies on P_t, represents the maximum production of the good and bad outputs in period t+1 when using process P_t. The distance function $D_{or}^{t+1}(x^{t+1}, y^t, b^t)$ represents the ratio 0a/0e. This can be rewritten as $0e = (1/ D_{or}^{t+1}(x^{t+1}, y^t, b^t)) \times 0a$.

The difference in the production of the bad output shown by points "d" and "e" represents the difference between the TSD and SDA and the joint production model. As a result, input growth is the sole factor associated with the increased production of the bad output from 0b to 0e and the change in the mix of good and bad outputs produced in periods t and t+1 results in a decline in production of the bad output from 0e to 0j.

Stricter environmental regulations, which result in an increased share of inputs being allocated to pollution abatement activities, result in reduced production of the good output. Since TSD and SDA models ignore the effects of pollution abatement activities not involving energy inputs on the production of the good output, they underestimate the quantity of the good output that can be produced by the regulated technology of period t+1 if it maintains the observed output mix of period t, P_t. This results in the TSD and SDA models understating (1) the increase in emissions that would occur when production of the good output increases in a less regulated environment and (2) the relative importance of the decline in emissions resulting from reduced production of the bad output per unit of the good output.

V. Conclusions

This study reviewed the TSD and SDA methods of determining the relative importance of the factors associated with emission changes from the perspective of modeling the joint production of good and bad outputs. The joint production model yields three important extensions to previous decomposition models. First, the use of a DEA model allows the possibility of technical inefficiency. Second, specifying a less restrictive regulated technology relating emissions to the factors associated with production of the bad output it is possible to provide a more accurate assessment of the relative importance of changes in the output mix on changes in production of the bad output when pollution abatement activities not involving energy inputs are allowed. Since the only method of reducing CO_2 emissions is either fuel switching or substituting other inputs for energy, this insight is not applicable to CO_2 emissions. Finally, modeling the regulated and unregulated technologies allows the joint production model to determine changes in production of the bad output associated with it not being freely disposable. This change in production of the bad output is not captured by previous models investigating the factors associated with changes in production of the bad output. As a result, the TSD and SDA decomposition techniques appear to underestimate the reduced production of the bad output resulting from increased pollution abatement activity.

Although the focus of this study is on the implications of modeling the technology when pollution abatement activities other than those involving energy inputs are available, the findings of this study have implications for modeling factors associated with changes in energy consumption and CO_2 emissions. For example, technical inefficiency can also exist when modeling factors associated with changes in energy consumption and CO_2 emissions. In addition, the reduced level of production of the bad output resulting from its lack of free disposability is also applicable to CO_2 emissions.

From the perspective of the joint production model, the direct effects of environmental regulations on production of the bad output are captured by changes in the output mix and by changes in production of the bad output associated with it not being freely disposable.

All decomposition models - including the one specified in this study - do not estimate the effect of environmental regulations on technical change and input growth. By ignoring the extent to which environmental regulations might affect the growth rates of these factors, all decomposition models may understate the effect of environmental regulations on emissions.

While the two “direct” effects of environmental regulations are changing to a process that produces fewer bad outputs per unit of the good output and changes in production of the bad output associated with its lack of free disposability, regulations can also indirectly affect production of bad outputs. For example, a change in regulatory intensity can influence input growth in a industry as resources are shifted among industries. Hence, if an industry declines as consequence of increased regulatory intensity, this may result in reduced production of the bad output as input use declines. Another indirect effect occurs if stricter environmental regulations induce technical change that results in fewer bad outputs being produced per unit of the good output. This change in the output mix can result in a decline in the observable growth rate of the bad output associated with technical change. Induced technical change can also cause a slowdown in growth associated with the free disposability frontier which affects the change in production of bad outputs associated with the bad outputs not being freely disposable.

The next phase of this project is to derive the expressions for the change in production of the bad output associated with technical change, changes in technical efficiency and regulatory intensity, input growth, lack of free disposability in terms of distance functions. This will allow us to empirically analyze the factors associated with changes in production of the bad output in terms of the joint production model (see Färe, Grosskopf, Norris and Zhang, 1994, for an example of decomposition analysis of changes in production of the good output using distance functions).

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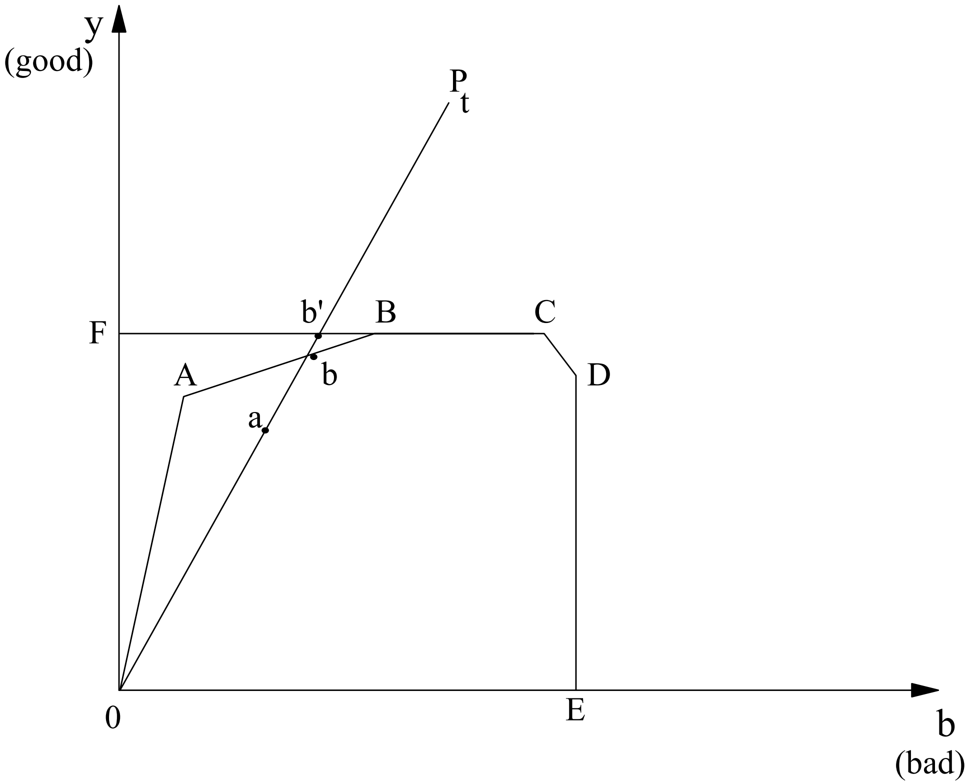

Figure 1. Actual Production Frontiers for Period t

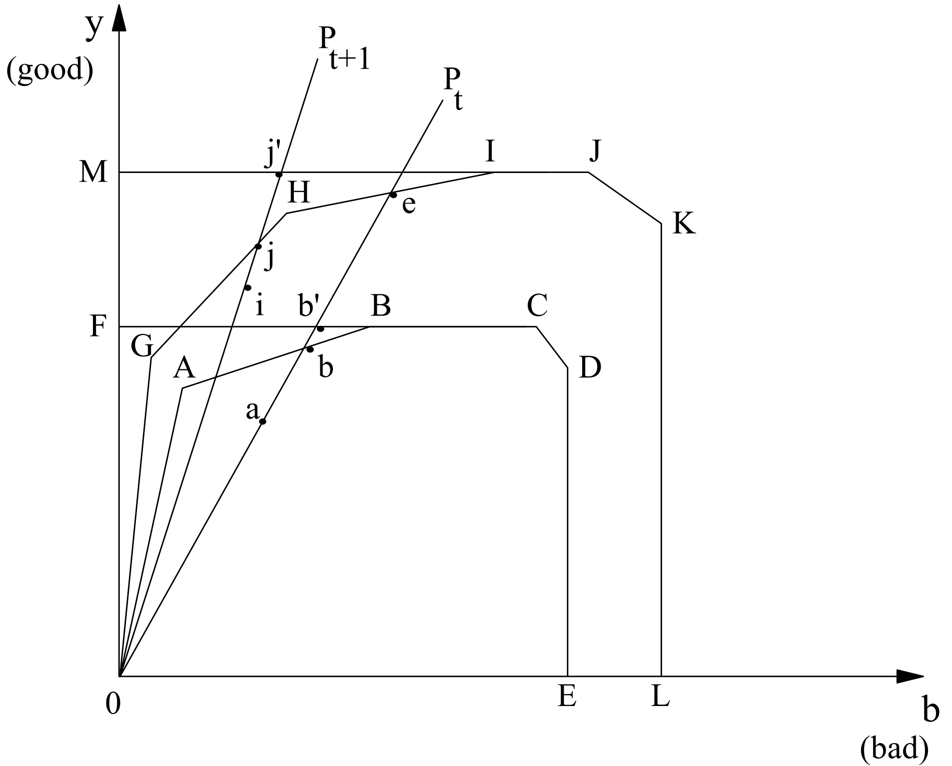

Figure 2. Actual Production Frontiers for Periods t and t+1

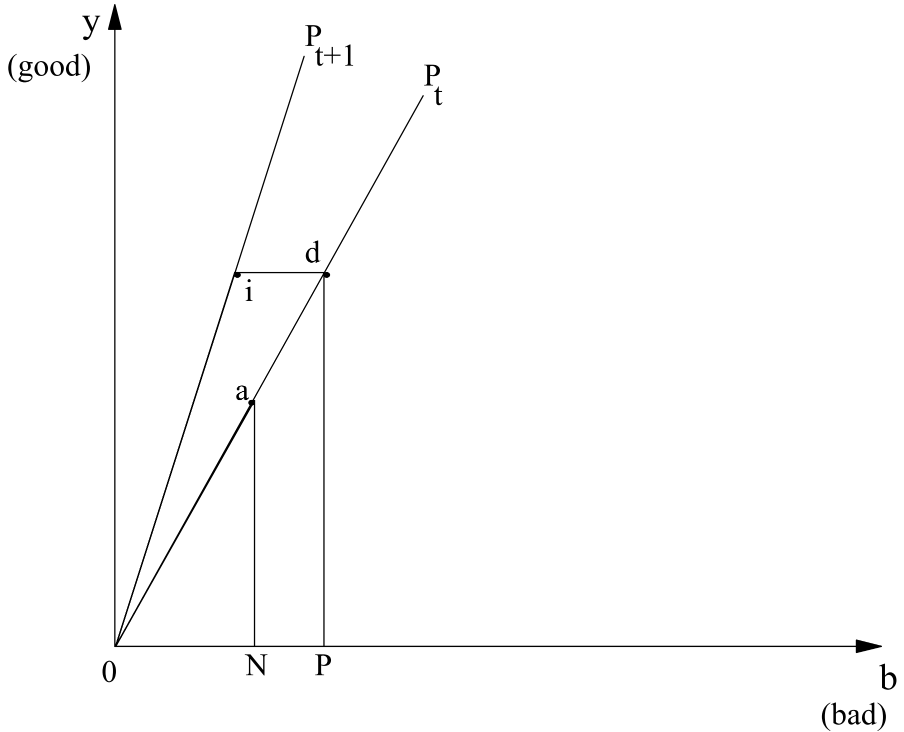

Figure 3. Production Frontiers Assumed by Existing Decomposition Models

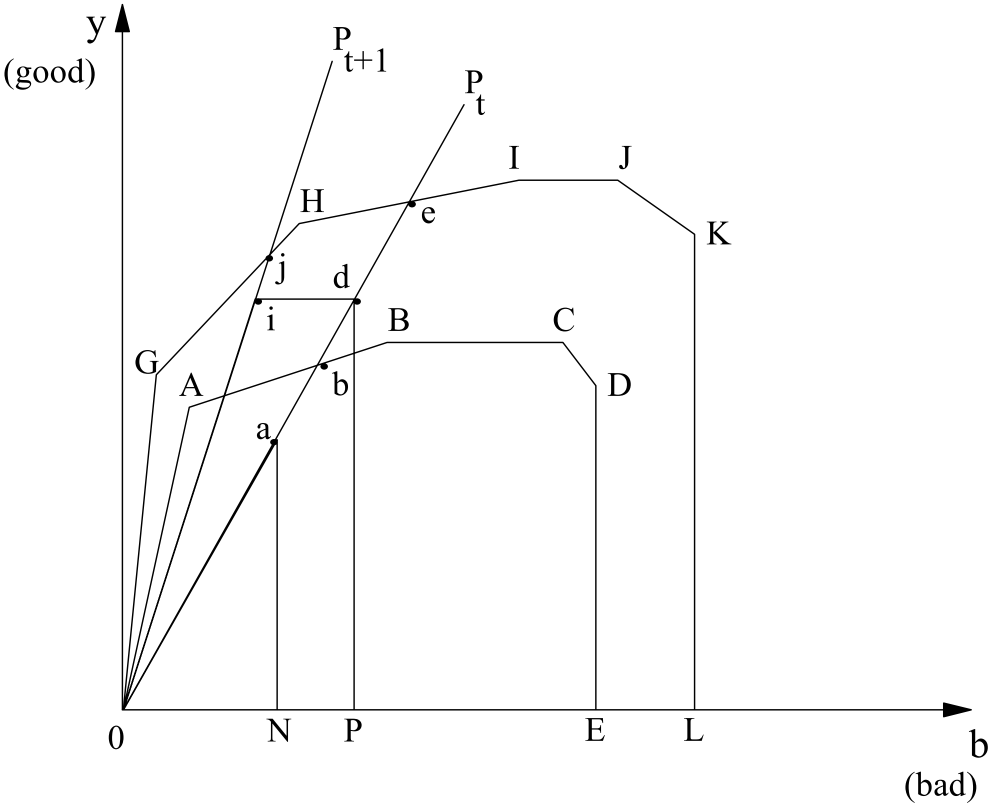

Figure 4. Actual and Assumed Regulated Production Frontiers

Notes

1. MacAvoy (1979, p. 101-104) used regression analysis to estimate the relation between emission-intensity and various factors, including environmental regulations.

2. Rose and Casler (1996) refer to the decomposition models that do not use an input-output table as the “index number approach.” Since issues associated with index numbers are inherent in all decomposition models, this study refers to models that do not use input-output tables as “time series decomposition” models. This allows us to distinguish this type of model from the SDA models.

3. Since separate domestic and import input-output tables are not constructed for the United States, it is assumed that each cell in the diagonal of M represents the import content for all cells in that row of the input-output table This means that each cell in a given row of the input-output table is assumed to have the same ratio of imports to domestic supplies (i.e., the domestic content ratio is the same for all cells in a given row).

4. Equation (4) differs from the Lee and Schluter (1993) model because changes in the composition as well as the level of domestic final demand and exports are allowed.

5. Equation (6), is similar to expressions specified by Meyer and Stahmer (1989) and Wier (1998). However, the SDA model specified in this study differs from Meyer and Stahmer (1989) and Wier (1998) in three respects. First, Meyer and Stahmer (1989) and Wier (1998) only modeled the factors influencing emissions associated with fuel combustion. Equation (6) includes both production process emissions and emissions due to fuel combustion by an industry. Second, Meyer and Stahmer (1989) and Wier (1998) specified a single category for "Final Demand", while, equation (6) presents separate categories for domestic final demand supplied by domestic production ($\mu Y \overline{y}$) and exports ($E \overline{e}$). Finally, Meyer and Stahmer (1989) and Wier (1998) did not incorporate the effect of changes in domestic content into their models. Equation (6) allows for emission changes due to changes in domestic content of intermediate inputs and domestic final demand.

6. The expression for total emissions (equation 6) can be disaggregated into four categories: (1) production process emissions associated with domestic final demand supplied by domestic producers, ε_1, (2) production process emissions associated with exports, ε_2, (3) emissions due to fuel use associated with domestic final demand supplied by domestic producers, ε_3, and (4) emissions due to fuel use associated with exports, ε_4. ε_3 and ε_4 are three-dimensional matrices whose elements consist of emissions per unit of fuel by industry and fuel type. Appendix A, which is available from the authors on request, contains a more detailed discussion of the derivation of equations (9a) through (9j) as combinations of ε_1, ε_2, ε_3, and ε_4. When using the simple average Divisia method, the values of ε_1, ε_2, ε_3, and ε_4 are simple averages of the amount of emissions in the initial period and final period for the each of the four categories of emissions: ε_1, ε_2, ε_3, and ε_4. This allows the derivation of expressions similar to those obtained by Lin and Chang (1996).

7. Rose and Casler (1996) present a detailed survey of the SDA literature.

8. Breuil (1992) used an input-output framework to investigate whether the assumption of fixed emissions-output ratios allowed accurate forecasting of SO_2 and NO_X emissions from industry in France. He assumed that all emissions generated by an industry are in fixed proportion to its output. Using the emissions data from CORINAIR for 1985, which includes emissions produced by fuel combustion and manufacturing processes, he forecasted emissions for 1986-89. Breuil concluded that even in the short-run, assuming fixed coefficients between emissions and output leads to inaccurate forecasts. This is especially true for emissions resulting from fuel combustion. He offered three explanations for the inaccurate forecasts: (1) changes in technologies and legislation, (2) changes in energy intensity of production, and (3) changes in the mix of fuels used by an industry.

9. Keilbach (1995) modeled emissions as inputs into the production process, in order to calculate the marginal productivity of emissions.

10. Färe, Grosskopf, Lovell, and Yaisawarng (1993) have demonstrated that a production technology with good and bad outputs can be specified as a translog distance function.

11. If the summation of the intensity parameters (i.e., the z_k) is constrained to equal unity, *variable returns to scale* is assumed.

12. Throughout this study, “good” output refers to the marketed good produced by an industry and the “bad” output refers to emissions of any pollutant.

13. Treating the good and bad outputs asymmetrically results in the possibility of a production unit using a production process other than what it was using originally (see Färe, Grosskopf, Lovell, and Pasurka 1989 or Chung, Färe, and Grosskopf 1997).

14. Kahn (1997, p. 95) specified a “... pollution production function.”

15. The direction and magnitude of this component depends on the relative importance of its three underlying factors. Input growth and the use of less emissions intensive production technologies will increase the distance between the strong and regulated frontiers. Technical change can either increase or decrease the distance between the regulated and unregulated frontiers. However, Pasurka (2001) found that technical change tends to reduce the distance between the regulated and unregulated frontiers.

16. However, Färe, Grosskopf, and Pasurka (1986) assume that both good and bad outputs are weakly disposable, while this study relaxes the assumption for good outputs and allows the good outputs to be freely disposable (see Färe, Grosskopf, Lovell and Pasurka 1989).

17. If 0a and 0i represent the same quantity of bad output, the increased production of the bad output due to increased production of the good output exactly offsets the reduction in emissions from the lower emission intensity of the production processes used by the producer.