Adjusting for Tax Interaction Effects in the Economic Analysis of Environmental Regulation:

Some Practical Considerations

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1. Introduction

Regulatory analyses in the U.S. Environmental Protection Agency's (EPA's) Office of Air Quality Planning and Standards (OAQPS), Innovative Strategies and Economics Group (ISEG) have traditionally relied on social cost estimates that are derived from partial equilibrium (PE) models of the regulated industry(s).[1] PE measures ignore effects in all other markets except those directly affected by the regulation. Therefore, they ignore the effect that a price increase in the affected market might have on welfare costs—and potentially benefits—in other markets.

A significant challenge to PE estimates of social cost has come from recent literature that focuses on how environmental regulations interact with tax-induced distortions in the labor market, often referred to as tax-interaction effects (TIEs). Parry (1997), Goulder et al. (1999), and Fullerton and Metcalfe (1997) are notable examples of this literature. Public finance economists, since Harberger, have known that welfare analysis of public policy can take place solely in the intervened-in market only when undistorted competitive conditions reign in all other markets. If one performs single-market analysis of a tax, say, or an environmental regulation, then one assumes that there are no other-market distortions or that the exacerbation and amelioration of other-market distortions caused by the intervention in question cancel one another out. The TIE literature argues that, in the case of environmental policy (as well as agricultural policy and trade policy; see Parry [1999] and Williams [1999]) the other-market effects do not cancel out. In particular, the nature of environmental regulation—through command and control, pollution taxes, or quota restrictions on pollution—systematically worsens the distortion in the labor market that arises from the existing income tax.

The economic literature on TIEs of environmental regulations has potentially important implications for the way ISEG estimates the social costs of these regulations. Several members of the Science Advisory Board (SAB) Council reviewing the Agency's Prospective Study, *The Benefits and Costs of the Clean Air Act 1990 to 2010* (EPA, 1999) raised this issue. These members point to studies that claim to have conservatively estimated the cost of this TIE at 25% to 35% of the direct cost of regulation and that even "small" regulatory actions raise prices, reduce the

[1]This is largely true elsewhere at EPA, except in (the not infrequent) cases where market behavior is not modeled at all. In those cases, an estimate of the "engineering" costs of compliance are used as proxies for the social cost. Under the most general circumstances (e.g., perfect competition), the engineering cost and PE social cost estimates are typically of similar magnitude. Therefore, the engineering cost estimates of social cost will also be referred to as "PE" measures for the purposes of this discussion.

real return to factors (wage), and add to the deadweight loss caused by distortionary taxation (labor tax). It has been argued that the Agency should use computable general equilibrium (CGE) models to account for this effect in estimating social costs. However, in lieu of CGE modeling, it has been proposed to employ an ad hoc adjustment factor of 1.35 to "correct" the direct cost estimates.

This paper presents an interpretation and preliminary assessment of suggestions that TIEs be included in current and future estimates of the social cost of regulation. It begins with a relatively nontechnical explanation of TIEs and then summarize policy conclusions from the academic literature. Next is a discussion of how the TIEs estimated in the main thrust of this literature fit with other TIEs that may result from the interaction of environmental regulation with the tax system that is followed by detailed discussion how the particular assumptions and model structure in the existing literature might bias the empirical measurement of TIEs. The paper concludes by reiterating the main conclusions and identifying areas of future research that might shed light on remaining uncertainties.

Overall, understanding the interaction of environmental regulation with the tax system is an endeavor that EPA should support. The social costs of regulation, and the merits of alternative policy instruments to control pollution, can be significantly influenced by these effects. However, this is a new and emerging literature where recent research in particular has given ample reason for caution in applying an across-the-board approximate correction to estimates of the social costs of regulation. For both theoretical and empirical reasons, the current state of economic knowledge does not, in the authors' opinion, provide adequate guidance on the magnitude on the sign of such a correction.

2. A Basic Explanation of TIEs

Economic analysis and measurement of the costs of pollution reduction have historically focused on firms' direct expenditures on pollution control and on the effects of these expenditures on the markets in which these firms operate. For example, the cost of regulations affecting power companies would be measured by utilities' expenditures on pollution control equipment and by the resulting change in the cost of producing electricity. Such analyses are generally referred to as PE analyses, meaning that they focus on a specific segment of the economy in isolation from all others.

Economists have recognized that such changes can have complex and far-reaching effects in other parts of the economy. Analyses that attempt to capture such interactions throughout the economy are known as general equilibrium (GE) analyses. There have been several efforts to systematically model and measure these GE effects (e.g., Hazilla and Kopp, 1990; Jorgenson and Wilcoxen, 1990; Kokoski and Smith, 1987; Nestor and Pasurka, 1995). The focus of the TIE literature is to capture extra-market effects that are thought to be important because they involve large distortions engendered by government's taxation of labor and investment.

2.1 Why Taxes are Inefficient

The first concept essential to understanding TIEs is the inefficiency engendered by raising revenue through distortionary taxes. The dominant economic models of labor supply assume that individuals work until the last hour they work gives them the same amount of utility in the form of income as they get in the form of direct utility from their last hour of leisure. If there were no taxes on labor income, a small increase in leisure at the expense of labor would have very little effect on utility because they would be almost equally valuable.

However, labor is taxed at marginal rates of around 40 percent in the U.S. (taking into account federal and state income taxes and social security taxes). The value of that labor to society is reflected in what employers are willing to pay (i.e., the pre-tax wage); however, workers only receive (about) 60 percent of that value for every additional hour they work. Consequently, labor supply models indicate: (1) workers work less and enjoy more leisure than they would without taxes, (2) they continue to reduce their hours worked until leisure begins to be less valuable to them, and (3) they choose their hours worked at the point where leisure is only worth the same as their after-tax wage (i.e., [about] 60 percent of their pre-tax wage).

However, the value of labor to society at large (the value of the worker's marginal product) is not directly affected by the tax. The divergence of the incentive to work and the value of that work causes a suboptimal amount of labor to be provided, and the total welfare of society drops as a result. There is an extensive theoretical and empirical literature on the losses caused by taxation of both labor and investment (see, for example, Browning [1987]). The literature broadly concludes that these effects are real and substantial. The loss is commonly expressed as the welfare loss that results from raising an additional unit of tax revenue. Typical estimates are on the order of 35 percent, meaning that raising $1.00 of tax revenue costs society $1.35 in resources, thereby creating a deadweight efficiency loss of $0.35 per dollar.

2.2 *Why Labor Decisions are Affected the Same Way by Pollution Control Regulations and Taxes*

The logic of the TIE literature is that pollution control regulations, whether in the form of taxes, quantity restrictions, or technology standards, have effects similar to taxes on labor. This occurs because the regulations increase the price of goods and services in affected industries. Because an hour of labor buys less than it did before the regulation, workers perceive a drop in their real wage and choose to supply less labor and consume more leisure—exactly as they would if the tax on labor were increased.

If there were no existing distortionary taxes on labor, then the loss to society of this drop in the real wage would be small. However, the existence of distorting taxes means that there is already a significant difference between the marginal value of labor and the marginal value of leisure. The additional reduction in labor supply caused by the pollution control regulation therefore creates a large deadweight efficiency loss. If labor were taxed at 40 percent, then each unit of labor reduced by pollution control regulations through higher prices imposes an excess burden of about 40 percent of the pre-tax wage to society. This loss is one primary component of TIEs. The empirical significance of TIEs depends a great deal on the way this component is modeled and measured as addressed in greater detail below.

The other component occurs because of the government's need for revenue. If regulation causes people to work less, then less revenue is collected from taxes on labor. This reduction in labor causes the government to receive lower income tax and payroll tax revenues. To make up for revenue shortfalls, the government must increase these taxes if they wish to maintain revenue neutrality. This increase once again causes workers to choose to work fewer hours, and a further reduction to the well-being of the average person results. It is important to recognize that this literature does *not* make any judgments about the value of government expenditures to society. The problem is not that the expenditures are not necessary or good. It is that raising those revenues reduces the individual incentives to work, thereby raising the social cost burden of the expenditures.

2.3 *A Basic Model of Environmental Regulation's TIEs in Labor Markets*

The primary emphasis of the TIE literature has been on the interaction between changes in the market price for a "dirty" good potentially subject to environmental regulation and pre-existing distortions in the labor market. Although, as described in Section 3, some of the more interesting elements of the TIE literature relate to alternative market-based instruments (e.g., emissions taxes versus marketable permits) and the interplay between potentially positive revenue recycling effects and potentially negative TIEs, the example below relates to "command and control" regulatory approaches. These approaches include the technology mandates and emission standards that have been the core of OAQPS regulations since its inception.

Goulder et al. (1999) develop a GE model of a representative consumer, producer, and government to develop testable hypotheses about TIEs, revenue recycling, and the potential for environmental taxes to generate a double-dividend. The last two of these issues are not directly relevant for analyzing command-and-control implementation of regulations and are not explored further here. In the case of a command-and-control policy to increase pollution abatement when labor is the only factor of production, Goulder et al. define the GE measure of the policy's welfare cost as[2]

$$dW^{GE} = \underbrace{c_a(a)X}_{dW^A} + \underbrace{[(1+M)\tau\,(-N_P{}^x) + M' s_G\,X]\,(dP^X/da)}_{dW^I} \tag{1}$$

where

dW^{GE}	=	the change in welfare cost measured by GE means
a	=	pollution abatement level
dW^A	=	direct cost of abatement
dW^I	=	TIE
X	=	quantity produced (consumed) of the regulated commodity
c(a)	=	cost of abatement per unit of X
M	=	marginal (PE) efficiency cost of a dollar of funds raised from labor tax revenue for public consumption = $e^u\,\tau/(1-\tau)/[1-e^u\,\tau/(1-\tau)]$
M′	=	the PE marginal excess burden = $e^c\,\tau/(1-\tau)/[1-e^u\,\tau/(1-\tau)]$
τ	=	labor tax rate

[2]See the Goulder et al. (1999) paper for more detail on the derivation of Eq. (8). In this example, the parameter θ is set to 1.0, indicating the least cost abatement technology is mandated.

e^u	=	uncompensated (Marshallian) elasticity of labor supply with respect to the change in the wage (or marginal tax rate)
e^c	=	compensated (Hicksian) elasticity of labor supply with respect to the change in the wage (or marginal tax rate)
P^X	=	(demand) price of the regulated commodity
$N_P{}^X$	=	change in the quantity of labor (N) supplied with respect to a change in the price of X
N	=	labor = time allotment (T^0) – leisure (L)
s_G	=	share of government transfers in household income

To estimate the size of the TIE, one needs representative parameter values for τ, e^u, e^c, P^X, $\partial L/\partial P^X$, and s_G . Values for τ and s_G are readily available from government data sources. Labor supply elasticities can be gleaned from the literature. Goulder et al. (1999) use values of $e^u = 0.15$ and $e^c = 0.40$ based on a survey of labor economists by Fuchs, Krueger, and Poterba (1998). The validity of assumed labor market parameters is an important issue for analysts to consider, but a more detailed discussion of these parameters is outside the scope of the present paper.

3. Core Literature

This section highlights the most policy-relevant parts of this literature for ISEG and EPA and gives an overview of the methodologies that were used to arrive at them. The section also identifies recent research that may substantially mitigate the conclusion that all social cost estimates should be revised upwards to account for TIEs. This paper does not attempt to provide in-depth review of all of the tax interaction literature; for a survey refer to Bovenberg and Goulder (2000).

The literature is virtually unanimous that GE effects are important for understanding the costs and benefits of environmental regulation. The literature is not unique in this regard; both traditional neoclassical environmental economists and ecological economists have recognized that it is economy-wide effects on welfare, and not narrow market-specific effects, that ultimately are important. Given the complexity of macroeconomic relationships and the associated uncertainties in both theory and measurement, however, there has not been any broad consensus on how to operationalize a quantitative consideration of economy-wide effects. One well-known example of using CGE models to quantify supply-side effects is Hazilla and Kopp (1990). Therefore, while few would argue that GE effects are unimportant, PE analyses based on single-market or sector-wide analyses have remained the norm for analyzing the social costs of environmental regulation.

The TIE literature is important for two related reasons. First, it focuses on a very specific mechanism for GE effects that has theoretical and empirical backing from the general literature on tax distortions. Second, it uses CGE models and tractable analytical models to generate quantitative predictions about the magnitude of welfare losses in a fairly transparent way. It marks the most significant and influential effort to date to move social cost estimation for environmental regulation out of a PE framework.

Two central findings from the TIE literature deserve special attention:

- GE costs are larger than PE costs, and
- regulatory instruments have very different relative impacts on costs than they do under PE assumptions.

The former is the most important finding for ISEG's work. Researchers in the field have argued that the costs of environmental regulation have been significantly and consistently underestimated by not considering TIEs, both from general analyses and analysis of specific programs (see Goulder et al. [1999] and Parry [1997]).

3.1 Relative Magnitude of GE and PE Costs

Regarding the hypothesis that GE costs always exceed PE costs, two observations are made here. First, its generality has been called into question in a number of recent papers. Parry and Bento (2000) find that when the tax system is distorted to favor certain goods such as housing and medical care, then environmental taxation has ambiguous effects on efficiency and may even enhance it. In addition, Williams (2000), using an argument similar to that presented in Section 5 of this paper, considers health and productivity effects of environmental regulation. When improvements in environmental quality enhance the ability of workers and firms to produce goods and services, then these efficiency-enhancing effects interact with the tax system to create (potentially large) *gains* in welfare. In essence, benefits that occur in production, as opposed to consumption, are magnified by TIEs.

A second observation is that the empirical estimation of TIEs for regulations that increase production costs depends critically on the structure of specific abatement technologies, markets, and the general substitutability of leisure and the output of the regulated sector. While the economic logic of these supply-side effects is compelling, the existing models may not adequately take account of the real state of production–consumption relationships. This causes some concern that the structure of the CGE models used magnifies the empirical significance of TIEs. Kahn and Farmer (1999) have recently argued that the assumption that output and leisure are substitutes is central to these models' results and is likely not to hold in a number of important cases.

Researchers active in this field have recognized the points made here. Goulder and Parry (2000) summarize these limitations in a recent essay on TIE. The point here is that this is a new and rapidly changing branch of economics literature, with new work offering stark changes in policy prescriptions from that produced a year earlier. While the literature is interesting and important, it seems premature to begin incorporating TIEs into EPA's primary estimates of the social cost of pollution control regulation given the current state of knowledge and existing doubts about current results and their broad applicability.

It bears mentioning that the TIE relies fundamentally on the *pre*-existence of distortions caused by the tax system. This raises a philosophical point about the sequencing of the tax and regulatory distortions and the attribution of each to the combined burden. This is addressed separately in Addendum 1.

3.2 Instrument Choice

The TIE literature is in substantial agreement that regulatory instruments that raise revenue are superior in efficiency terms to those that do not. This follows from the fact that the tax revenue raised can be used to lower taxes on labor without affecting total revenues, thus reducing the distorting effect of the labor taxes. Goulder et al. (1999) found that this revenue-recycling effect was not large enough to offset the tax-interaction effect from increased real output prices in their multi-sector CGE model of the U.S. economy. Fullerton and Metcalfe (1997), however, found that a Pigouvian tax on emissions exactly counterbalanced TIEs by taxing away all of the scarcity rents generated by pollution restrictions.

The finding that taxes (or auctioned permits or quotas) are superior to other instruments is in line with the findings of the green tax/double dividend literature. The issue of how much better, and how much inefficiency is produced by the interaction of pollution and labor taxes, brings up the same issues discussed in the preceding section—how are environmental inputs to production modeled and how are the quantity restrictions and resulting price changes in the market for the regulated industry modeled?

Two related papers (Goulder, Parry, and Burtraw, 1997; Goulder et al. 1999) compare environmental taxes with various forms of nonrevenue-raising regulatory instruments. These papers find pollution quotas (either tradable permits given out at no cost or quantity-based performance standards) to be the least efficient form of regulation when TIEs are taken into account. Rate-based performance standards and technology standards fare better because they do not confer the same magnitude of scarcity rents (since they do not set rigid limits on either per-firm or overall emissions). Burtraw and Cannon (1999) argue that tradable permits are not as inefficient as in the Goulder et al. (1999) model when there is significant heterogeneity in abatement costs in the regulated population.

These comparisons, like all TIE effects, are driven by the role of regulation in increasing prices to consumers. The larger the price increase in the output market, the larger the TIE. The empirical significance of these effects in determining the relative efficiency of alternative instruments also depends on how firms and markets actually respond to regulation as implemented.

The size of the TIE in Eq. (1) depends critically on the relationship between the regulatory cost and its price effect in the market for X. An increase in abatement requirement costs will place upward pressure on the price of X. The extent of the price effect is determined by conditions related to market supply (the shape of the marginal cost of output function) and market demand. While there is little controversy regarding the basic relationship between a price change and the quantity demanded (Marshallian demand functions are typically downward sloping), the supply response depends on assumptions regarding the underlying industry cost function. As shown below, that assumption can be critical to the size of the price change and, therefore, to the size of the TIE.

4. Measurement Issues: Abatement Costs, Industry Cost Functions, and Regulatory Coverage

The magnitude of welfare losses resulting from TIEs depends on a number of key empirical relationships, but an initial and very critical one is the extent to which industries react to pollution control regulation by restricting output, thus raising consumer prices. The ultimate price increase depends on substitution in consumption, trade, and other market-wide factors. However, the first step is the reaction of the individual firm to a tax or quantity constraint: does the variety of pollution-reducing options available to a firm cause abatement-decreasing investment that leaves output little changed, or does a firm react by reducing output as a major component of its compliance strategy? The result of theoretical and numerical models depends on the way that abatement technologies are specified. It is argued here that the assumption that costs are linear in output (not in abatement) provides larger estimates of consumer price increases than other specifications, *ceteris paribus*. Such an assumption may be questionable for many types of abatement technologies.

This section formalizes the concerns that the estimation of TIEs in analytical and CGE models may magnify the real price increases caused by regulations in turn, biasing upward the measures of the social cost of regulation. Three related issues are discussed: the specification of abatement costs for individual firms, the way that aggregating firm output responses to an industry level affects out prices, and the effects of having producers differentially affected by environmental regulation.

4.1 Specification of Abatement Technologies and Costs

The specification of abatement technologies and costs is of central importance to the size of the TIE distortion. When faced with an environmental regulation, firms can reduce output, add end-of-pipe abatement technologies, change input mixes, or invest in new production processes or other innovative pollution control activities (or some mix of these activities). It is the reduction of output that results in higher prices, which then leads to real wage decreases and reduced labor supply. The extent to which regulation leads to a reduction in output is therefore critical to the magnitude of TIE welfare losses. Following Goulder et al.'s (1999) GE model, consider an emissions standard rule and let the total emissions constraint be $E = (e - a)X$

where

X is the level of output

e is the unconstrained emissions per unit of output

a is the level of emissions abated *per unit of output*

Letting C(X) represent a cost function for nonpollution-related production costs and A(a,X) represent the total costs of abatement, the profits of the firm are given by

$$\prod(X,a) = P^x X - C(X) - A(a,X) \tag{2}$$

subject to a constraint that total emissions are less than some total $\bar{E}$:

$$L(x,a) = P^xX - C(x) - A(a,X) + \lambda(\bar{E} - (e - a)X). \quad (3)$$

The first order condition with respect to output implies that at the firm's optimal choice,

$$P^X - C_x(X) = A_x(a,X) - \lambda(e - a). \quad (4)$$

where the X subscript refers to the derivative of the function with respect to output.

For a given price, the reduction in output that maximizes firm profits depends on both terms on the right side of Eq. (4). The Lagrangean term reflects the technical relationship between abatement effort and output levels in meeting the pollution constraint $\bar{E}$. It reflects the ability of firms to reduce output *to reduce pollution, not to change the cost of reducing pollution per unit of output.* The more expensive it is to reduce pollution holding output constant, the more output will be reduced as part of the firm's cost-minimizing strategy. This effect also reduces output, which *ceteris paribus* will lead to higher output prices in the market.

The assumption that *pollution* is linear in output (holding abatement technology constant) seems plausible for most pollution management strategies. The more binding the constraint, the bigger the wedge caused by this term between marginal cost and price in the firm's output decision. Note that the size of this effect also depends on the choice of a: higher levels of abatement investment reduce the importance of this term in the firm's output decision.

The first term on the right of Eq. (4) is the effect that may be particularly important in the existing TIE models. This term is the change in the total cost of reducing pollution (holding abatement per unit of output constant) that results from a marginal unit of output. The larger the magnitude of $A_x(a,X)$, the larger the wedge between price and marginal production costs (*ceteris paribus)* and the larger the output reduction. Goulder et al. assume that *abatement* costs are linear with respect to output

$$A(a,X) = c(a)X \quad (5)$$

At first glance, this assumption appears reasonable in that the total cost of abatement depends on the amount spent per unit of output times the quantity of output. On closer inspection it seems much less reasonable as a general proposition for evaluating marginal changes in abatement costs. The specification in Eq. (5) means that the abatement cost part of an additional unit of output is constant for all levels of output. One can easily think of pollution control that is not well described by this functional form. For instance, many abatement technologies require a large fixed cost and then a depreciation/maintenance cost that one would expect to be declining in output over some range of output (if it has an age as well as throughput component to depreciation). Similarly, investments in research and development, training, or engineering process changes would not produce the same abatement expenditure for all units of output; the marginal expenditure would be closer to zero. This has potentially important effects in the tax-interaction CGE models, because it is not the size of investments in abatement that matters, but how that investment varies with the quantity of output. At the extreme, $A_x = 0$.[3] Output reductions will still occur as further abatement investments exceed the price of the additional output they allow (the second right-hand side term in Eq. (3). If pollution abatement involved paying more for a less polluting input, or if it had a high labor share that is linear in output, then the specification in Eq. (5) would be reasonable, and we would expect to see large output reductions if overall pollution quotas were binding.

Assumptions that tend to keep $A_x(a,X)$ high produce larger adjustments in output (which cause price increases in output markets) compared to investments in abatement. It is hard to draw any firm conclusions, because the result on output levels depends on the actual abatement cost specification as well as the industry supply function (see below). However, *ceteris paribus*, there is reason to be concerned that the assumption that $A_x(a,X) = c(a)$ will tend to magnify output-reducing effects of more binding quantity restrictions on emissions.

4.2 Returns to Scale and the Slope of the Industry Cost Function

Another empirical consideration in TIE measurement is the nature of the industry cost (supply) function. Consider two possibilities for the second derivative (slope) of industry production cost function:

- constant returns to scale (CRS): $C_{xx}(X) = 0$, and
- decreasing returns to scale (DRS): $C_{xx}(X) > 0$.

[3]Consider, for instance, rules that impose pollution limits per unit of product. An example of this in OAQPS is the product limits for volatile organic compounds (VOCs) in architectural coating products (*Federal Register*, 1998). Regulated producers were required to ensure that VOC content per product did not exceed a certain level. Compliance primarily required an initial investment in research and development to develop a new coating formula. The size of the reformulation investment had essentially no relationship to the rate of output; thus, there was a very weak, and certainly not a linear, relationship between compliance costs and output.

The analytical and numerical models referenced by Goulder et al. (1999) in developing Eq. (1) and most of the other contributions to the TIE literature rest on the first possibility, CRS. Under CRS, industry profits are zero and all abatement costs are passed on to consumers in the form of a higher price for X. Removing the specific emissions constraint from Eq. (3) above, the firm's profit maximization condition with respect to output becomes

$$P^X = C_x(X) + A_x(a,X) \tag{6}$$

For the remainder of this section, the linear abatement cost assumption is applied, A(a,X) = c(a)X. This is done to simplify the mathematics and keep the focus on the production cost function characteristics.

Following standard assumptions of producer theory, marginal costs are nonnegative [$C_x(X) \geq 0$] and nondecreasing in output [$C_{xx}(X) \geq 0$]. An increase in the abatement requirement, then, has the following effect on the price of good X:

$$dP^x = C_{xx}(X)dX^* + c_a(a)da \tag{7}$$

The term dX^* represents the change in the GE output level of good X in response to the change in market conditions (prices) caused by the abatement requirement. Specifically, under CRS, Eq. (7) reduces to

$$dP^x = c_a(a)da \tag{8}$$

where c_a is the change in the unit cost of abatement with respect to the change in abatement level. Under CRS in production, consumers of good X absorb the full brunt of the abatement cost increase, and the TIE caused by consumption price-induced reductions in the real wage is maximized. This is the scenario Goulder et al. (1999) and Parry (1997) model when computing the empirical range of TIE mark-ups on social cost used as a point of reference for this discussion.[4]

This result begs the question, however, of the applicability of CRS for regulatory analysis. Microeconomic theory provides ample conditions under which an industry marginal cost function

[4]Parry (1997) does indicate in footnote 7 that his model generalizes to upward-sloping supply curves (DRS). Yet the numerical results estimating the relative magnitude of TIE clearly depend on the CRS assumption used to generate them, to the extent that the TIE depends on the size of the price change which, in turn depends on whether CRS or DRS is assumed.

(and competitive supply curve) might not be constant throughout the range of output considered in a modeling exercise. They include

- Scarce factor inputs
  - capital fixity
  - fixed natural resource endowments
  - specialized labor
- Technological heterogeneity across suppliers

To some extent, these are short-run phenomena that can be overcome by investment in capital, R&D, and resource discovery, for example, thereby making the long-run supply function flatter than the short-run function and, in the extreme, perfectly flat (CRS). However, if the industry facing the regulation cannot adjust all factors of production by the time the regulation comes into effect, then some deviation from CRS is warranted for the purposes of evaluating regulatory price effects. Even if these are transitory, time preference and discounting suggest that transitory effects could have a significant effect on the present value of social costs.

Suppose production is subject to fixed factors and DRS.[5] Then following Eq. (7) the change in price will depend not only on the abatement cost, but on the equilibrium change in the quantity of X. With standard Marshallian downward-sloping demand functions for X, the equilibrium quantity will decline (dX<0) subject to the higher equilibrium price. Under DRS, $C_{xx}(X) > 0$; therefore, the decline in the aggregate output will result in a decline in the marginal cost of production. Thus, the first term in Eq. (7) is negative, and the change in price is less than the change in abatement cost:

$$dP^x < c_a(a)da \tag{9}$$

Figure 1 provides an example of industry supply under DRS, with a unitary elastic supply function and a unitary elastic Marshallian demand function. In that case, price rises by exactly one-half of the abatement cost increment. The remainder of the burden is imposed on producers, whose

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[5]Williams considers the possibility of DRS in the context of TIEs with trade tariffs (1999) and labor productivity improvements from pollution control (2000). Parry (1999) also considers fixed factors (land) and DRS in the context of agricultural policy. None of these analyses specifically addresses the question about the effect of DRS (vs. CRS) on the magnitude of TIE.

abatement costs rise more than the price they can recover in the markets, and thus their profits fall. To fully capture TIE under DRS, then, some accounting for the drop in producer income must be considered.

Full household income is the amount that can be spent on leisure and consumption. It equals the after-tax value of the time allotment (T^o) and profit distributions (Π), plus the lump-sum redistributions from the government on labor and profit taxes:

$$Y = wT^o(1 - \tau) + \Pi\,(1 - \tau) + tw(T^o - L) + \Pi\,(\tau) = w(T^o - \tau) + \Pi \qquad (10)$$

Differentiating Eq. (2) with respect to changes in P^X, X, and a, the change in profits due to imposition of abatement costs for X is

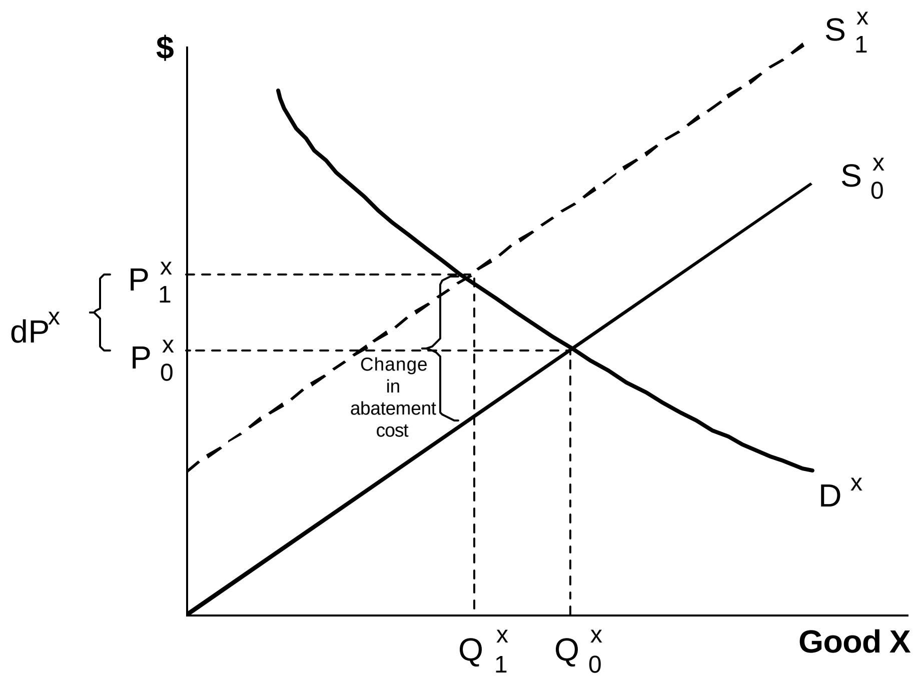

Figure 1. Partial Pass-through of Unit-Cost Increase[a]

[a]Unit supply elasticity ($e^x = 1$) and demand elasticity ($E^x = -1$).

$$d\Pi = [dP^X - c_a(a)da]X + [P^X - C_x(X) - c(a)]dX \tag{11}$$

The first-order condition in Eq. (6) indicates that the second bracketed term is zero, thus

$$d\Pi = [dP^X - c_a(a)da]X \tag{12}$$

As indicated in Eq. (9), under diminishing returns, the bracketed term is negative. Thus, profits fall ($d\Pi<0$) under DRS. Under CRS, $d\Pi=0$. Because firm profits are simply redistributed back to households, the direct burden on society is just re-channeled, it does not disappear. However, the effect on the labor market distortion is different than with the pure P^X effect. The Marshallian demand function for leisure is a function of the leisure price (after-tax market wage), P^X, and income, Y:

$$L=L[w(1 - \tau), P^X, Y] \tag{13}$$

Assuming the tax rate remains constant, the change in leisure demand can be expressed as a function of the change in the wage, goods price, and income:

$$dL = L_W \, dw + L_{PX} \, dP^X + L_M \, dY \tag{14}$$

where the subscript indicates the argument of the derivative. It is generally assumed that leisure's own price effects (L_W) are negative and cross-price effects with consumption (L_{PX}) are positive (leisure and consumption are substitutes). Assuming that leisure is a normal good, its income effect (L_Y) is also positive. The full contribution of changes in the market for good X in the leisure/labor decision are illustrated in Figure 2. The leisure demand function is inverted to create the labor supply function S_N. The labor demand function is D_N.[6] First consider the shift in the labor supply function from baseline, $S_N(P_0^X, Y_0)$, to the farthest away function, $S_N(P_C^X, Y_0)$. This reflects the shift in response to a price change equal to the full abatement cost increase ($P_C^X = P_0^X + c_a(a)da$ (i.e., that which is found under CRS). This is tantamount to the TIE identified by Goulder et al. (1999) under the command-and-control instrument. The reduction in equilibrium labor quantity from N_0 to N_C generates a TIE measured by the entire gray-shaded area, adeh. Under DRS, however, the price of X rises to P_D^X, an increase less than the full abatement cost. Holding income fixed at the baseline level, Y_0, the labor supply function shifts only to $S_N(P_D^X, Y_0)$, yielding a smaller TIE (acfh) than under CRS. Then, allowing for the effect of declining profit distributions on household income, assuming that leisure is a normal good, there is a shift back out in the labor supply function to $S_N(P_D^X, Y_D)$. Here the TIE is abgh, which is substantially smaller than the original TIE estimate.

4.3 The Role of Unregulated Producers in the Market

The co-existence of producers in the same market who are unequally affected by the regulation is particularly relevant to environmental regulations implemented by OAQPS. The clearest case occurs when one segment of producers in Market X faces the environmental constraint, while another segment of the market is completely unconstrained. This situation might occur through direct competition with foreign suppliers for an internationally traded commodity. It might reflect differential standards for producers from different regions within the United States (e.g., NAAQS attainment versus nonattainment areas). A potentially relevant case is that there may be very different pollution intensities of alternative technologies for producers in the market.

[6] Somewhat contrary to most depictions in the TIE literature, D_N is illustrated here as sloping downward, exhibiting the potential for diminishing returns to labor and/or final good price feedbacks under labor (output) expansion.

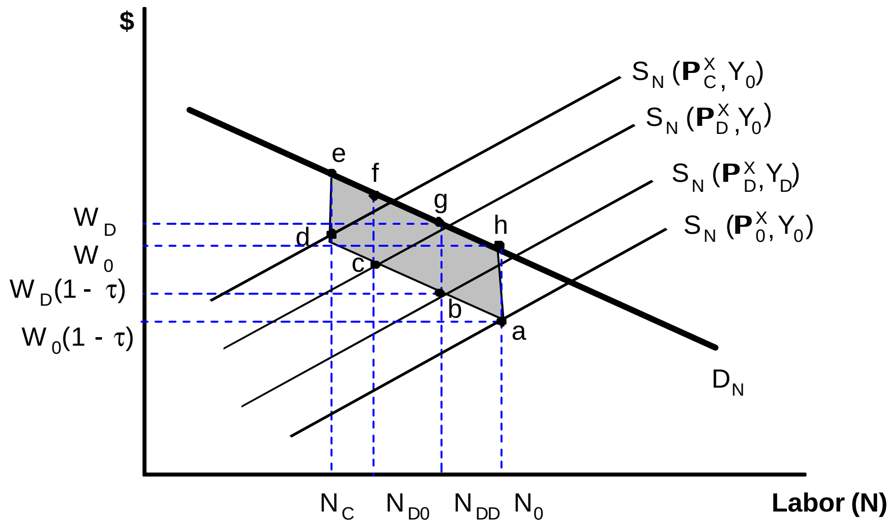

Figure 2. TIEs with Diminishing Returns and Income Effects from Profit Distributions

When only part of the market is constrained by the abatement requirements, it is more difficult for the costs imposed on the regulated producer to be passed on to consumers via higher prices. Figure 3 illustrates this point. Here, the regulated supply segment (S^{XR}) is small relative to the entire market. This situation is more likely to occur when the goods market is very large relative to domestic production (e.g., a global commodity such as oil) or the regulation is very specific to a subset of producers (e.g., Midwestern coal producers). Now increase production costs per unit by c(a). Because the aggregate supply function for the commodity sums across the supply functions of regulated and unregulated producers ($S^X = S^{XR} + S^{XU}$), the cost/supply shift for regulated producers is diminished when translated to a shift in the aggregate supply function (i.e., the shift in S^X is relatively smaller than the shift in S^{XR}). At the new equilibrium, unregulated producers expand their output from Q^{XU}_0 to Q^{XU}_1, which partly offsets the decline in regulated output from Q^{XR}_0 to Q^{XR}_1. Thus, the effect of the regulation on the market price is muted by the ability of the unregulated producers to substitute for the regulated producers in satisfying market demand. In this situation, the regulated producers withstand a loss in profits while the unregulated producers experience an increase in profits from the higher price.

5. Toward a More "General" GE Analysis

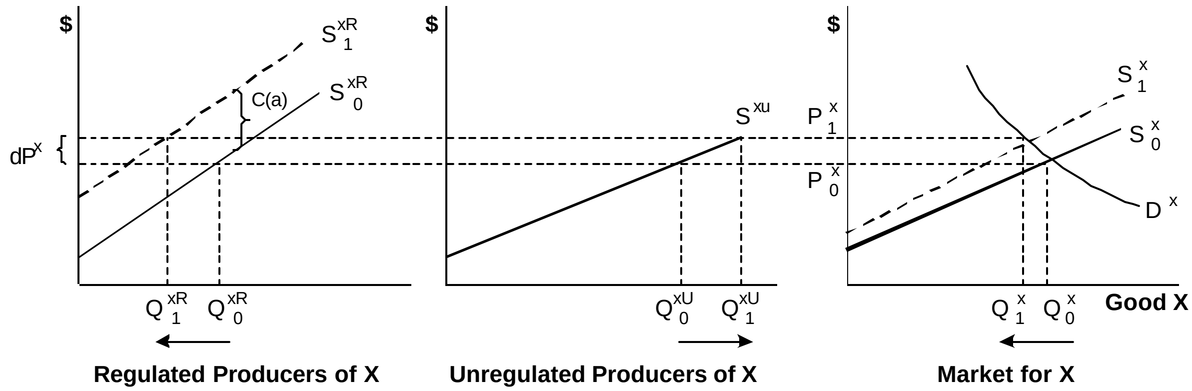

Figure 3. Co-existence of Regulated and Unregulated Producers in the Same Market

As discussed in Sections 2 and 3, the TIE literature has until recently focused on GE effects that result from real price increases caused by environmental regulation. This section formalizes an argument that is more expansive in that regulatory analysis should include the GE effects of environmental benefits as well. In a setting where agents in the economy have preferences over environmental quality, both the consumption of market goods and the demand for and supply of labor will be affected directly by environmental quality. When one considers these effects, the overall effect on welfare of the TIE is not so clear. While a PE analysis of the costs of environmental regulation is incomplete, as Parry, Goulder, and others argue, bringing in GE concerns while still focusing only on regulatory costs can be misleading from the GE perspective.

This last point is acknowledged in a recent paper by Williams (2000). In analysis consistent with the approach discussed here, he takes into account benefit-side interactions with the tax system. He concludes that the sign of the TIE is ambiguous and hinges critically on the way in which environmental improvement affects labor supply. Two of Williams' conclusions are particularly relevant. The first is that if environmental improvement enhances labor productivity, then the benefit-side tax interaction works to counterbalance the cost-side interaction and can more than offset it. This same point is made in the stylized model to follow here. Williams' second conclusion is that if environmental improvement does not improve labor productivity on the job but, instead, reduces workers' health care expenditures, then the benefit-side interaction is negative, offsetting some of the direct benefits from regulation.

In this section, a model economy is developed that accounts for benefits-side interaction between environmental regulation and the tax system. Consider an economy in which a representative agent derives utility from consuming an aggregate market good (X), hours of leisure (L), and environmental quality (E). The agent's utility function is given by U(X,L,E), where utility is increasing in each of its arguments. Markets for the consumption good and for labor are competitive. The level of environmental quality is exogenous. It is a public good, both nonrival and nonexcludable.

The production side of the economy is represented by a production function that relates employment of effective labor (N^*) and a second input (Z) to the production of the market good. The production function is given by

$$X = f(N^*,Z).$$

The quantity of effective labor, N^*, is related to the quantity of labor employed, N, and to environmental quality:

$$N^* = g(N,E).$$

Environmental quality influences effective labor most directly for those changes in environmental quality that are linked to health status. For example, reducing sick days and increasing the productivity of workers subject to chronic disease are effects that increase the effective units of labor employed.[7] The function g(N,E) is increasing in E and could plausibly be taken to be linearly homogenous in N. The nonlabor input, Z, is assumed to be perfectly elastically supplied from outside the economy. A representative firm hires labor from within the economy and Z from without, selling its output to consumers and returning to them all profits.

The environmental issue in the economy is that employment of Z degrades the environment. There is an inverse relation between Z and E:

$$E = h(Z),$$

where $h'(Z)<0$. The goal of the analysis here is to account, in GE, for the effects of a regulation that reduces the use of Z.

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[7]Williams (2000) treats health care costs separately from labor productivity.

The role of the government in the economy is as follows. The government taxes all forms of income at the proportionate rate τ and uses the revenue to finance transfer payments in the amount G. In a representative agent model, transfer payments are hard to motivate. But, following Parry, they are used here to introduce a balanced budget requirement and the reality of distortionary taxation. The government will be assumed to balance its budget, both initially and after any changes brought about by environmental regulation.

In this setting, price-taking consumers face the following budget constraint:

$$P^X X = w(T^o - L)(1 - \tau) + \pi(1 - \tau) + G, \tag{15}$$

where P^X is the price of the market consumption good, w is the wage rate, T^o is total available labor, and π is the agent's share of firm income. The consumer maximizes utility with respect to choice of X and L, taking dividend income, π, and transfer payments, G, as given. Rearranging the budget constraint to put choice variables on the left yields

$$P^X X + w(1 - \tau)L = Y, \tag{16}$$

where $Y = wT^o(1 - \tau) + \pi(1 - \tau) + G$ is the sum of the exogenous components of income: the after-tax values of the labor endowment and dividends and the value of government transfer payments.

Consumers equate the marginal rate of substitution between X and L to the distorted price ratio:

$$MRS_{XL} \equiv U_L/U_X = w(1 - \tau)/P^X. \tag{17}$$

This first-order condition and the budget constraint give Marshallian demands for X and L:

$$X^*(w, P^X, \tau, Y) \text{ and}$$

$$L^*(w, P^X, \tau, Y). \tag{18}$$

The last expression implies the optimal supply of labor:

$$S_N(w, P^X, \tau, Y) = T^o - L^*(w, P^X, \tau, Y)\ . \tag{19}$$

Finally, the behavior of firms is modeled as the maximization of profits:

$$\prod = P^X X - wN - P^Z Z. \tag{20}$$

Profit maximization by firms is represented by the setting of each factor's value marginal product equal to its market price:

$$
\begin{aligned}
VMP^{z} &= P^{x} \cdot f_{z} = P^{z}, \text{ and} \\
VMP_{N} &= P_{x}\, f_{N} \cdot g_{N} = w\,.
\end{aligned}
\tag{21}
$$

The two profit-maximizing conditions for firms do not take into account the two external costs from the employment of Z: increased employment of Z reduces E, which imposes direct costs on consumers and which reduces the productivity of labor by reducing the number of effective units of labor. Thus, the social value marginal product of the employment of Z is less than the private value marginal product. This fact is illustrated in Figure 4, where Z_o is the privately chosen employment of Z and Z^* is the level of Z corresponding to a PE optimum (i.e., one that does not take into account interaction with pre-existing tax distortions.) The Pigovian tax of ϕ would result in the PE efficient outcome and would result in a net welfare gain of the shaded area by PE accounting.

Now consider the GE effects of imposing a tax on Z. Comparative static results are presented in Addendum 2. A graphic depiction of the effect appears in Figure 2, which displays the equilibrium in the labor market. The initial equilibrium is formed by the initial supply of labor, S_N, the initial value of marginal product of labor, VMP_N, and the income tax rate, τ. In that equilibrium, N_o units of labor are employed. The market wage is w_o. The wage net of income tax is $w_o(1 - \tau)$.

Now suppose that a tax is levied on Z, the polluting input, and that the proceeds of the tax are returned as a lump sum by increasing G, the government's transfer payment.[8] If there were no production benefit from environmental quality, the polluting-input tax would only shift left the supply of labor, say from S_N to $S_N{}'$, increasing the pre-existing distortion in the labor market by τw times

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[8]An alternative assumption would be to adjust the rate of income tax to keep the government budget balanced as in Parry (1997) and in Fullerton and Metcalf (1997). By balancing the budget through lump-sum rebates, there is no revenue recycling effect (as referred to by Parry) but there remains a TIE. The assumption of lump-sum rebates of the Z-tax also makes the analysis formally similar to an analysis of a system of pollution quotas in which the quota rights are sold by auction to private firms.

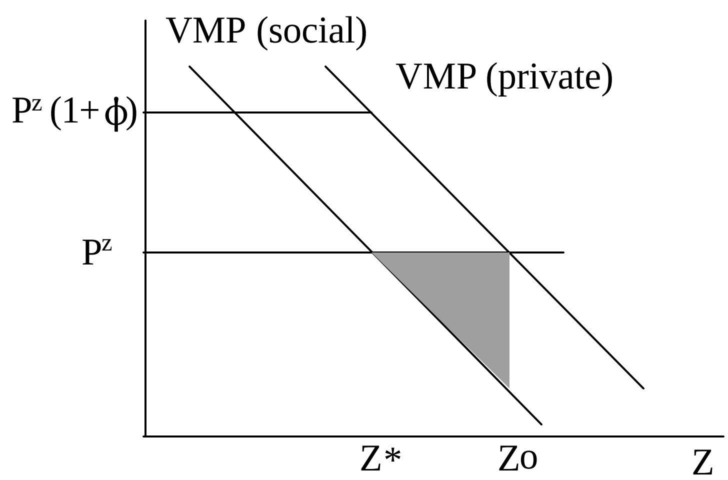

Figure 4. Optimal Selection of Nonlabor Polluting Input Z

the reduction in equilibrium labor employed. This is the TIE discussed in the literature. But with an increase in environmental quality brought about by the reduction in Z, the effective labor input is enhanced. This shifts the demand for labor to the right from VMP_N to VMP_N', which offsets to some degree the reduction in equilibrium employment of labor.

There is another effect in the present model, and implicit in Figure 5, beyond what is captured in a model like Parry's: by explicitly including environmental quality in the consumer's utility function, there is the scope for complementarity between environmental quality, E, and the market good, X.[9] From the consumer's perspective, there are then two offsetting effects on the supply of labor: (1) an increase in the equilibrium price of market goods, which induces a shift toward leisure (a leftward shift in the supply of labor), and (2) an exogenous increase in E, which might be complementary with some market goods. If higher levels of environmental quality induce

[9]Goulder, Parry, and Burtraw (1997) also model environmental quality in a representative consumer's utility function, but restrict utility to be strongly separable between environmental quality on the one hand and market goods and leisure on the other. This restricts environmental quality to be a substitute individually with all goods, so complementarity cannot arise. See Deaton and Muellbauer (1980).

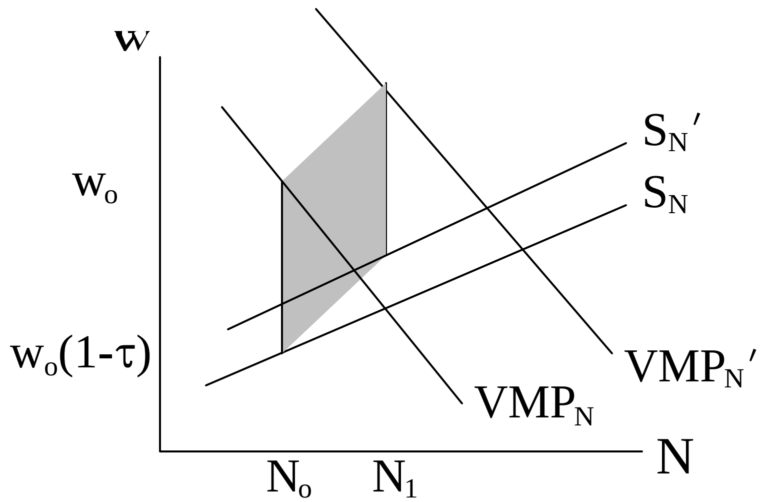

Figure 5. Labor Market Equilibrium

expenditures on complementary market goods (such as eco-tourism expenditures, cameras, and down-filled parkas) then, to some extent, there is a rightward shift in the supply of labor: workers have incentives to work harder to earn the money to spend on goods complementary with environmental quality.

Figure 5 focuses on the TIE and not the complete welfare calculation. Further, it is not calibrated with any particular empirical measures of the effects discussed. If the VMP_N and S_N curves were to shift as drawn, such that the post-pollution-tax quantity of labor were larger than the pre-tax quantity, then the TIE would be a welfare gain equal to the size of the shaded parallelogram. Added on to the PE measure of Figure 4, the TIE would provide an added benefit from the pollution tax. As in Harberger (1964), the sign of the TIE, the extra-market distortion, is entirely dependent on the sign of the change in the quantity of labor.

The general point is this. Once one considers an integrated analysis of the costs and benefits of environmental regulation, it is not clear on which side of the ledger GE welfare accounting falls. To introduce pre-existing distortions only while considering the costs of environmental policy is a partial application of GE methodology and can be misleading.

6. Summary and Directions for Future Research

This paper has identified three significant challenges to the straightforward application of an upward correction to account for TIEs in social cost estimation. The first is the empirical relationship between specific environmental regulations and changes in the real wages of workers must be measured in real world conditions with all of the complexities of real-world markets and regulatory strategies. The models presented in Section 4 show that the size of theorized efficiency losses depend critically on how abatement and output markets are modeled and measured. It can be argued that the assumptions in much of the existing literature tend to increase the estimated size of efficiency losses. Empirical studies of specific regulations and markets can help to establish just how large these effects are in practice.

The second significant challenge is gauging the importance of environmental benefits. If the environment is understood as an essential input to economic production, and not simply as a consumption good, then effective environmental regulation can be expected to have important interactions with the tax system that can cause social costs to be lower than those found in PE analyses. A model of how this occurs in specific instances was presented and interpreted in Section 5 and echoes the concerns of Williams (2000). The importance of environmental quality as a production input is so central to environmental policy that this challenge must be fully addressed before a complete view of TIEs can emerge.

Third, there is the concern of picking a specific distortion and modeling the second-best consequences in isolation of all others. Parry and Bento (2000) demonstrate that when other tax distortions are considered, very different (third-best) consequences of environmental regulation may result. Addendum 1 raises the question of the appropriate frame of reference for considering the TIEs of environmental regulations.

It is to be hoped that progress in the understanding of environmental economic phenomena will move toward a consideration of economy-wide effects, just as it is to be hoped that intertemporal efficiency and ecological service flows (to name just two examples of important phenomena characterized by limited economic knowledge) will be similarly incorporated. EPA should fully support these efforts. However, caution should be used in treating interesting but largely theoretical results as empirical fact in applying economics to specific policy questions. For the time being, the current state of knowledge gives good reason for caution.

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Addendum 1: Multiple Distortions and the Sequence of Social Cost Accounting

This addendum addresses a basic and nontechnical issue concerning the philosophy of cost-benefit analysis of multiple government policies. There are two interventions contemplated in the TIE literature: an income tax and an environmental regulation. The analytical stance is that the income tax is the incumbent policy, which has generated a deadweight loss. The environmental regulation is proposed as an incremental policy and there is conceived no adjustment of the income tax system to the regulation. The TIE literature then properly proceeds to calculate the change in social welfare, by the potential Pareto improvement criterion, from the imposition of the regulation. The central point is that the two policies interact and in a negative way.

If one takes the negative interaction as fact, there is an issue as to which policy one charges for the interaction's cost. One logical possibility, with strikingly different welfare conclusions from the usual TIE approach, is as follows. Suppose that in an initial no-policy state there is an environmental externality and no income tax. If from this state one proposed a Pigovian tax on the externality, the true social gain could be calculated entirely in the taxed market. Even though the increase in the market price of the taxed good shifts the supply of labor, there is no increment in distortion from the labor market because there is no distortion to begin with. The value marginal product of labor equals the marginal supply price before and after imposing the pollution tax.

If one next imposed an income tax, the standard PE calculation of its welfare cost would be complete and accurate as well. Even though the tax shifts demand, and perhaps supply, for the polluting good, there is no divergence between marginal social cost and marginal social benefit in that market because of the correction due to the pollution tax.

Thought of this way, there is no TIE because the environmental tax or regulation is being applied to an undistorted economy. The sum of the welfare effects of the income and pollution taxes is independent of the order in which the policies are applied (income effects aside). But, if one analyzes the pair of policies by first considering the income tax and, second, the pollution tax, then the TIE reappears as a necessary adjustment to the cost of the pollution tax. A seemingly unnoticed implication of this order of measurement is that there is an “externality interaction effect” due to shifts in the distorted market induced by the income tax. If the TIE is negative, the EIE is positive and roughly the same size. The advice for policy analysts from the TIE literature should, then, not only be that cost-benefit analysis of environmental regulation should be reconsidered and adjusted for extra-market effects, but that so should the excess burden of taxation be recalculated to consider interactions with externality-distorted markets.

Addendum 2: Comparative Static Results from the GE Model

The model comprises seven equations.

Production

Under constant returns to scale, the cost function for the firm can be written as $C(w^*,P^Z,X) = c(w^*,P^Z)X$, where c(.,.) is the unit cost function. The wage, w^*, refers to the price per effective labor unit: $w^* = w/\alpha(E)$. Shephard's lemma gives the output-conditional demand for Z as the

$$c_z\left(\frac{w}{\alpha(E)}, P^z(1+\phi)\right)\cdot X = Z, \tag{1a}$$

derivative of C(.,.,.) with respect to P^Z:

where c_Z denotes the partial derivative of unit cost with respect to P^Z, and ϕ is the proportionate rate of tax on the polluting input.

Similarly, the conditional factor demand for effective labor units can be expressed in terms of the cost function. The demand for actual labor units is related to the demand for effective units and equated to labor supply:

$$\frac{1}{\alpha(E)}c_{w^*}\left(\frac{w}{\alpha(e)}, P^z(1+\phi)\right)\cdot X = T^o - L, \tag{1b}$$

where c_{w^*} denotes the partial derivative of unit cost with respect to w^*, T^o is the total endowment of labor, and L is the chosen quantity of leisure.

Because the production function is assumed to be constant returns to scale, the previous two expressions are combined to determine the ratio of factors employed. The scale of production is determined by demand and the condition that unit cost equal output price, P^X, which is normalized to equal one (all prices are expressed in terms of X):

$$c\left(\frac{w}{\alpha(E)}, P^{Z}(1+\phi)\right) = 1. \tag{2}$$

Preferences

Consumers have preferences over the market good (X), leisure (L), and environmental quality (E). They choose levels of X and L given their income (Y). Their Marshallian demands are given by

$$X = X^{*}\,(w\,(1-\tau),\, P^{X} = 1,\, E,\, Y), \text{ and} \tag{3}$$

$$L = L^{*}\,(w\,(1-\tau),\, P^{X} = 1,\, E,\, Y). \tag{4}$$

Budget Constraints

The consumer budget constraint is $Y = wT^{o}\,(1-\tau) + G$. The government's budget constraint is $G = \tau w(T^{o} - L) + \phi P_{Z} Z$. Assuming that all tax revenues, labor, and input are returned as lump sums implies the following combined constraint:

$$Y = w(T^{o} - \tau L) + \phi P^{Z} Z. \tag{5}$$

The Environment

$$E = h(Z),\; h_{Z}\,(Z) < 0. \tag{6}$$

Eqs. (1) through (6) fully describe the equilibrium of the economy with P^{Z}, τ, and ϕ taken as exogenous.

To examine the comparative statics of the system, express Eq. (1) through (6) in log-differential form. For notational convenience, all differentials below refer to log-differentials. That is, dZ refers to dlnZ, dX to dlnX, etc. The one exception to this rule is that $d\phi$ will be understood to refer to changes in levels, not logarithms, of the tax rate. The log-differential system, evaluated at an initial equilibrium of $\phi=0$, and with $dP_{Z}=d\tau=0$ can be written as

$$-d_Z + \sigma d_W + (1-\sigma)\eta_E^{\alpha} d_E - \frac{L}{T^{o}-L} d_L - \sigma d\phi = 0 \qquad (1')$$

$$s(d_W - \eta_E^{\alpha} dE) + (1-s)\, d\phi = 0 \qquad (2')$$

$$dX = \eta_W^X\, dw + \eta_E^X\, dE + \eta_Y^X\, dY \qquad (3')$$

$$dL = \eta_W^L\, dw + \eta_E^L\, dE + \eta_Y^L\, dY \qquad (4')$$

$$dY = dw - \mu dL + \psi d\phi \qquad (5')$$

$$dE = \eta_Z^E dZ \qquad (6')$$

where the system variables are

Z	= polluting input,
E	= environmental quality,
X	= market consumption good,
ϕ	= proportionate rate of tax on X,
T^o	= time endowment,
L	= leisure ($N = T^o - L$ = labor supply),
P^X, P^Z, w	= market prices of X, Z, and N,
Y	= income, and
τ	= proportionate rate of tax on labor income.

Parameters of the system Eqs. (1′) through (6′) are defined as

s	= labor cost share = $wN/(wN+P_Z Z)$,
σ	= elasticity of substitution between effective labor, N^*, and Z,
η_E^{α}	= elasticity of effective labor w.r.t. environmental quality,

η_W^X = elasticity of X demand w.r.t. w,

η_E^X = elasticity of X demand w.r.t. E,

η_Y^X = income elasticity of demand for X,

η_W^L = elasticity of L demand w.r.t. w,

η_E^L = elasticity of L demand w.r.t. E,

η_Y^L = income elasticity of demand for L,

ψ = $P^Z Z/[w(T^o - \tau L)] > 0$, and

μ = $\tau L/(T^o - \tau L) > 0$.

Substituting for dE from Eq. (6′) into Eqs. (1′ through 4′) and for dM from Eq. (5′) into Eq. (3′) and Eq. (4′) gives

$$[(1 - \sigma)\, \eta_E^{\alpha}\, \eta_Z^E - 1]dZ + \sigma dw - \frac{L}{T^o - L} dL = \sigma d\phi \qquad (1'')$$

$$s\, \eta_E^{\alpha}\, \eta_Z^E d - s dw = (1 - s)\, d\phi \qquad (2'')$$

$$dX - \eta_E^X\, \eta_Z^E dZ + \eta_{P^x}^X\, dw + \mu \eta_X\, dL = \psi \eta_X d\phi \qquad (3'')$$

$$-\, \eta_E^L\, \eta_Z^E dZ + \eta_{P^x}^L\, dw + (1 + \mu \eta_L)\, dL = \psi \eta_L d\phi \qquad (4'')$$

where η_j^i generally describes the elasticity of variable i with respect to argument j.

The homogeneity of the Marshallian demands ($\eta_W^X + \eta_{P^x}^X + \eta_Y^X = \eta_W^L + \eta_{P^x}^L + \eta_Y^L = 0$) was used to reduce Eq. (3″) and Eq. (4″).

Substituting for dZ from Eq. (2″) into Eq. (1″), Eq. (3″), and Eq. (4″) gives

$$(\eta_E^{\alpha}\eta_Z^E - 1)\, dw - \frac{L}{T^o - L}\eta_E^{\alpha}\eta_Z^E dL = \left\{\sigma\eta_E^{\alpha}\eta_Z^E - \frac{1-s}{s}[(1-\sigma)\eta_E^{\alpha}\eta_Z^E - 1]\right\} d\phi \qquad (1''')$$

Eqs. (1′′) and (4′′) comprise a subsystem determining dw and dL for exogenous dϕ. The solution to the two-equation system relevant to the TIE is

$$\frac{dL}{d\phi} = \frac{\eta_Z^B\left\{\eta_B^E\left[\eta_{w*}^L\left(\frac{1-\sigma-s}{s}\right) + \psi\eta_Y^L\right] + \frac{\sigma}{s}\eta_B^L\right\} - \frac{1-s}{s}\eta_{w*}^L - \psi\eta_Y^L}{\eta_B^E\eta_{w*}^L - \eta_B^L} \tag{7}$$

$$\eta_B^X dX - (\eta_B^X + \eta_w^X \mu \eta_L^E)\, dw - \eta_B^E \eta_Z^B - \mu \eta_B^E \eta_Y^X\, dE_Z = \frac{L}{T^\circ - L}\left[\psi \ldots + \left(\frac{1-s}{s}\right)\eta_B^X\right] d\phi \tag{3′′}$$

$$(\eta_B^E\eta_{w*}^L - \eta_B^L)\,dw + \eta_B^E(1+\mu\eta_Y^L)\,dL = \left[\psi\eta_B^E\eta_Y^L + \left(\frac{1-s}{s}\right)\eta_B^L\right]d\phi\,. \tag{4′′}$$

This expression cannot be signed without placing restrictions on the parameters. That is, the TIE can be positive or negative. If dL/dϕ is positive, then the pollution tax induces an increase in leisure, a decrease in labor, and an increase in the income tax distortion. If dL/dϕ is negative, then the TIE is a benefit to the pollution tax beyond what is measured in PE.

The equation for dL/dϕ is complex, even in this relatively simply GE model. Two special cases are of interest, however, and can be analyzed without recourse to simulation. The first is to set $\eta_Z^E = 0$, implying that the input Z has no effect on environmental quality, thus turning off all interaction between the tax scheme and the environment. In this case,

$$\left.\frac{dL}{d\phi}\right|_{\eta_Z^E=0} = \frac{\frac{1-s}{s}\eta_{w*}^L + \psi\eta_Y^L}{1+\mu\eta_Y^L}\,. \tag{8}$$

If leisure and the market good are substitutes, then the effect of the pollution tax is to increase leisure, which has a negative TIE. This condition is sufficient but not necessary.

A second special case is one where employment of Z degrades the environment ($\eta_Z^E < 0$), but there is no effect of environmental quality on labor productivity

$$\left.\frac{dL}{d\phi}\right|_{\eta_E=0} = \frac{-\frac{\sigma}{s}\eta_Z^E\eta_E^L + \frac{1-s}{s}\eta_{Ex}^L + \psi\eta_Y^L}{1 + \mu\eta_Y^L + \frac{L}{T^o - L}\eta_E^L\eta_Z^E} \quad . \tag{9}$$

In this case, the role of complementarity between leisure and environmental quality can be seen. If η_L is negative and large (L and E are strong substitutes), then leisure and the income tax distortion are reduced by the introduction of the pollution tax. The η_L measure is the elasticity version of Madden's (1991) substitution measure in a mixed system.

The model just presented is, of course, highly abstract and meant to illustrate broad forces. It could be refined to address the issues of GE welfare analysis more subtly. Useful refinements include modeling more than one type of market good, allowing different degrees of complementarity between environmental quality and market goods; modeling more than one type of leisure time, allowing leisure to have different degrees of complementarity with environmental quality; and modeling more than one input, allowing there to be polluting and nonpolluting inputs. It should also be noted that the model just discussed is specialized in that it assumes constant returns to scale technology (see the discussion in Section 4 of this report) and it assumes that the economy faces a perfectly elastic supply of the polluting input. These specifications could be altered as well.