NBER WORKING PAPER SERIES

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Working Paper 7259
http://www.nber.org/papers/w7259

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
July 1999

This paper was prepared for the NBER-FEEM Conference on Distributional and Behavioral Effects of Environmental Policy to be held in Milan, Italy on June 11-12, 1999. For funding the authors thank the NBER and the National Science Foundation (SBR-9811324). For helpful suggestions, the authors thank Eliana de Bernardez Clark, Larry Goulder, Gilbert H.A. van Hagen, Rob Williams, and participants at the conference in Milan. This paper is part of NBER's research program in Public Economics. The views expressed herein are those of the authors and not necessarily those of the National Bureau of Economic Research or the National Science Foundation.

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NBER Working Paper No. 7259
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ABSTRACT

We explore the effects of environmental taxes that imprecisely target pollution. A review of actual policies indicates few (if any) examples of a true tax on pollution. More typically, environmental taxes target an input or output that is correlated with pollution. We construct a simple analytical general equilibrium model to calculate the optimum tax rate on the input of the polluting industry, in terms of key behavioral parameters, and we compare this imprecisely-targeted tax to an ideal tax on pollution. Finally, we consider incremental tax reforms such as a change in either tax from some pre-existing level. Using a utility-based money-metric measure of welfare, we examine the losses that arise from not taxing pollution directly. With no existing tax, under our plausible parameters, the welfare gain from an output tax is less that half the gain from an emissions tax.

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I. Introduction

A tax per unit of pollution can induce all the cheapest and most efficient forms of pollution abatement (Pigou, 1932). To reduce its tax liability, the firm can switch to a less-polluting fuel, add a scrubber, change disposal methods, or otherwise adjust its production process. These methods of substitution in production reduce the pollution per unit of output. In addition, the tax raises the overall cost of production, so the higher equilibrium output price chokes off demand for the output. Thus the tax has a "substitution effect" that reduces pollution per unit, and an "output effect" that reduces the number of units.

Yet few actual taxes are targeted directly on pollution (Barthold, 1994). Taxes on gasoline are prevalent around the world, and the use of gasoline is indeed correlated with vehicle emissions. This gas tax might provide some incentive to reduce emissions by driving less, but it provides no incentive to reduce emissions per gallon (such as by adding pollution control equipment). The United States taxes chemical feedstocks associated with contaminated Superfund sites, and this tax may help reduce pollution, but it provides no incentive to use a cleaner production process, to avoid spills, or to use any other method of reducing pollution per unit of chemical input (Fullerton, 1996). In Europe, some industrial effluent taxes are calculated using an assumed industry-wide rate of effluent per unit output, so the firm cannot reduce its tax by reducing its own effluent per unit (Hahn, 1989). These taxes miss the substitution effect.

In this paper, we measure the welfare effect of improperly-targeted instruments. We build a simple analytical general equilibrium model with substitution in production and demand by consumers, and we derive second-best optimal tax rates on emissions or on output. These rates are based on preference parameters, technological parameters, and pre-existing tax rates. We discuss these optimal tax rates, and then we choose plausible values of the parameters to calculate the effects of a small change in each tax rate. For alternative initial conditions, we use the model to calculate the cost of missing the target: the welfare gain from a targeted tax on emissions minus the gain from an imperfectly-targeted tax on output of the polluting industry.

Actual taxes may miss the target for several reasons. First, actual policy may not fully appreciate the importance of hitting the target. Policymakers may have been concerned primarily with equity considerations, trying to ensure that polluting industries are made to pay for pollution -- without realizing that the form of these taxes affect incentives to reduce pollution. Second, actual emissions may be difficult or impossible to measure. In these cases, the best available tax may apply to a measurable activity that is closely correlated with emissions. To reduce vehicle emissions, for example, the gasoline tax may be the best available instrument. Third, the technology of emission measurement is improving over time. Policymakers may be slow to adjust the tax base to reflect the newly-reduced cost of measuring a particular pollutant.

We do not measure or model the costs of targeting the tax on pollution, that is, the costs of measurement, monitoring, and enforcement. We only measure the benefits of properly targeting the tax. Thus our results can be taken as a measure of the importance of developing new measurement or enforcement technologies and of reforming the law to take advantage of those technologies. That is, we calculate the improvement over an output tax that can be obtained by a targeted tax on pollution that can capture the substitution effect as well as the output effect.

The next section reviews actual environmental taxes around the world and describes the extent to which they miss the target. The following section reviews existing economic literature on this subject. Most early economic models ignored the substitution effect, assuming that pollution was associated only with output. More recently, others model substitution in production but assume that the emissions tax is fully available. Schmutzler and Goulder (1997) provide a partial equilibrium model of the difference between an output tax and an emissions tax. Our paper contributes to this literature by providing a general equilibrium model to compare the welfare effects of these taxes.

If emissions cannot be monitored at reasonable cost, and policy is limited to a tax on the output of the polluting industry, then how should that tax rate be set? One might think that the imperfection of this blunt instrument would reduce the optimal rate of tax.

In our results section, we show that is not the case: the second-best output tax should be set to capture the exact same output effect that would have been captured by the emissions tax. If the unavailable emissions tax would have raised output price by 12 percent, for example, then the output tax should be set to 12 percent. We also solve for the optimal emissions tax in a second-best world with some fixed pre-existing output tax.

Finally, we use plausible parameters to calculate the incremental effects on welfare of slight increases in any pre-existing output tax or emissions tax, and we show the "welfare gap." We find that the welfare gain from an initial emissions tax is more than twice the gain from an initial output tax. This cost of missing the target does not depend on the size of the pre-existing output tax, or on the size of the elasticity of substitution in utility, but it does depend on the elasticity of substitution in production. A larger ability to substitute between emissions and other inputs in production substantially raises the importance of hitting the target.

II. Environmental Taxes Around the World

While the economics literature has long championed the use of market-based instruments (e.g. environmental taxes and tradable permits), most countries have long relied on a system of regulations including command and control regulations. In the past ten years, however, countries have begun to shift to the use of environmental taxes of some sort. In this section, we review the types of taxes that are typically used and consider to what extent these taxes "hit the target."[1]

As we noted above, the problem of targeting environmental taxes accurately in most cases follows from a difficulty in monitoring emissions. This has led Eskeland and Devarajan (1996) to distinguish between "direct" and "indirect" instruments to control pollution. Direct instruments require knowledge of actual emissions, while indirect instruments do not. A Pigouvian tax, as developed in textbooks, is a tax on emissions themselves. The difficulty with direct taxes is that monitoring emissions is technologically difficult and administratively complex. Thus, most actual policies fall back on indirect approaches to reduce emissions; the problem of hitting the target can be reframed as a problem of the administrative need to use indirect instruments.

A. Air Pollution

A variety of taxes are employed around the world to combat air pollution. Sweden applies a charge on actual Nitrous Oxide (NO_x) emissions of large heat and power producers (final sale only) at a rate of roughly 40 Swedish Crowns per kg of NO_x ($7.17 per kg) (OECD, 1994). For companies without emission measurement equipment, standard emission rates (in grams of NO_x per Joule) exceed typical average actual emissions. The higher assumed emission rate provides an incentive for companies to install measurement equipment. Tax collections are rebated to firms on the basis of final energy production. Thus the combination is revenue neutral, as it provides a subsidy to low emitting firms and a tax on high emitting firms. The Swedish experience suggests that technological limitations to the use of directly targeted taxes may fall with technological progress. Moreover, this tax provides an interesting example of allowing firms to choose whether to be subject to a direct or an indirect tax. For firms that do not adopt monitoring equipment, the tax becomes a tax on fuel consumption; the actual NO_x emissions are irrelevant.

Japan levies a charge on SO_2 emissions, with the rate varying across regions. The tax is based partly on historic emissions (1982-1986) and partly on emissions from the previous year. The tax rate in 1992 was 124 yen/Nm^3 for historic emissions, and it was between 95 and 860 yen/Nm^3 depending on the geographic region in which emissions occurred (OECD, 1994). Allowing the rate to vary across geographic region provides the possibility of linking the rate more closely to marginal environmental damages. Whether Japan does in fact link the rates closely to marginal environmental damages is a question beyond the scope of this paper.

Taxes on coal illustrate how technological differences can significantly affect the ability to target emissions directly. A number of European countries levy a tax on the sulfur content of various fuels. Norway levies a charge on the sulfur content of oil. Sweden levies a charge on the sulfur content of oil, coal, and peat. A strict sulfur-content tax is an indirect tax in that it does not require any monitoring of emissions. It also does not provide any incentives to use scrubbers or otherwise reduce sulfur emissions (other than by shifting from high to low sulfur content fuel). Sweden rebates the tax to firms that can demonstrate significant reductions in SO_2

emissions from the use of technologies such as flue gas cleaning. As of 1993, Finland levied a tax differential between standard and sulfur-free oil.

A tax on carbon content can be viewed as a direct tax on CO_2 emissions in the sense that it is economically infeasible to alter the ratio of carbon emissions to carbon content of the fuel in the industrial process.[2] Thus, whatever carbon is embodied in a fuel will be released to the atmosphere upon burning. As of 1992, six OECD countries had either explicit or implicit carbon taxes (Denmark, Finland, Italy, Netherlands, Norway, and Sweden). Most of the countries tax different sectors at different rates, with some sectors exempted altogether. These taxes, to our knowledge, do not provide any incentive for carbon scrubbing.

The Montreal Protocol of 1989 required the eventual phasing out of halons and chlorofluorocarbons (CFC's). In the United States, Congress imposed taxes on these ozone-depleting chemicals at the same time that it implemented quantity regulations. The tax rate depends to some extent on the degree of ozone depletion. Merrill and Rousso (1991) note that the purpose of this tax was to capture monopoly rents arising from quantity restrictions. While the tax rate is not explicitly set equal to social marginal damage, it is a direct tax in that these chemicals have a direct relationship to the ozone depletion damage stemming from their use. They are indirect and thus imprecisely targeted, however, in the sense that CFC emissions to the atmosphere are assumed rather than measured. No distinction is made in the use of CFCs regarding circumstances where release to the atmosphere is more or less likely.

B. Water Pollution

Taxes related to water pollution are of two general types: user charges for sewage treatment and wastewater effluent charges. The latter is of more concern to us than the former. Better targeted taxes would be based on "load," a measure of the pollutants contained in the wastewater. It can be measured on an instantaneous basis (so many parts per million) or on a flow basis (so many grams per hour or day). Sewage treatment charges for households are based on water consumption rather than load on the treatment plant, and so they serve as an indirect charge. Industry is more likely to be metered with charges based on load. In 1992, for example, Denmark, Finland, Norway, and Sweden all levied charges on firms based on pollution loads exceeding some minimum amount.

In 1976, Germany implemented a water effluent charge for firms (to go into effect in 1981), with different rates for different pollutants (e.g. Chemical Oxygen Demand (COD) and heavy metals). Firms are taxed on the basis of "damage units," defined approximately as the amount of pollution generated by one individual. Damage units are defined in terms of the amount of discharge of various pollutants.[3] While the tax is a tax on emissions, certain features of the system make it more an enforcement mechanism for technology standards. In particular, firms get a 75 percent reduction in rates if they can demonstrate compliance with specific technology standards. Thus, the tax might be viewed as a tax on old technology rather than on pollution. To the extent that the tax induces a shift to new, less polluting technology, however, these standards may improve targeting relative to standards that do not induce technology improvement.

C. Solid and Hazardous Waste

The OECD distinguishes between municipal waste user charges and waste disposal taxes. Municipal waste user charges may be collected as a flat rate, but they are increasingly based on actual waste, and they are used to finance the cost of collection and disposal. In contrast, waste disposal taxes generate revenues that either go into the general budget or are earmarked for environmental expenditures (e.g. subsidies for recycling). Since no effort is made to monitor the contents of waste, any pollution to ground water from solid waste in a landfill does not affect the charge to households or to firms producing the waste. In other words, these taxes are indirect taxes with no incentive for shifting the composition of the waste stream.

As of 1992, five OECD countries had some form of tax that they characterize as hazardous waste taxes. As the United States experience makes clear, these taxes may be described only very loosely as taxes on hazardous waste. The United States levies a number of Superfund taxes detailed in Fullerton (1996). These are taxes on petroleum ($.097 per barrel) as well as on 42 organic and inorganic chemical feedstocks -- with rates ranging from $.22 to $4.87 per ton in 1992. The chemicals to be taxed were chosen to some extent on the basis of their presence in hazardous waste sites to be cleaned up under the Superfund law. In particular, the tax rates are set to raise a specified sum necessary to clean up Superfund sites, where required collections on oil and chemicals are based on their relative importance in waste sites. These are indirect taxes at best, and, like many of the taxes discussed above, they do not provide incentives for emissions reduction. They might reduce purchase of the petroleum or chemical products, but they do not influence its handling, use, or amount that becomes waste.

For hazardous waste, the form of disposal affects the marginal environmental damages quite dramatically. This fact suggests that a tax on the disposal of hazardous waste could reduce welfare if it shifts the mode of disposal from safe, monitored disposal sites to illegal dumping in unmonitored, unsecured sites. The welfare impact of a tax on hazardous waste disposal will depend importantly on the cost of monitoring disposal activities as well as the cost of enforcement and illegal disposal activities. The more costly it is to monitor disposal activities and enforce rules for proper disposal, the more likely it would be that a tax on hazardous waste disposal would reduce welfare.

As of 1992, several countries levied taxes on the disposal of automobile batteries (Canada, Denmark, Portugal, and Sweden) with differing rates based on the type of battery. Some countries levy charges on waste oil disposal (Finland, France, Italy, Norway, and the United States). Numerous countries levy charges on packaging. Other taxes are levied on disposable diapers (Canada), car tires (Canada, the United States), and plastic shopping bags (Italy).

D. Taxes on Products Associated With Pollution

Product taxes are indirect taxes by definition. As of 1992, ten OECD countries levied some form of one-time sales tax differential on cars based on weight (Canada), degree of compliance with emission standards (Belgium, Greece, Japan, Netherlands, and Sweden), fuel efficiency (Canada, Japan, and the United States), or the lack of a catalytic converter (Finland, Germany, and Norway).

In 1992 three OECD countries levied higher *annual* taxes on vehicles that lack a catalytic converter (Austria and Denmark) and on average emissions for major pollutants for each class of car (Germany). All OECD countries levy excise taxes on gasoline. In addition, many OECD countries levy a higher tax on leaded than unleaded fuel. For example, Denmark, Finland, and Norway levied a surtax on leaded fuel of $.11 per liter in 1992.

E. Summary

This brief survey of environmental taxes suggests that few taxes anywhere are precisely targeted taxes on emissions. The failure to target emissions precisely may follow from significant costs associated with measuring emissions, from costs associated with monitoring point and non-point source emissions at reasonable cost, and – as a consequence – difficulties with preventing tax evasion and illegal disposal activities.[4] To some extent, however, the imprecise targeting may result when policymakers do not fully appreciate the costs of missing the target.

III. Prior Literature

The literature on environmental taxes is extensive. Most papers, however, do not focus on the distinction between taxes on emissions and taxes on inputs or outputs that are imperfectly correlated with emissions. In an early example that is typical of this literature, Sandmo (1975) carries out an optimal tax exercise in the presence of externalities. One of the consumption goods enters the utility function directly as a negative externality. Because of the one-for-one relation between the good itself and pollution, a tax on the good corresponds exactly to a tax on pollution. If the good itself is associated with pollution, instruments to discourage pollution can only operate through an output effect (as discussed above). Actually, the tax on output can still perfectly correct for pollution associated with an input – if output must be produced using a fixed amount of pollution per unit.[5] With substitution in production, however, the output tax is no longer equivalent to a tax on pollution.

A recent paper by Cremer and Gahvari (1999) extends the Sandmo analysis to allow for pollution to be associated with one of several inputs in production of a "dirty good." In a standard optimal tax analysis, Cremer and Gahvari show first that emissions taxes and output taxes are not equivalent and, second, that both emissions and output taxes may be needed to achieve optimality in a second-best world. In effect, the emissions tax corrects externalities while the output tax rates handle tax collections for general revenue needs in an optimal fashion. While it is an important extension to the original Sandmo analysis, the Cremer and Gahvari paper does not consider the loss from using an output tax instead of an emissions tax. That is, it still assumes that taxes on emissions are feasible.

A recent paper by Schmutzler and Goulder (1997) directly examines the trade-off between the use of emissions taxes and output taxes in the presence of imperfect monitoring of emissions. They note that previous authors (e.g. Cropper and Oates, 1992) have recognized that output taxes may be preferable to emissions taxes if emissions are difficult to monitor, and they attempt to make more precise what it means to be "difficult to monitor." They enumerate four factors that affect the choice between emission and output taxes: 1) monitoring costs, 2) technological factors, 3) the regulator's information structure, and 4) social preferences for consumption goods versus environmental quality. As the costs of monitoring emissions rise, the advantage of precisely targeted emissions taxes falls. This effect relates to evasion possibilities, as discussed in the previous section about hazardous waste disposal taxes. Technological factors come into play by determining the scope of substitution in production away from pollution. If emissions are a fixed proportion of output, then an output tax would be equivalent to an emissions tax without the need to measure emissions directly. The regulator's information structure determines what it can monitor. Regulators face difficulty monitoring emissions, but they may face even more difficulty trying to tax certain inputs or output (thereby affecting the relevant target). Finally, the loss from poorly-targeted instruments is a loss in the value of output, while the loss from high cost of monitoring may be a loss in environmental quality, so the trade-off in utility between consumption and the environment may also affect the choice of instruments. The paper by Smulders and Vollebergh (1999) presented at this conference explores many similar issues.

Policy can miss the target in another important sense that we note here but do not pursue in this paper. In the presence of multiple pollutants, targeting one pollutant may cause substitution out of that pollutant and into other pollutants. Devlin and Grafton (1994) explore this topic in the context of determining the optimal number of tradable permits for a pollutant when multiple pollutants co-exist.[6]

All of these papers ignore general equilibrium considerations. A large literature starting with Bovenberg and de Mooij (1994) explores the welfare consequences of environmental taxes and other instruments in a general equilibrium context with pre-existing taxes.[7] These papers have typically focused on the interactions among taxes rather than on the issue of emissions taxes versus output taxes (or otherwise imperfectly targeted taxes). In the model that we present below, we allow for general equilibrium considerations as well as the existence of other distorting taxes.[8] We turn now to that model.

IV. A General Equilibrium Model of Production and Consumption

The review of environmental taxes in the previous section indicates a slow movement away from output taxes toward emissions taxes. Having said that, the predominant existing environmental taxes still miss the target in that they tax a purchased input to production or an output sold, but not emissions per se. In this section, we carry out a general equilibrium analysis of the costs and effects of using mistargeted environmental instruments. The model allows us to investigate the welfare effects of a commodity or emissions tax in a second-best world with a pre-existing labor distortion. We allow for choices in production and consumption, using the same notation as in Fullerton and Metcalf (1997). The model has a homogeneous population (of size N) and the possibility to substitute inputs in production. We assume perfect competition, complete information, and perfect factor mobility. The model has a clean good (X) and a dirty good (Y) which is produced using labor (L_Y) and emissions (Z).

A number of policies can be analyzed with this model. We can solve for the optimal second-best tax rate (either on emissions, Z, or on output, Y) as a function of preference and production parameters as well as pre-existing tax rates. In addition, we can consider various incremental tax reforms. With respect to the latter, we consider the four possible scenarios listed in Table 1.

Table 1. Policy Experiments
1. Pre-existing tax on Y only
A. increase tax on Y
B. new tax on Z
2. Pre-existing tax on Z only
A. new tax on Y
B. increase tax on Z

Most actual taxes fall into category 1, as noted in our review above, and the relevant policy reform is either an increase in one of these taxes or the introduction of a new more-targeted tax. Taxes on gasoline are an output tax, for example, so proposals in the United States to increase the gasoline tax would be an example of scenario 1A. On the other hand, proposals for a new carbon tax in the context of current taxes on gasoline would be an example of scenario 1B. As an example of a pre-existing tax on emissions, a carbon tax was implemented in the Scandinavian countries in the early 1990s. Policy reforms to implement new taxes in those countries on goods associated with pollution would be examples of scenario 2A, while proposals to increase the carbon taxes would be examples of scenario 2B. We begin by developing the model in the case with pre-existing taxes on either emissions or output, but we first consider only an incremental tax on output (t_Y).

A. Production

The clean good is produced in a constant returns to scale technology using only labor (L_X) as an input:[9]

$$X = L_X \tag{1}$$

For convenience, the numeraire is taken to be labor (or equivalently the clean good). The dirty good (Y) is produced in a constant returns to scale production function using labor (L_Y) and emissions (Z):

$$Y = F(L_Y, Z) \tag{2}$$

Also, emissions entail some private cost in terms of resources (labor), and we can define a unit of emissions as the amount that requires one unit of resources:[10]

$$Z = L_Z \tag{3}$$

Aggregate emissions adversely affect environmental quality:

$$E = e(NZ) \quad e' < 0 \tag{4}$$

Finally, a public good is produced using labor:

$$G = NL_G \tag{5}$$

The amount of this public good is held constant in revenue-neutral reforms below.

B. Consumption

In this model, the N identical households derive utility from the two private goods (X and Y), leisure (L_H), the public good (G), and environmental quality (E):

(6) $$U = U(X, Y, L_H; G, E)$$

The household budget constraint is given by

(7) $$X + (p_Y + t_Y)Y = (1\text{-}t_L)L$$

where

(8) $$L = L_X + L_Y + L_Z + L_G.$$

Government finances the public good with a pre-existing tax on labor income (t_L) and possibly a tax on output (t_Y). The nominal net wage is $1\text{-}t_L$. A fixed amount of time ($\bar{L}$) can be allocated between work (L) and leisure (L_H).

C. Comparative Statics

Below, we consider the effect of changing various prices through the use of taxes. We employ a log-linearization technique for the analysis, an approach that is appropriate when considering small changes. This technique allows us to capture important behavioral attributes of producers and consumers with a few key parameters. It also makes for a tractable analysis by allowing us to solve a system of linear equations. The goal in this section is to develop the various equations that trace through the impacts of a tax change on prices, quantities, and welfare. We begin by noting how any changes affect utility:[11]

(9) $$\frac{dU}{\lambda L} = t_L \hat{L} + t_Y\left(\frac{Y}{L}\right)\hat{Y} - (t_Z - \mu)\left(\frac{Z}{L}\right)\hat{Z}$$

where dU is the change in a representative agent's utility and λ is the private marginal utility of income. The term μ equals $-NU_E e'/\lambda$ and is the marginal social damage from pollution. A hat over a variable indicates a percentage change (e.g. $\hat{Z} = dZ/Z$). The left hand side of this expression is the change in welfare (in dollars) as a fraction of the total resource in the economy. The right hand side is composed of three parts. The first two parts are the welfare effect of the environmental policy through its impact on labor supply and the amount of the dirty good. Since labor is already discouraged as a result of the tax on wage income, any policy that further discourages labor supply will reduce welfare. A similar effect holds for any pre-existing tax on the dirty good. If either t_L or t_Y is zero, the corresponding welfare effect on labor or the dirty good disappears from the equation. The third term is the welfare impact resulting from the change in pollution.

In order to find tractable solutions to the welfare equation in (9), we make some simplifying assumptions on consumer preferences. In particular, we assume that environmental quality and the public good are separable from the consumption goods and that the consumption goods enter utility in a homothetic sub-utility function[12]:

(10) $$U(X,Y,L_H,E,G) = U(V(Q(X,Y),L_H), E,G)$$

where V and Q are both homothetic. For later use, define p_Q as a price index on $Q(X,Y)$ such that

(11) $$p_Q Q = X + (p_Y + t_Y)Y$$

and let w be the real net wage,

(12) $$w = (1-t_L)/p_Q .$$

Thus the change in the real net wage ($\hat{w} \equiv dw/w$) will be related to the change in the labor tax ($\hat{t}_L$, defined as $dt_L/(1-t_L)$) and the change in p_Q ($\hat{p}_Q \equiv dp_Q/p_Q$). From (11), the change in p_Q depends on the change in the producer price p_Y and the change in the output tax ($\hat{t}_Y \equiv dt_Y/(1+t_Y)$). Finally, let c_Y be the consumer price for Y

(13) $$c_Y = p_Y + t_Y \ .$$

Our assumptions on consumer preferences allow us to characterize the general equilibrium response to a change in the tax on Y with four equations:

(14) $$\hat{Y} - \hat{X} = \sigma_Q(\hat{p}_X - \hat{c}_Y) = -\sigma_Q\hat{c}_Y$$

(15) $$\hat{L} = \varepsilon\,\hat{w}$$

(16) $$\hat{w} = -\,\hat{t}_L - \phi\hat{t}_Y$$

(17) $$(1-\phi)\hat{X} = \hat{L} - \hat{t}_L - \phi(\hat{Y} + \hat{t}_Y)$$

In these equations, σ_Q is the elasticity of substitution in consumption between X and Y, ε is the uncompensated labor supply elasticity, and ϕ is the share of the consumer's after-tax income spent on Y. Equations (14) and (15) follow directly from our definition of σ_Q and our assumptions on consumer preferences. Equation (16) follows from totally differentiating equation (12) and using equation (11), while equation (17) follows from differentiating the consumer's budget constraint.

We totally differentiate the government budget constraint, hold G fixed, and assume that the revenue from the change in t_Y is offset by a change in t_L. These assumptions provide the fifth equation in our system:

(18) $$\hat{t}_L = -\left(\frac{t_L}{1-t_L}\right)\hat{L} - \left(\frac{t_Z Z}{(1-t_L)L}\right)\hat{Z} - \phi\left[\hat{t}_Y + \left(\frac{t_Y}{1+t_Y}\right)\hat{Y}\right]$$

This is the change in t_L necessary for government to balance the budget when changing t_Y. Next, we turn to the equations implied by production. As yet, we do not allow for a change in the tax on emissions. Thus any change in inputs or output comes entirely from an output effect. Because of constant returns to scale in production, we have

(19) $$\hat{Y} = \hat{Z} = \hat{L}_Y$$

Also, the producer price is fixed,[13] and so

(20) $$\hat{c}_Y = \hat{t}_Y$$

Equations (14)-(20) represent eight linear equations that can be solved for the eight variables ($\hat{Y}, \hat{X}, \hat{w}, \hat{t}_L, \hat{c}_Y, \hat{L}, \hat{L}_Y$, and $\hat{Z}$), all as functions of the exogenous $\hat{t}_Y$.

After we solve for changes in Y, L, and Z as functions of the change in t_Y, we substitute these expressions into equation (9) and express the welfare change as a function of the incremental tax reform:[14]

(21) $$\frac{dU}{\lambda L} = -\left\{ \frac{\sigma_Q(1-\phi)\left[(1-t_L)\left(t_Y\left(\frac{Y}{L}\right) + (t_Z - \mu)\left(\frac{Z}{L}\right)\right) + \varepsilon t_L \mu\left(\frac{Z}{L}\right)\right]}{(1 - t_L - \varepsilon t_L) - (1+\varepsilon)\left(t_Y\left(\frac{Y}{L}\right) + t_Z\left(\frac{Z}{L}\right)\right)} \right\} \hat{t}_Y$$

Despite the complexity of this equation, we can make some general observations about the welfare impact of an incremental tax reform. First, note that the welfare impact does *not* depend on the ability to substitute out of emissions in production (σ_Y). Since we have limited our instrument to a tax on the dirty output, the only welfare gain comes about from an equilibrium output effect (arising from substitution in consumption). The change in the output tax provides no substitution effect in production.

Second, the first term in the denominator must be positive to ensure that the government is on the upward sloping side of the Laffer curve for wage taxation. We will assume that this is always the case. A condition for the entire denominator to be positive is for $\varepsilon < (NL-G)/G$, or that ε be bounded above by the ratio of private output to government output.[15] We will also assume that this condition holds throughout.

Third, note that the formula simplifies considerably with no pre-existing taxes:

(21')
$$\frac{dU}{\lambda L} = \sigma_Q(1-\phi)\mu\left(\frac{Z}{L}\right)\hat{t}_Y$$

Welfare is unambiguously increased by an initial output tax, so long as consumers can substitute from Y to X.[16]

Next we turn to a model for the case where the policy shock is a change in the tax on emissions rather than on output. The relevant equations (14) and (15) are unchanged, and other equations change as noted by primes:

(14)
$$\hat{Y} - \hat{X} = \sigma_Q(\hat{p}_X - \hat{c}_Y) = -\sigma_Q\hat{c}_Y$$

(15)
$$\hat{L} = \varepsilon\,\hat{w}$$

(16')
$$\hat{w} = -\,\hat{t}_L - \left(\frac{(1+t_Z)Z}{(1-t_L)L}\right)\hat{t}_Z$$

(17')
$$(1-\phi)\hat{X} = \hat{L} - \hat{t}_L - \phi(\hat{Y} + \left(\frac{(1+t_Z)Z}{Y}\right)\hat{t}_Z)$$

(18')
$$\hat{t}_L = -\left(\frac{t_L}{1-t_L}\right)\hat{L} - \phi\left(\frac{t_Y}{1+t_Y}\right)\hat{Y} - \frac{(1+t_Z)Z}{(1-t_L)L}\left[\hat{t}_Z + \left(\frac{t_Z}{1+t_Z}\right)\hat{Z}\right]$$

(19.1')
$$\hat{L}_Y = \hat{Z} + \sigma_Y\hat{t}_Z$$

(19.2')
$$\hat{Y} = \left(\frac{L_Y}{Y}\right)\hat{L}_Y + \left(\frac{(1+t_Z)}{Y}\right)\hat{Z}$$

(20')
$$\hat{c}_Y = \left(\frac{(1+t_Z)Z}{(1+t_Y)Y}\right)\hat{t}_Z$$

Equations (19.1') and (19.2') require a bit of explanation. The first equation is the behavioral relationship in production given by the elasticity of substitution in production (σ_Y). Then the second equation follows from the first order conditions in production.

Combining these equations and using the zero profits condition, we can solve for the welfare impact of a change in the tax on emissions:

(22)

$$\frac{dU}{\lambda L} = -\left\{ \frac{\begin{array}{c} \sigma_Q(1-\phi)(1+t_Z)\left(\frac{Z}{Y}\right)\left[(1-t_L)\left(t_Y\left(\frac{Y}{L}\right)+(t_Z-\mu)\left(\frac{Z}{L}\right)\right)+\varepsilon t_L \mu\left(\frac{Z}{L}\right)\right] \\ +\sigma_Y\left(\frac{L_Y}{Y}\right)(1+t_Y)\left[(1-t_L)(t_Z-\mu)\left(\frac{Z}{L}\right)+\left(\varepsilon t_L+(1+\varepsilon)t_Y\left(\frac{Y}{L}\right)\right)\mu\left(\frac{Z}{L}\right)\right] \end{array}}{(1+t_Y)\left[(1-t_L-\varepsilon t_L)-(1+\varepsilon)\left(t_Y\left(\frac{Y}{L}\right)+t_Z\left(\frac{Z}{L}\right)\right)\right]} \right\} \hat{t}_Z$$

The top term in the numerator of equation (22) is very similar to the whole numerator in equation (21) and reflects substitution in consumption (that is, the effect on output). The second term in the numerator reflects the substitution effect in production, as we now have the possibility of changing relative input prices. With no pre-existing taxes of any kind, the expression simplifies to

(22') $$\frac{dU}{\lambda L} = \left\{\sigma_Q(1-\phi)\left(\frac{Z}{Y}\right)+\sigma_Y\left(\frac{L_Y}{Y}\right)\right\}\left(\frac{\mu Z}{L}\right)\hat{t}_Z .$$

The first term in equation (22') corresponds to equation (21'), adjusted for the fact that the tax is on emissions rather than output. It represents the output effect from the emissions tax. In addition, a substitution effect is captured by the second term.

V. Model Analysis

A. Optimal Tax Rates

We begin the analysis by considering the optimal tax in the various scenarios described above. First consider the optimal emissions tax in the case with a pre-existing tax on labor but no tax on output. This is, we ask what is the tax t_Z in equation (22), where $t_Y=0$, such that no further change $\hat{t}_Z$ can affect welfare (dU=0). We set equation (22) to zero and solve for the tax rate on emissions:

$$t_Z^* = \mu\left(1-\left(\frac{t_L}{1-t_L}\right)\varepsilon\right) \tag{23}$$

Unless the tax rate t_L or the uncompensated labor supply elasticity is zero, the term in brackets is less than one, and the optimal emissions tax is less than the social marginal damages ($t_Z^* < \mu$). This result is consistent with Bovenberg and de Mooij (1994).

To see how our expression (23) relates to other results in the literature, let Ψ be the partial-equilibrium marginal cost of public funds for the labor tax. Goulder and Williams (1999) show that

$$\psi = 1+\frac{t_L \frac{\partial L_H}{\partial t_L}}{L - t_L \frac{\partial L_H}{\partial t_L}} \tag{24}$$

Then some simple manipulation of this formula provides

$$\psi = \left[1-\left(\frac{t_L}{1-t_L}\right)\varepsilon\right]^{-1} \tag{25}$$

With positive tax rate and positive labor supply elasticity ε, the marginal cost of funds is $\Psi > 1$. Thus equation (23) can be rewritten as

(23') $$t_Z^* = \frac{\mu}{\psi},$$

as noted by Sandmo (1975) and Bovenberg and van der Ploeg (1996).[17]

Analogously, if the emissions tax is unavailable (t_Z=0), we can solve for the second-best tax on output as the t_Y in (21) such that a change $\hat{t}_Y$ does not raise welfare (dU=0). We set the numerator of equation (21) to zero and find:

(26) $$t_Y^* = \left(\frac{\mu}{\psi}\right)\left(\frac{Z}{Y}\right)$$

A striking result is that the optimal tax on output is so similar to the optimal tax on emissions.[18] This tax is "second-best" in two respects. First, this t_Y is reduced when divided by $\Psi>1$, to account for the pre-existing tax on labor. Second, one might think that it should be reduced even more, to account for missing the target. The output tax is a blunt instrument for dealing with pollution. On the other hand, perhaps t_Y should be increased to get *more* of an output effect since it misses the substitution effect. Yet equation (26) shows that the output tax should be set to generate exactly the same output effect as the ideal emissions tax. To see this, note that the second best emissions tax ($t^*_Z = \mu/\psi$) would raise production costs by $(\mu/\psi)Z$. Divide this amount by Y to get the extra cost per unit of output, which is exactly the amount that t_Y^* would raise the price of output.[19]

In other words, the fact that the output tax cannot achieve the desired substitution effect should not deter policymakers from its use to achieve the desired output effect. The optimal t_Y^* is the damage per unit of output -- calculated as the desired the tax per unit of emissions (t_Z^*) times emissions per unit output (Z/Y).

If the ideal t^*_Z were unavailable, could the authorities set t^*_Y and enforce it? If firms differ, one might think that authorities would need to know each firm's Z (or equivalently Z/Y) to set that firm's output tax rate using equation (26). Yet, if authorities knew Z, it seems they could employ an emissions tax directly. However, authorities only need to measure (or estimate) Z/Y once to set the output tax rate. The tax can then be enforced simply by counting units of output. In contrast, the emissions tax requires continuous measurement of Z, especially after firms change their Z/Y ratio in response to the tax. Moreover, if firms are similar, authorities only need the average Z/Y to set the output tax rate. Even if firms are similar, the emissions tax requires authorities to measure (or at least threaten to measure) each firm's emissions.

Next, consider the possibility of pre-existing taxes either on emissions *or* on output. Equation (26) generalizes readily in the presence of a pre-existing tax on Z:

(27) $$t^*_Y = \left(\frac{\mu}{\psi}\right)\left(\frac{Z}{Y}\right) - t_Z\left(\frac{Z}{Y}\right)$$

The first term in (27) is the output effect from the optimal output tax if t_Z were zero. The second term adjusts the tax rate to account for the output effect already obtained from taxing emissions. If the emissions tax is fixed suboptimally, then the additional required output tax is simply the additional desired output effect to account for the undertaxation of emissions. If emissions are taxed optimally (t_Z equals μ/ψ), then (27) shows that the optimal tax on output is zero.

To find the optimal tax on emissions (t_Z^*) in the case of a pre-existing tax on output, we find the tax rate on emissions that cannot raise utility. That is, we find t_Z in equation (22) such that dU=0. The solution to this equation is more complicated:

(28)
$$\sigma_Q(1-\phi)(1+t_Z^*)Z\left[(1-t_L)\left(t_Y Y+(t_Z^*-\mu)Z\right)+\varepsilon t_L\mu Z\right] + \sigma_Y L_Y(1+t_Y)\left[(1-t_L)(t_Z^*-\mu)Z+\left(\varepsilon t_L+(1+\varepsilon)t_Y\left(\frac{Y}{L}\right)\right)\mu Z\right]=0$$

While solving for t_Z^* is not possible, we can rewrite equation (28) to make a basic point:

(28')

$$t_Z-\mu=-\left(\frac{(1-t_L)\sigma_Q(1-\phi)(1+t_Z)t_Y Y+((\sigma_Q(1-\phi)(1+t_Z)Z)\varepsilon t_L+(\sigma_Y L_Y(1+t_Y)\varepsilon t_L+(1+\varepsilon)t_Y\left(\frac{Y}{L}\right)))\mu}{(1-t_L)(\sigma_Q(1-\phi)(1+t_Z)Z+\sigma_Y L_Y(1+t_Y))}\right)$$

While we have not explicitly solved for the optimal emissions tax (since t_Z appears on both sides), we can show that the right hand side is less than zero. Thus the optimal emissions tax rate is less than social marginal damages ($t_Z^*<\mu$), with pre-existing t_Y and t_L. A sufficient condition for the emissions tax rate to equal social marginal damages is that ε and t_Y both equal zero.[20] Note that if either the t_L or ε is zero (so $\psi=1$), then t_Y non-zero still means that the optimal tax on emissions is less than μ.

For the special case where $Y=Z$ and $\sigma_Y=0$, equation (28) collapses to

(28")
$$t_Y+t_Z=\frac{\mu}{\psi}$$

In this case, we need not distinguish between taxes on emissions or output, since the production function is such that output itself is polluting. Once again, the optimal tax is marginal social damages divided by the marginal cost of public funds.

B. Incremental Tax Reforms

We now turn to a numerical analysis of tax reforms. We measure the impact on welfare of a small change in either t_Z or t_Y. In order to carry out these calculations, we need values for a number of key parameters. Table 2 presents the assumed values for our base case calculations; justification for these selections appear in Fullerton and Metcalf (1997).

Table 2. Parameter Assumptions	
Parameter	Value
μ	0.3
ε	0.3
σ_Q	1.0
Y/L	0.3
σ_Y	1.0
Z/L	0.15
t_L	0.4

Little evidence exists on some of these parameters, especially σ_Q and σ_Y, and so we present sensitivity analysis in the next section. Also, marginal environmental damages (μ) could be considerably higher for some pollutants (and lower for others). Tax rate results are proportional to μ, however, so it is easy to see how results change with that parameter.

Consider Scenario 1, with no pre-existing tax on emissions but with a pre-existing tax on labor and (perhaps) on output. With these values, the *first-best* Pigouvian tax would be μ=0.3, but the marginal cost of funds is ψ=1.25, so the second-best tax on emissions is 0.24 (from equation 23'). Then, since emissions constitute half of output, equation (26) says that the second-best tax on output is 12 percent. For our measure of welfare, we use $dU/\lambda L$, the monetary value of the change in utility as a fraction of total income.

Figure 1 depicts the general welfare effects of a small change in either the output tax or the emission tax, assuming no pre-existing emissions tax, for alternative values of a pre-existing output tax. The horizontal axis indicates the level of the output tax prior to the reform, and the vertical axis shows the net change in welfare as a proportion of national income. The absolute welfare change may be in billions of dollars, but dividing by GDP makes the relative gains look small on the vertical axis. Consider the lower dashed line, which indicates the change in welfare for a change in t_Y. First note that it crosses the horizontal axis at $t_Y = .12$. Since the optimal output tax with this configuration of parameters is .12, welfare does not change when the tax rate is altered from this level. At tax rates below this optimum, welfare rises when the tax on Y is increased a small amount. The maximum gain occurs with no pre-existing tax on output.[21] The line falls below the horizontal axis in the region where t_Y exceeds 12 percent, indicating that a further increase in the tax rate would reduce welfare.

The solid line shows the welfare gain from introducing a small emissions tax. First, note that this line is everywhere above the line for raising the output tax. For any pre-existing tax on output, welfare is raised more by introducing a tax on emissions than by increasing the tax on output. Recall that the major distinguishing difference is that the emissions tax provides both output and substitution effects while the output tax only provides an output effect. As an approximation, then, the substitution effect is the gap between these two lines. With no initial taxes, the welfare gain from a small output tax is less than half that of a small emissions tax: more than half of the gain from an emissions tax comes from the shift in production processes as emissions become more expensive. This decomposition depends directly on σ_Y, because the crucial distinction between an output tax and emissions tax is the ability of the latter to operate through the substitution effect. Below, we provide some sensitivity analysis on this parameter.

Second, the welfare gain from introducing an emissions tax is everywhere positive. At high pre-existing output tax rates, the additional output effect *reduces* welfare, but the initial substitution effect from the first introduction of t_Z is sufficiently strong to overwhelm any negative output effect.

Figure 2 corresponds to Scenario 2 (no pre-existing output tax). The horizontal axis now indicates the level of a pre-existing emissions tax. The optimal emissions tax for this set of parameter assumptions is 24 percent, so the solid line measuring the incremental gains from an incremental emissions tax crosses the horizontal axis at 0.24 (where welfare cannot be raised by any change in t_Z). Interestingly, the output tax curve also crosses the horizontal axis at 24 percent. In other words, if the pre-existing emissions tax is already at the second-best optimal rate of 0.24, then the initial introduction of t_Y has no first order effect on welfare. Back at the vertical axis, where the initial t_Y and t_Z are both zero, the introduction of an initial t_Z dominates the introduction of an initial t_Y (since t_Z has both substitution and output effects). In other words, the "Emissions Tax" curve starts out higher than the "Output Tax" curve, and they must both cross the horizontal axis at 0.24 (the second-best optimum). If the emissions tax rate *exceeds* the second-best optimum, a further increase in this tax is more welfare reducing than an increase in the output effect, since the increase in the emissions tax has both an unwanted substitution effect as well as an unwanted output effect.

C. Sensitivity Analysis

The first two figures are drawn using one set of preference parameters and technological parameters. Clearly, however, the size of the substitution effect depends on the elasticity of substitution in production (σ_Y), and the size of the output effect depends on consumer demand (the elasticity of substitution in utility, σ_Q). We vary those parameters in Figures 3 and 4, but we still show the effect of missing the target -- the "welfare gap" -- defined as the gain from adding a tax on emissions minus the gain from adding to the tax on output.

Figure 3 shows this welfare gap (on the vertical axis) for different values of the elasticity of substitution in utility (on the horizontal axis). The three curves in the figure correspond to three initial values of t_Y (0.0, 0.12, and 0.24). Since σ_Q most directly affects the output effect, and not the substitution effect, it does not much affect the cost of missing the target. When the initial tax rate is 12 percent or lower, the welfare gain from the emissions tax exceeds the gain from the output tax by a relatively constant amount. At higher levels of pre-existing t_Y, a higher σ_Q raises this amount.

Figure 4 shows the welfare gap for different values of the elasticity of substitution in production (again for initial t_Y equal to 0.0, 0.12, or 0.24). The assumed value of σ_Y clearly affects the size of the welfare gap. For any initial tax on output, the ability to substitute in production dramatically increases the importance of hitting the target.

VI. Conclusion

A tax on pollution has been suggested by Pigou (1932) and thoroughly analyzed in the economics literature ever since, but a true Pigouvian tax is essentially never employed by actual policy. Most actual environmental taxes apply to the output of a polluting industry or to an input that is correlated with emissions, rather than directly to emissions. Perhaps policymakers think that the "polluter pays principle" is satisfied, since the polluters bear the burden of the output tax, but this paper shows the loss in welfare from missing the target in this fashion. Using plausible parameters, the introduction of a tax on emissions raises welfare by more than twice as much as a tax on output of the polluting industry. We find that the ability of producers to substitute away from emissions directly affects the cost of missing the target, but it does not affect the second-best optimal tax on output. In the case where emissions cannot be taxed, perhaps for technological reasons, we find that the second-best output tax should still be set to obtain the same effect on output price as would occur with the desired but unavailable emissions tax.

Other research directions are not explored in this paper but represent important avenues for further study. First of all, we ignore the administrative cost of trying to monitor emissions. If the ability to measure and tax emissions is a matter of degree, then we would expect a tradeoff at the margin between the falling marginal benefits of hitting closer to the target versus the rising marginal costs of doing so. The optimum might then involve some optimal *degree* of effort to measure and tax emissions.

Second, our model considers a tax on output of the polluting industry, for comparison with the ideal emissions tax, but some of the actual environmental taxes apply to an input to production that is correlated with pollution. To analyze such a tax, our model would have to be modified such that the polluting industry uses three inputs to production: labor, emissions, and some other input that is correlated to emissions.

Third, our model is rather stylized, with one clean output, one dirty output, and one very-general technology of switching from emissions to the other input in production. Our results are valuable for conceptual understanding of the importance of hitting the target, but specific policy problems should be analyzed for particular industries with carefully-specified technologies of pollution abatement.

Fourth, as indicated in our review of actual taxes above, some programs may allow the firm to choose between paying an output tax or purchasing abatement and monitoring equipment to pay a lower emissions tax. In addition, waste taxes may be earmarked for public spending on abatement. Hazardous waste taxes may increase illegal, unmonitored activities.

Finally, we note that our model relies on many other standard simplifying assumptions and thus could be extended to consider effects of uncertainty, imperfect competition, heterogeneity among firms, distributional effects among consumers, traded goods, transboundry pollution, and many other interesting problems.

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Figure 1. Proportional Change in Welfare From a Change in Emissions Tax or Output Tax (with Pre-Existing Labor and Output Taxes)

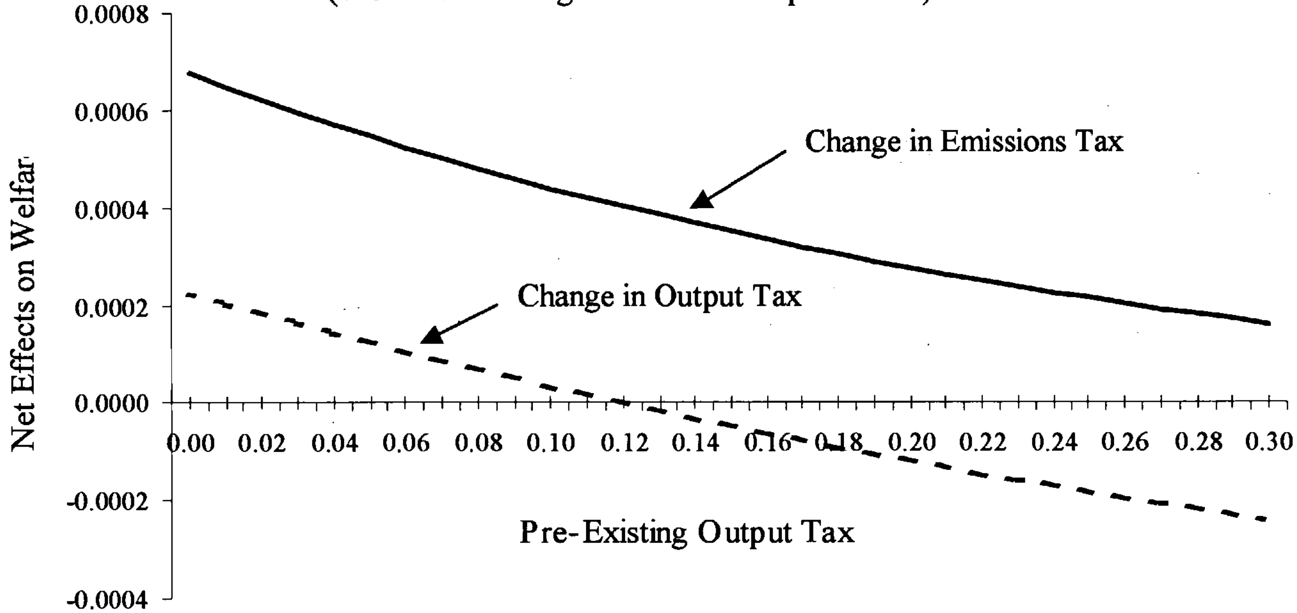


Figure 2. Proportional Change in Welfare From a Change in Emissions Tax or Output Tax (with Pre-Existing Labor and Emissions Taxes)

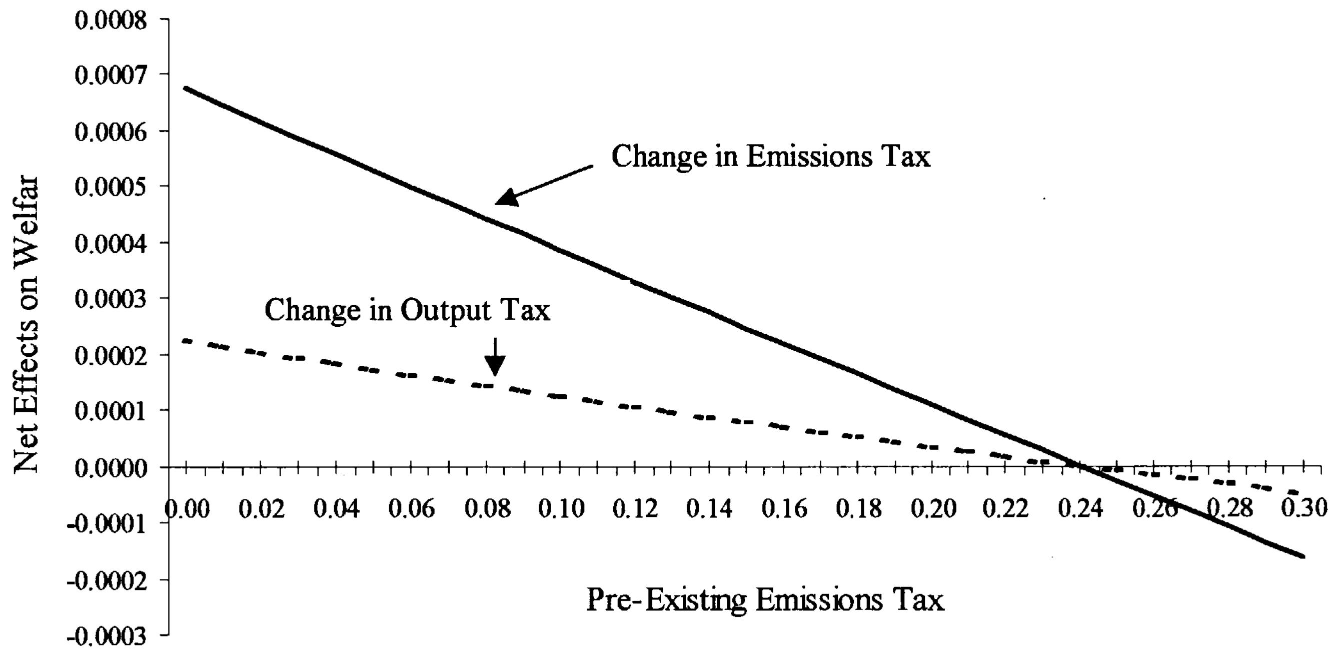


Figure 3. How the Welfare Gap depends on Substitution between Outputs: the Proportional Gain from Adding a Tax Emissions minus the Gain from Adding to the Tax on Output

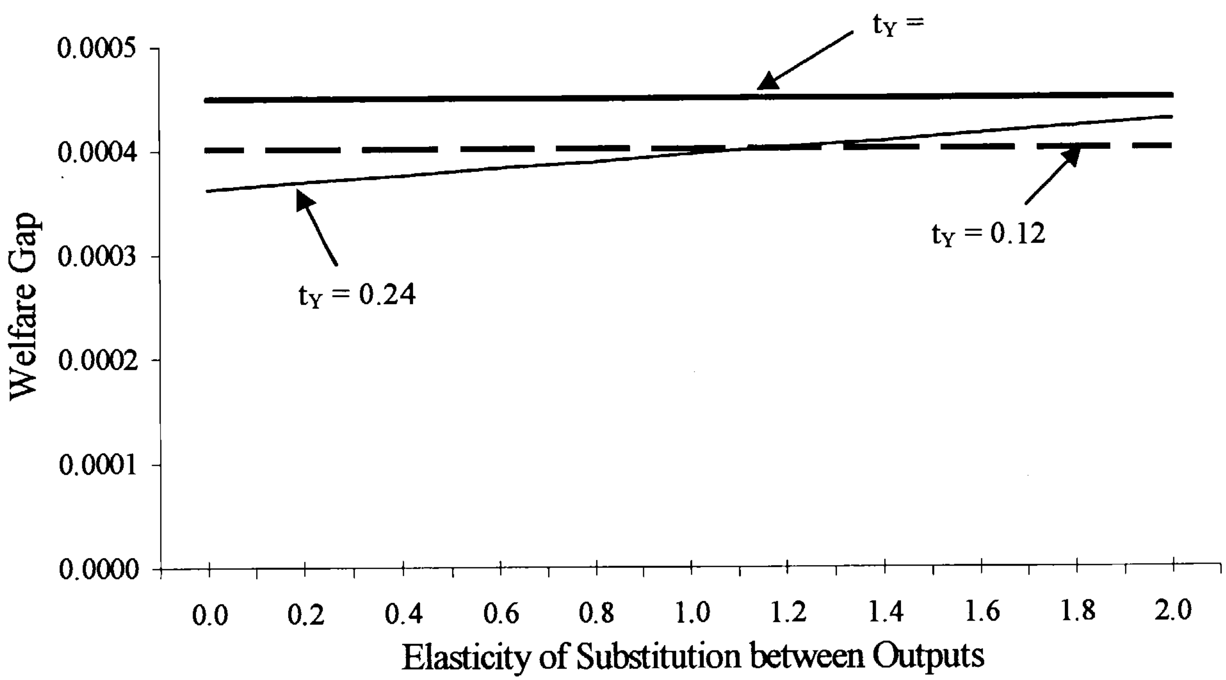
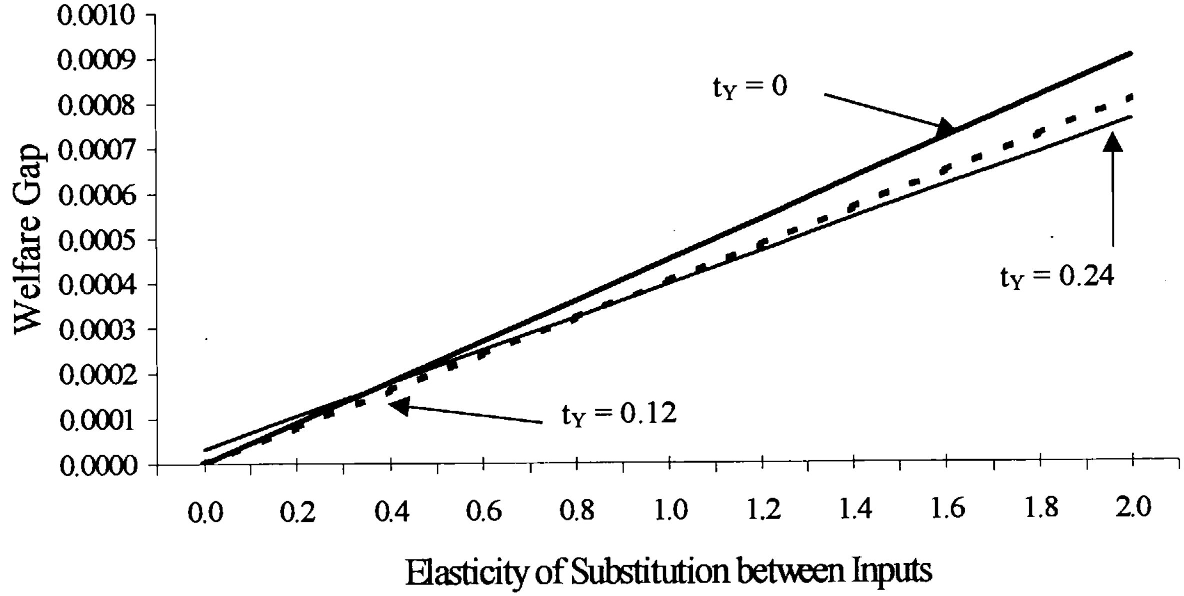


Figure 4. How the Welfare Gap depends on Substitution between Inputs: the Proportional Gain from Adding a Tax on Emissions minus the Gain from Adding to the Tax on Output



Endnotes

[1] Roughly speaking, market-based instruments may be either price-based or quantity-based instruments. Taxes are a form of price-based instrument, while tradable permits are a quantity-based instrument. This paper compares different kinds of taxes, while Fullerton and Metcalf (1997) use a similar model to consider quantity instruments.

[2] Processes for carbon scrubbing are described in Astarita et al (1983), but these technologies generate such a vast amount of solid waste (e.g. carbonic acid or forms of carbonates) that disposal costs become prohibitive. Sulfur scrubbing, on the other hand, involves a small amount of sulfur per ton of coal (or barrel of oil) and so does not lead to such significant sulfur disposal problems.

[3] The following amounts of effluents (in addition to others not listed) each add up to one damage unit: 50 kg of organic matter (COD), 3 kg of phosphorus, or 1 kg of copper and copper compounds (Anderson and Lohof, 1997).

[4] The paper by Siniscalco et al (1999) at this conference discusses the possibilities of voluntary compliance with pollution control rules.

[5] See, for example, the recent paper by Sandmo and Wildasin (1999). This statement is true so long as emissions per unit of output are constant across firms. Nichols (1984) notes that the cost of using an output tax rather than an emissions tax rise with variation across firms in the emissions to output ratio (even if this ratio is fixed for each firm). Nichols also notes that targeting emissions per se is not precisely correct, as the tax should distinguish among emissions according to their

marginal damages. This point justifies, for example, time-varying emissions taxes where marginal damages vary during the day.

[6] A similar idea was analyzed by Metcalf, Dudek, and Willis (1984) who consider the effect of controlling one form of disposal medium for a pollutant in a situation with multiple disposal media.

[7] A very partial list includes Bovenberg and Goulder (1996), Parry (1995), Goulder (1995), Goulder, Parry, and Burtraw (1997), and Fullerton and Metcalf (1997). This literature is surveyed in Fullerton and Metcalf (1998).

[8] The paper by Schmutzler and Goulder (1997) is closest in spirit to our paper. Their analysis is explicitly partial equilibrium, however, and they do not consider other pre-existing tax distortions.

[9] Our model assumes one factor of production, for simplicity called "labor," but under some circumstances this factor can be taken to represent a homogeneous composite of all clean resources used in production.

[10] Note that emissions are positively related to the use of these resources: L_Z is not to clean up or reduce emissions, but just to cart it away. Abatement is undertaken by substituting away from Z and into L_Y. This overall production function is still constant returns to scale, since Z is a linear function of L_Z. The private cost for emissions helps justify our assumption of an internal solution with a finite choice for Z, even without corrective government policy.

[11] This equation follows from totally differentiating the utility function and substituting in the consumer's first order conditions. Details are available from the authors.

[12] The assumption of separability is standard in this second-best tax literature because it is tractable and because it is a central case with neither complements nor differential substitutes. We only have two private goods (X and Y). With more disaggregation, particular private goods would undoubtedly be complements to leisure, or to the environment, and receive unique tax treatments for those reasons.

[13] We normalize the initial producer price of Y to be one, for any given emissions tax. In this section, where we do not allow for the emissions tax to change, the producer price will be unaffected by changes in the output tax.

[14] Details are available upon request from the authors.

[15] This follows from the fact that government spending is financed entirely by taxes: $G/N = t_L L + t_Z Z + t_Y Y$.

[16] The output effect disappears if σ_Q equals zero, because then consumers do not substitute X for Y when the latter's price rises. In addition, if ϕ equals 0 or 1, then the consumer is at a corner and again does not substitute X for Y (note that $\phi = 0$ implies $Z = 0$).

[17] This result is also consistent with Cremer and Gahvari (1999). They solve for optimal second-best tax rates on emissions and on outputs in the general case without separability, but in our case with separability, their emissions tax would be μ/ψ and their output tax would be zero (using t_L for revenue).

[18] For the special case where Y=Z, equation (26) collapses to (23').

[19] Actually, the optimal t^*_Y in (26) uses the Z/Y without any t_Z, without any substitution effect, so that Z/Y is higher than the optimal Z/Y. The "rule" in (26)

gives the same output effect, but the "level" of t^*_Y in (26) is higher than the output effect of t^*_Z (at optimal Z/Y).

[20] Alternatively, the optimal tax rate equals μ if t_Y and t_L are zero (that is, a first best world).

[21] It is tempting to integrate under this curve to measure the welfare impact of a large change in t_Y, say from zero to 12 percent. This would be a legitimate exercise if the private marginal utility of income were constant across this interval. In general λ is not constant, however, so the increments to welfare are measured in different units of income and are not additive.