Environmental Protection and Optimal Taxation

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Abstract

This paper brings together applied analysis under simplifying assumption and new research on principles for environmental protection when government is costly. The cost effectiveness analysis—the ranking in the control cost curve—applies under optimal taxation in the more general case, but the optimal environmental quality is adjusted.

I. Introduction

As I engaged in discussions on how to reduce air pollution in Mexico City with technical experts and representatives of the government of Mexico City, confidence in a text-book approach was shaken by several observations. One of these observations was that the government examined in detail how classes of vehicles and fuels could be made less polluting – or "cleaner". The textbook recommendation of an arms-length approach - an emission tax - was not only unpractical, but also not providing much guidance on principles.

It struck me then that economists did not have a plausible model for why emission standards and mandated technologies play a dominant role in practice. I would later become convinced that this blind spot in important ways have hampered our impact in practice, even in conveying well-founded insights. There were a number of guidelines I searched for, but did not find. Two important questions that I asked are explored in these essays:

- Should one stimulate emission reductions in the same way from firms and households, rich and poor?
- How should one combine instruments that make activities cleaner, with instruments that shift the economy towards less polluting activities?

Over the following years, I tried to contribute to practical advice under simplifying assumptions, while at the same time trying to develop principles under more general assumptions. The following essay reports on the lessons from this journey. As in the chronology of my own work, I start with applied analysis made with restrictive, simplifying assumptions. I then explore consequences of making less restrictive assumptions to see whether there is broader support, more general principles. In the subsequent essays, we go from quite general to more applied analysis. Eskeland 2000a and 2000b present the general theoretical analysis, while Eskeland, 1994 and Eskeland and Fezioglu, 1997 are applications to the problem of air pollution control in Mexico City. Thus, some readers may choose to skip Eskeland 2000a and 2000b, on generalizations of the assumptions under which the analysis can be justified. The cost effectiveness analysis for Mexico City (Eskeland, 1994, and Eskeland and Feyzioglu,

1997) is performed under conditions of "no distortionary taxation" and "a representative consumer", while Eskeland 2000a and 2000b, analyze under broader assumptions whether the same or similar analysis would apply.

One theme in this work will be that simple concepts from partial equilibrium analysis under first best have close parallels in general equilibrium with costly funding and redistribution, if one can assume that the tax structure is optimal. Another is that environmental protection is more like a problem of public goods provision than has been previously acknowledged. We see this as we introduce pollution abatement in the traditional public finance model.

The reader will see that there were some simple guideposts yet to be erected – principles to be highlighted - even though the literature in public finance and in environmental economics was quite dense with sophisticated principles.[1]

II. Our platform

We shall highlight a few key building blocks in what we shall call the public finance approach to environmental protection. The first is what Arthur Cecil Pigou explained as a difference between private and social net product; Pigou used the lighthouse as one of his examples. We shall use a very specific and stylized example giving rise to such a difference; what professor Paul Samuelson (1954) called *collective consumption goods.* Later, the accepted term came to be *pure public goods* "which all enjoy in common in the sense that each individual's consumption of such a good leads to no subtraction from any other individual's consumption of that good" (Samuelson, 1954).[2]

We shall use air quality as our main example of a pure public good. We can all understand how the air quality is there for everyone, though some may care more than

[1] I will continue in the active form, but switching here from *I* to *we*. *We* reflects in part that I hope I reason with the reader as we go along, in part recognition of what I have learned from those who have reasoned with me, worked with me.

[2] For the lighthouse example (later used by Ronald Coase), Pigou credits Sidgwick. Pigou also dwells on discrepancies in returns due to tenance relationships, showing awareness of: the role property rights; the challenges in structuring property rights well; and the role of government in this regard. Samuelson lets us know that he - through discussions with Richard Musgrave - learns that the principle he lays out is not new, but known. Victor Norman familiarized Norwegian students of economics with pure public goods by explaining "King services" as "superpublic goods", each person enjoying the King's services more the more others enjoy them.

others, and some may be exposed more than others. This example serves well also to demonstrate how a good is public, or "nonrivalrous", in one end - where we breathe fresh air and enjoy seeing the mountains - but "rivalrous" in the other, providing end: As one person or firm emits pollution, this subtraction from the public good must be compensated by another's reduction in emissions - if everyone's enjoyment is not to be reduced.

In the public finance approach to pollution control, environmental quality has typically been presented as a pure public good. A pollution indicator, *e*, may appear as an argument in a consumer *h*'s utility function (i.e. in her preferences),

(1) $u^h = u(x^h, e)$,

where x^h is a vector of quantities of private goods consumed by *h*, thus bearing her identity as a superscript, while the pollution level (or the air quality level) is the same for everyone.[3] This setup is used in Sandmo's seminal (1975) article "Optimal taxation in the presence of externalities", and it is used invariably in subsequent treatments, such as Bovenberg and van der Ploeg (1994), and Cremer, Gahvari and Ladoux (1998). Among others, Sandmo (1972) have analyzed collective factors of production, the analogy to pure public goods represented by a nonrivalrous input. Variations offered here are to analyze collective factors of production in a setting of costly revenue generation, and to allow environmental quality to be such a collective factor of production. This formulation should not be confounded with the typical depiction of the environment as a cost-reducing recipient of waste, which is rivalrous. We rather think of examples such as the tourism industry needing clean air, the brewer needing clean water, pharmacists needing a gene pool and farmers needing good weather.

A second key building block is that those reducing the environmental quality cannot readily be charged for their disservices, giving rise to *externalities* (equivalently: those who contribute to environmental quality cannot readily be compensated).[4] Since pure public goods are enjoyed by everybody to the exclusion of no-one, an exclusion

[3] See, for instance Sandmo (1975). The essential element is not that the pollution level is the same to everyone - a model characterized by Meade (1952) as atmospheric pollution. It is essential that the pollution level experienced by one person is influenced not only by herself but also (or only) by others. Often the approximation is used that the individual polluter views the pollution level as independent of her own emissions - a good approximation when the number of polluters is large.

mechanism does not in the outset offer itself to mobilize funds – or authority - to modify the actions of polluters. One perspective on government is a club that can weigh costs and benefits in areas such as pollution control on behalf of members. Thus, government can take on the role of charging for the disservices - or by other means to rectify the incentive problem.[5]

An important representation in the public finance literature of how the environmental good is provided is to describe pollution as proportional to output in a polluting industry *j* or to a polluting consumption activity (Sandmo, 1975):

(2) $e = f_j \Sigma_h x_j^h$.

The variation offered in the following shall be that polluters, or those who deliver to polluting activities (say, gasoline refiners and car makers) may devote resources to reduce those proportionality factors $e = \ _h f_j(a_j, b_j^h) x_j^h$, where a_j and b_j^h are resources devoted to abatement of emissions for good j by producers and by consumer *h*, respectively. We shall see that one unexpected reward for this generalization is new insights from parallels to the traditional problem of public goods provision.

The third key building block is government, represented by a benevolent planner whose objectives can be characterized by an individualist *welfare function* in the Bergson-Samuelson tradition:

(3) $w = w(v^1,..,v^h)$.

In (3), $v^h = v^h(q, I^h, e)$ is the indirect utility function corresponding to (1) for individuals 1,..,*h*. The individuals are assumed to take as given a vector of consumer prices *q*, lump sum private incomes I^h (which may be zero), government revenue and the quality of the environment. (3) embodies two statements about the objectives of the planner: he builds on individual preferences, and can compare utility differences (utility is cardinal).

In the context of environmental protection, it may be important to highlight that (3) is an anthropocentric framework. On the one hand, there is no environmental obligation - or moral code with regard to the environment - inserted in the model from the

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[4] The qualification that the "disservices to others" can not be charged for is due to Pigou (1932).
[5] Such a club would suffer under free-riding problems and would not mobilize much willingness to pay for the environment if membership were voluntary. This free-riding problem - being solved by compulsory

outside. On the other hand, the framework embodies individual preferences, not only people's hunger to consume. It includes and aggregates what individuals find to be their obligations and interests.

The fourth key building block is a government *revenue requirement* (or a set of public expenditure opportunities) and a set of policy instruments. The policy instruments may be insufficient to fund government programs without resorting to distortionary taxation. In our case, a contribution will be to show the role of emission taxes, and what can be done by surrogate instruments such as emission standards when an emission tax is not available.

Apart from these building blocks for our models, important guideposts have been erected by prominent travelers. In the field of taxation, Frank Ramsey (1927) and Paul Samuelson (1951) laid out how linear commodity taxes should be used to raise revenue in a way minimizing welfare costs. Pigou – who instigated Ramsey's analysis - conjectured that government expenditures should be lower in the case when revenue generation is costly than they would be otherwise (and made similar observations on distributional grounds, as Sandmo, 1999, points out). Stiglitz and Dasgupta (1971), Atkinson and Stern (1974), King (1986) and others have helped analyze and qualify Pigou's conjecture, providing insights and delineating exceptions. We shall show that this question is closely related to one raised recently in the debate on "double dividends" (Bovenberg and de Mooij, 1994). Diamond and Mirrlees (1971) and Dasgupta and Stiglitz (1972) provided the conditions under which efficiency in aggregate production is desirable even when the government must resort to distortionary revenue generation – findings of great relevance for the current study.

In the areas more closely associated with environmental protection and externalities, Ramsey (1927) noted that the task of revenue generation is distinct from the need to charge for damage for corrective purposes. Answering the challenge, Sandmo (1975) was first to deduce optimal principles under the dual objectives of correcting for externalities and mobilizing revenue. He concluded: "even in a world of distortionary taxation… there is scope for taxing externality generating commodities according to the

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membership - is equally serious whether citizens have the right to a clean environment - or polluters have the right to pollute. For an elaboration on this point, see Eskeland and Devarajan (1996).

Pigovian principle." The optimal tax structure is characterized by an "additivity property", where the revenue motivated terms apply to all commodities in a well-known fashion, and the term motivated by the need to correct the externality applies only to the tax on the polluting good. Among his findings was that the need for distortionary revenue generation in itself does not introduce reference to complements or substitutes to the polluting goods in the corrective part of his tax formula.[6]

We are now ready to introduce our applied analysis into this general framework, first by making very restrictive assumptions. In section IV, we visit the more general theoretical model. This gives us a chance to check whether the applied analysis is given support under more general assumptions, and also to extend the theoretical framework.

III. A presumptive Pigovian tax: to balance "cleaner" with "less"

Emission standards should be matched with commodity taxes

Drawing from Eskeland 1994 (which provides more detail), let us think about the problem in terms of a representative consumer and a government able to make lump-sum transfers, so there is no need to resort to distortionary revenue generation. Thus intervention to facilitate provision of the public good - environmental quality - is the only rationale for government intervention. Let us further think of environmental quality, or the absence of pollution, as a pure public good in the Samuelsonian sense of nonrivalry in consumption. Finally, let us assume that individual emissions, e, from a polluting activity - say driving - is determined by a technology parameter called abatement, a (say - the emission control equipment in the vehicle), and the scale of the activity, x, measured for instance by vehicle miles traveled or by gasoline consumption.

We simplify further by assuming only two private goods, so we can let $c=c(x,a)$ represent the cost of the quantity x and abatement a in terms of the other private good. We let $e=e(x,a)$ take the place of (2); a generalization since we do not restrict attention to costs and emissions that are proportional to consumption ($c=c(a)x;\ e=e(a)x$). A cost

[6] As Sandmo carefully points out ("our conclusion is no more than a statement about the terms in the formula"), the apparent additivity in the formula implies no independence between the environmental tax and the other taxes. This is not only because the shadow price of public revenue is a part of the corrective tax term, but also because all parameters in the formulas are functions of the tax structure.

effective pollution control program now can be found by maximizing $u(x,-c(x,a))$ subject to $e(x,a)=\bar{e}$. The first order conditions for optimum reduce to:

(4) $$\frac{u_x/u_y - c_x}{e_x} = -\frac{c_a}{e_a}.$$

The right hand side is the marginal cost of emission reductions through abatement. Relative to a unit of the other good a cost effective program requires a wedge between the marginal utility and the marginal cost of *x* which – per unit of marginal emissions – is equal to $-c_a/e_a$.

As is readily known – and easily checked - an emission tax equal to the Samuelsonian sum over consumers of the marginal rates of substitution between the public good and the numeraire good can implement the optimal solution. Such a tax satisfies (4), optimally combining inducement to abatement and reduction of demand for the polluting good. Furthermore, an emission tax at any other rate will implement cost effective environmental protection (4), meaning that the pollution reductions that are attained come at minimal costs, even if the reductions are not optimal.

An instrument that is equivalent to the emission tax in models with lump sum transfers is an exogenous quota for emissions. With multiple polluters, individual quotas will also have this property, if their allocation is exogenous and they are tradable. In contrast, individual emission quotas will typically result in some flaw in the incentive framework if their allocation is not exogenous. The allocation mechanism we shall focus on here is one in which the emission quota is given in association with some output choice (or input choice). One design frequently observed in practice is an *emission standard*, as when cars are allowed a maximum of 9 grams of carbon monoxide (CO) per mile driven (Harrington, 1997). Another one, with similar implications, is an *abatement standard*, as when cars are required to come with a catalytic converter. Quite intuitively, now, pollution reductions stimulated by an abatement standard (or an emission standard) alone will not achieve cost effective pollution control, since the standard awards emission quotas conditional on expanding output. For cars, an emission standard alone may or may not increase the marginal cost of driving, but will at any rate not discourage driving in the way commanded by a cost effective program (4). Polluters could be made better off if allowed to do less abatement, compensating by reducing the scale of the polluting activity

so as to leave total emissions unchanged. Similarly, an output tax alone will compress activity too much, ignoring low-cost technological abatement opportunities.

Public finance models have often made the simplifying assumption that emissions are determined by aggregate output alone, thus abstracting from the option of polluter abatement, making each unit of output less polluting.[7] Another consequence of such a modeling assumption is to make redundant the distinction between a corrective tax levied on emissions themselves and a corrective tax levied on the output of the polluting activity. In our context this distinction is important, and we use the term *presumptive Pigovian tax* when the corrective instrument is levied not on emissions but on an input or an output (say gasoline) in presumption of emissions.[8]

Observing that emission regulations typically apply to emission factors (grams emitted per mile driven, per ton of paper produced), the proposition that these empirically observed instruments should be accompanied by presumptive Pigovian taxes was made in "A presumptive Pigovian tax: Complementing regulation to mimic an emissions fee" (Eskeland, 1994). This is an alternative way of implementing the condition stated in (4), and is then given a practical illustration. The analysis of pollution control options for vehicular emissions in Mexico City allows us to focus on the dichotomy between "cleaner cars" and "fewer trips". The principle is spelled out in terms of a simple rule for cost effectiveness, to separate the message from the discussion of environmental benefits. The rule for how an optimal "matching gasoline tax" depends on the standard for abatement, $\bar{a}$, or the emission standard (equivalent, given our assumptions) is

$$\text{(5)} \qquad \frac{t_x}{e_x(x,\bar{a})} = -\frac{c_a}{e_a}(x,\bar{a}).$$

Thus, when the two instruments "match" each other to implement pollution reductions cost effectively, the corrective tax on gasoline, per gram of emission, is equal to the marginal cost of emission reductions through abatement. If we include another polluting

[7] Examples are Sandmo (1975), Bovenberg and van der Ploeg (1994), Bovenberg and de Mooij (1994), Cremer, Gahvari, Ladoux (1998). Diamond (1973), Sandmo (1976), Balcer (1980), and Wijkander (1985) focus on Pigovian taxes levied on goods that are imperfect as tax bases from the perspective of correcting the externality, using taxes and subsidies on associated goods as remedies for the imperfection.

[8] The term "presumptive" stands for a presumed relation to emissions, drawing on how the term is used in for instance presumptive income taxes. See Eskeland (1994), Eskeland and Devarajan (1996). Fullerton and Wolverton (1999) use the term in a similar way. Innes (1996), as well, proposes such an instrument to complement regulation in the context of polluting vehicles and fuels.

good, a corresponding formula applies for that good, and in addition it is required that the costs of emission reductions are the same across polluting goods.

The tax, quoted by the left hand side of (5) per unit of emissions, is translated to a tax rate per unit of the polluting good by multiplying both sides of (5) by the emission factor, $e_x(x,a)$. The resulting formula - a tax proportional to the polluting good's emission factor - is equivalent to Sandmo's (1975) formula in the case when the pollution reductions attained are optimal and lump sum transfers are available.

A positive theory of emission standards

It is puzzling to us that the principle of a presumptive tax on outputs to complement emission standards (5) has not – to our knowledge - been highlighted in the rich literature on environmental economics. Reasonable economists probably find the proposition unsurprising, but we shall dwell a little on why the correspondence in a cost effective program between emission standards and output reductions has not been highlighted.

It is possible to reason that if monitoring costs make emission taxes unworkable, then emission standards also cannot work. It is harder, however, to argue that a regime of emission standards cannot be complemented by commodity taxes in presumptions of emission (the emissions that are presumed to remain after abatement, that is). We shall argue that there are some practically important observations that economists failed to make which allowed them - or us - to miss the point that emission standards should be accompanied by output taxation.[9] These omissions were related to a lack of adequate positive models for emission standards - we did not understand sufficiently why the standards were out there in the first place.[10]

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[9] For a thorough review of the literature an environmental economics, see Cropper and Oates, 1992. In public finance, see Atkinson and Stiglitz, 1980. Baumol and Oates (1988) in the chapter "Efficiency without Optimality: the charges and standards approach" develop cost effectiveness criteria. They note that standards are "somewhat arbitrary", omitting to mention, let alone model, that standards award quotas proportional to input or output. Eskeland and Jimenez (1992), in a review of instruments, also failed to make this observation. Recently, Innes (1996) recommends combinations of standards and fuel taxes, and Fullerton and Wolverton (1999) have adopted the term presumptive Pigovian taxes to highlight combinations of taxes on gasoline and instruments applied to emission factors or vehicle characteristics.

[10] Buchanan and Tullock (1975) provides a plausible positive model for regulation (in effect, for standards), and later authors have in the same vein seen standards as a way of distributing property rights to the environment. However, these models are rendered powerless in the context of more general policy design

The first omitted observation is that the emission quotas allocated by an emission standard empirically take the shape of *conditional* property rights. Theoretically, such a conditionality – a quota if you drive a mile – can result from a particular structure for the costs of monitoring, enforcing and delivering reductions emissions. However, while economists had dealt with costly monitoring and enforcement (examples are Sandmo, 1976; Schmutzler and Goulder, 1997; Magat and Viscusi, 1990), they had not dealt with the possibility that plausible cost structures for monitoring would yield policy instruments applied to intermediate measures such as emission factors. We elaborate on this in Eskeland (1994) and in Eskeland and Devarajan (1996), but our simple contention is that quota allocation takes the shape of a regulation applied to emission factors because an emission factor is monitored at a lower cost than is an individual's cumulative emissions. An important part of this is – in the case of cars – that it is easier to associate emissions with a car than with a person. Cumulative emissions can then be addressed by the policy indirectly, as the policy maker imagines – or models - how the scale of the polluting activity is determined. For cars, the emission standard is typically a quota for emissions which expands for each mile driven (Harrington 1997), thus representing an implicit subsidy to driving. This does not imply that emission reductions become elusive, but it means that the emission reductions sought with emission standards alone could be attained at a lower cost.

The second, related observation is also both a theoretical one and a practical one: Theoretically, the proposition that allowing trade in quotas can lead only to efficiency gains no longer holds when quotas are allocated conditionally on behavior. The reason is that the allowance of trades will influence the behavior determining the allocation of quotas.[11] Practically speaking, if driving an old Buick in California gives you an

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in which instruments include compensating transfers (In the Mexico context, such a broader design context appeared relevant: unions accepted gasoline price increases compensated by reductions in general sales taxes). Moreover, as a positive theory, these models fail to explain why the pollution quotas, once distributed, rarely are considered tradeable. Another important debate came about on the relative merits of intervening with instruments of "price" or "quantity" (See Weitzman, 1974; Roberts and Spence, 1976; Baumol and Oates, 1988), where the relevant arguments concerned aggregate uncertainty. This perspective, however, still yielded the verdict that the quantity instrument should be tradeable, thus retaining the cost effectiveness properties of the analogous price instrument.

[11] An illustration of this is as follows: if restaurant seats are allocated on a first come first serve basis, a norm that a given position in a line is nontradeable may appear to obstruct efficiency enhancing trades. "Removing" the norm could, however, make people line up with no intention to be seated. "Races for

emission quota of 9 grams of CO per mile driven (Harrington, 1997), delinking the quota from the car and/or from driving would require an alternative institutional machinery; fundamentally changing the nature of the emission quota.[12]

Economists have - and often rightly - been harsh in their criticism of emission standards and regulatory approaches to pollution control (Baumol and Oates, 1988; Tietenberg, 1992). Perhaps because of the attention demanded to make those points, the statement on how standards should be accompanied by output taxes (5) has to this author's present knowledge not been made before the appearance of the 1994 article.

Demand management in pollution control: Is it important?

Pollution control agencies typically have regulated polluting activities, and typically to make them less polluting per unit of output or input.[13] In the public finance literature, in contrast, shifting the balance of the economy towards less polluting goods and sectors has been emphasized. Two reasons come to mind for this latter emphasis: First, shifting the balance between activities fits easily in a traditional modeling framework. Second, economists have had an important message, given the overly restricted focus on abatement – or ways to make each activity less polluting – in policy-making bodies. In terms of applied studies, several authors have analyzed the responsiveness of an economy to environmental policies - either simply considering effects on measured income or to include effects on pollution as well.[14] Most such studies - when they include pollution implications, concentrate on greenhouse gas emissions, for which it is fairly accurate to model emissions as strictly proportional to fuel consumption, i.e. without abatement options. As such, these studies benefited greatly from an earlier wave of applied studies in energy demand, fueled by the 1973 energy crisis (Pindyck, 1979; Fuss 1977).

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property rights", "tragedies of the commons" and "overfishing" all can be seen as consequences of conditional property rights.

[12] Buyback programs can be seen as introducing an opportunity for a car owner to sell the remaining "emission quotas" represented by her car by scrapping it. It should be tried only for exceptional cars, of course (and typically is: see Alberini et al., 1995) since for the representative car the program would be reducing pollution only if driving up the price of cars - a job better done by tax instruments.

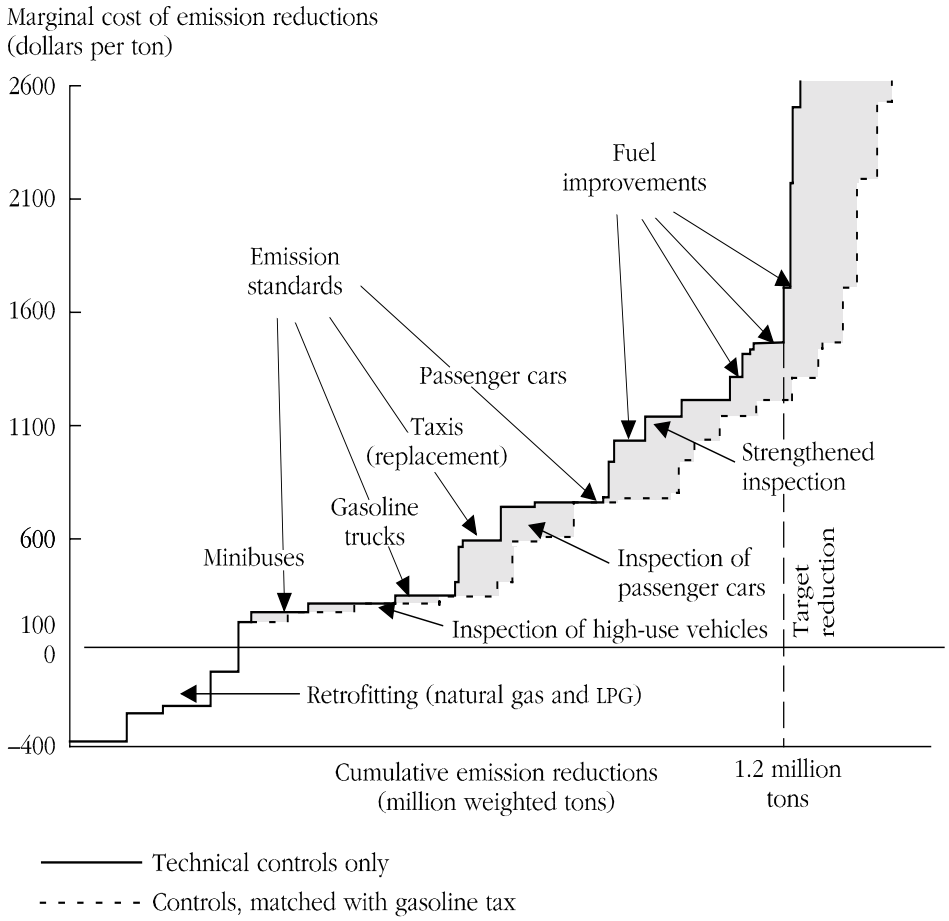
[13] Apart from the automobile examples (Harrington, 1997; Eskeland, 1994), see Magat and Viscusi (1990).

[14] Examples are Hazilla and Kopp (1990); Goulder et al. (1999); Konrad and Schroder (1991); Glomsrod, Johnsen and Vennemo (1992); Whalley and Wigle (1998); Jorgenson and Wilcoxen (1993); Eskeland, Jimenez and Liu (1998); Eskeland and Devarajan (1996); Alfsen (1992).

Eskeland (1994) gives a detailed examination of control options and implications for emission factors, with a total of 28 measures being "admitted" to the control cost curve.[15] In other areas, the model is very simple: a representative consumer, no other taxes or tax reasons, and a general equilibrium framework with three goods: car travel, air quality, and other goods and services. Using the best available estimated demand function for gasoline (Berndt and Botero, 1985), the matching gasoline tax shifted the control cost curve down by a significant amount (figure 1).

Figure 1.

Program to Reduce Air Pollution Emissions from Transport in Mexico City, with and without a Gasoline Tax



Note: Calculations are based on –0.8 elasticity of demand for gasoline. Eskeland, 1994.

[15] Several aspects additional to the "matching tax" result were novel: Multiple pollutants were weighed with a benefit-based metric; a cost-minimizing control cost curve was constructed. In a companion study, the proposition of a market based demand management was supplemented with a quantitative evaluation of an existing rationing scheme for driving (Eskeland and Feyzioglu, 1997b).

The conclusion was that a well-composed program of "cleaner cars" would cost 24 percent more if restricted not to include a gasoline tax in the tool chest. In terms of annual US dollars, the difference was $111 million, or $6 per citizen, much more per car. The proposed strategy, using (5), minimizes the welfare cost of emission reductions by viewing "cleaner cars" and "fewer trips" as competing providers of emission reductions.

In "Is demand for polluting goods manageable? An econometric study of car ownership and use in Mexico", Eskeland and Feyzioglu (1997) make an effort to obtain more suitable estimates for the demand function. Using richer and more recent data, and techniques capable of addressing additional challenges, the estimated model resulted with a price elasticity for gasoline consumption of -1.3 to -1.1, as opposed to the original -.8 from Berndt and Botero (1985). With those results, the estimated additional cost of excluding the demand management instrument increased to 44 percent.

Our conclusion from this analysis is that demand management belongs in environmental protection not only as a matter of principle, but such as to make a significant difference quantitatively. It was interesting to have this demonstrated in a field such as automotive emissions, since it is important empirically in the world's pollution problems. Also, the field of automotive emissions combines technical controls that are quite powerful in terms of reducing emission factors with a pessimism amongst many about the manageability of demand. We made similarly encouraging findings on air pollutant emissions (Sulfur oxides, particles, others) when we estimated input demand functions from manufacturing industries in Chile and Indonesia (Eskeland, Jimenez and Liu, 1998). The estimated elasticities of different pollutant emissions with respect to the price of heavy fuels (combining differences in emission coefficients with own- and cross price elasticities) resulted in the range of -.4 to -1.3, so a forty percent price increase could reduce emissions by twenty to fifty percent.

We now turn to the more involved theoretical analysis, with the motivation to see whether the simple principles demonstrated above apply under more general assumptions, in particular regarding costly revenue generation.

IV. Provision of environmental quality when revenue generation is costly

An insight from the theory of the second best is that with one distortion given in the economy, it may be attractive to have others as well. Greenwald and Stiglitz (1986) forcefully demonstrated the implications when showing how *imperfections* of one policy instrument with regard to one market failure leaves it attractive to look across all instruments for compensating remedies.

In the light of that challenge, one may ask under what conditions the intuition is still correct, that the planner should use *one price* to induce emission reductions? Do the challenges of distortionary revenue generation and costly redistribution imply that the provision of the environmental good departs from simple efficiency principles? If it does, will it influence the cost effectiveness analysis and the control cost curve? Also, what does it take for us to categorize an environmental policy instrument as imperfect, in the sense that it should be combined with other instruments to protect the environment?

Externalities and production efficiency

Setting aside, for the moment, the question of how much pollution control (i.e. pollution) there should be, an important question is whether provision of pollution reductions should be efficient in the sense that the marginal rates of transformation between abatement and emission reductions are equalized.[16]

The question of whether the marginal cost of emission reductions shall be the same for different polluting activities (or ways to reduce emissions) is not asked in studies such as Sandmo (1975) and Cremer et al. (1998). These models include only one polluting good, and an aggregate demand reduction is the only way to reduce emissions. We introduce multiple polluting activities and resources devoted to pollution abatement (reducing emission coefficients). Furthermore, abatement can be done by producers to reduce emissions in production, or by producers and consumers and government to reduce emissions in consumption, so we can ask the question of equality in rates of transformation across many dividing lines.

[16] The equalization of marginal costs of emission reductions through abatement is a concept of efficiency corresponding to what is called "cost effectiveness" in the environmental economics literature (see, for instance, Baumol and Oates, 1988; Tietenberg, 1992). The more cumbersome term (marginal rates of transformation…) is required when the comparison is across agents that may face different prices, as here.

The answer to the question of efficiency in provision of the environmental good is a quite affirmative yes (Eskeland, 2000a). The analysis is set under the following general assumptions: constant returns to scale; the environmental good is separable from other goods; within each activity consumers have uniform emission functions; linear taxes on inputs, outputs and emissions can be differentiated by commodity (or emission standards can be differentiated by commodity); different regimes can apply for the three sets: producers, government and the *h* consumers. We should notice that the assumption of constant returns to scale is more restrictive than in the previous section, since $c(a,x)$ and $e(a,x)$ here must be of the form $c(a)x$ and $e(a)x$. The assumption of constant returns to scale plays a quite central (though not indispensable) role for traditional results on production efficiency in optimal taxation, and plays an equivalent role as we analyze their applicability in the context of externalities.

Under these assumptions, a first result is that in optimum the marginal rates of transformation between abatement and emission reductions are equal across polluting activities (i.e. goods, sectors, $j \in N$), and equal for consumers, producers and government. One implication of this is that, when asking how much one should do to make a vehicle less polluting, one need not ask whether it is used by rich or poor, by households, producers or government, by the health ministry or the military.

It is implicit in Diamond and Mirrlees' (1971) result on production efficiency that the marginal rates of transformation between abatement and emission reductions shall be equal for entities within industries and government. We have simply included an additional good as relevant to consumers, and the result that efficiency in aggregate production should apply to this expanded vector of outputs is not surprising. Cremer and Gahvari (1999) also find that marginal costs of emission reductions are equal in optimum for firms with homogenous technologies, but do not place this finding in the context of the theorem on aggregate production efficiency. The part of our production efficiency result that was more unexpected was that polluting consumers, too, should abate to provide emission reductions at the same marginal rates of transformation.

These findings provide considerable relief in terms of implementation. First, if pollution reductions can be stimulated with emission taxes and abatement is untaxed, then optimal abatement can be implemented by the same tax levied on emissions

everywhere where they occur. This holds independently of whether the polluter is a producer, consumer or government, commuting to work or mowing the lawn. It also holds whether the abatement opportunities arise where emissions occur or at a prior stage, as when a car's emission factor can be reduced by the manufacturer. The intuition, here, is that auto makers and consumers who are exposed to an emission tax will work – as if together – to minimize the all-inclusive unit cost, which includes emission taxes and abatement costs at any stage.

The results are relieving also in terms of analytical simplicity. If emissions are taxed uniformly, then the formula for commodity taxes is identical to the one for optimal commodity taxes in the traditional problem without external effects. Thus, the emission tax that induces optimal abatement also induces the substitution desired towards less polluting goods, so that the formulas for optimal commodity taxes bears no evidence of the environmental problem. The formula for the emission tax, similarly, bears no evidence of the revenue generation problem, apart from through the shadow price of public funds (see below).

A second result of the listed assumptions is that if emission taxes cannot be used, then Sandmo's (1975) formula for commodity taxes that includes a term for presumptive Pigovian taxation applies. The presumptive Pigovian terms are proportional to the good's emission factor, thus uniform per unit of emissions across polluting goods. This latter result holds for any given emission factors, including when emission standards are being used to reduce emission factors. If standards can be used in combination with presumptive Pigovian taxes, then (5) is equalized across goods, and the same allocation as under emission taxation is implemented.

These results thus give support - conditional on the assumptions - to the intuition that environmental protection is much like a procurement problem - we should think of the emission tax more like a producer price than as a tax. The principle that procurement should equalize the marginal costs across potential providers is not shaken by the fact that this good is provided as a negative externality, by government, firms, and consumers; rich and poor. Thus, we find support for the cost-effectiveness analysis under more general assumptions than those originally invoked.

We shall highlight here one particular aspect that we believe may be surprising to some – hoping to assist intuition. In the Mexico City analysis, we looked across vehicle types (e.g. buses, luxury cars) and applied a representative consumer model. In Eskeland, 2000a, we obtain support for this equal treatment of different vehicles, even under costly taxation and redistribution. Why does the planner not differentiate emission taxes (or standards) across different vehicles for redistributive reasons, for instance to let the rich do more for the environment than the poor? The answer is simple, and shows the close links to the traditional result on aggregate production efficiency. The planner is assumed to have commodity specific commodity taxes available. These can be used to pursue the redistribution that is feasible by changing relative consumer prices, without the additional resource cost of reallocating abatement efforts in an inefficient pattern.

The production efficiency result does not apply if consumers are heterogenous in their access to pollution abatement possibilities. If consumers differ in access to (i.e. effectiveness of) abatement, consumers exposed to the same emission tax may have different emission factors for the same good.[17] As a consequence, the combination of an emission tax and a commodity tax confronts consumers of the same good with different unit costs, giving the planner an instrument possibly attractive for redistribution. The case of different emission factors also gives the planner a chance to price differentiate to reduce the costs of taxation. These results are presented in section IV of Eskeland 2000a. Many of them are analogous to findings in the literature on imperfect corrective pricing (starting with Diamond, 1973), which prove to translate quite intuitively to a context of distortionary revenue generation.

Pigou's conjecture about public expenditures, and the double dividend

We have employed the assumption typically used, that there is separability in preferences between the environmental good and market goods, so that uncompensated demand for market goods $x_j^h(q, I^h, e)$ is not influenced by changes in pollution, $x_{je} = 0, \quad j = 1,..,n$. This yields a rule equivalent to the established one for optimal provision of public goods

[17] *The same good* here has a particular meaning: consumption that cannot be differentiated in the commodity tax structure (Eskeland 2000a, section IV).

(e.g. Atkinson and Stern, 1974; Auerbach, 1985; King, 1986), or with *h* identical consumers

(6) $$-\frac{1}{f_{jb}} = h\alpha\frac{\beta}{\mu}, \text{ all } j=1,..,n.$$

On the left hand side we have the marginal rate of transformation between emission reductions and abatement in sector *j*, whether abatement is by producer or by consumer (see the generalization indicated for equation 2). On the right hand side, $h\alpha$ is aggregate marginal willingness to pay for the public good (i.e. for pollution reductions), and β/μ is the ratio between the marginal utility of income to the consumer, β, and the shadow price of the government's budget constraint, μ. In the context of an environmental program, (6) can be implemented either by an emission tax or by an emission standard. An emission tax will be combined with commodity tax rates satisfying the formulas for optimal taxes in the traditional problem without externalities, while emission standards will be combined with commodity taxes satisfying a generalized Sandmo (1975) formula, including presumptive Pigovian terms (see Eskeland 2000a).

The generalization under non-separability again results in a rule equivalent to the one for optimal provision of public goods (King, 1986). The formulas for the optimal commodity taxes are unchanged, but the optimality formula characterizing optimal provision of environmental quality (6) in the case of two taxed goods changes to:[18]

(7) $$-\frac{1}{f_{jb}} = h\alpha\frac{\beta}{\mu} - \quad {}_{i=1,2}\, t_i x_{ie}, \; j=1,..,n.$$

In other words, provision of the public good, minus *e*, is adjusted as if it were credited with contributions that the public good makes to the proceeds from commodity taxes. This equivalence between the traditional problem of public goods provision and environmental protection (equations 6 and 7) has not formerly been highlighted, since models of environmental externalities without abatement render no expressions corresponding the left hand sides, the marginal rate of transformation.

Pigou conjectured that costly revenue generation reduces public programs (see Eskeland, 2000b). We shall see that one of the questions raised in the double dividend

[18] See annex to Eskeland 2000b.

debate is a question addressed by Pigou's conjecture, well sorted out by Atkinson and Stern (1974) for the case of pure public goods.

The first factor that may cause Pigou's conjecture to be turned around is if nonseparability results in a positive marginal contribution from provision to the tax base (in our case that $-\Sigma_i t_i x_{ie} > 0$, so that emissions reduce demand for taxed goods). More than a curiosity, this term is worth noticing in the present context for several reasons. First in environmental economics, benefit estimation methods such as hedonic price models, wage-amenity studies and the travel cost method are based on the assumption that willingness to pay for environmental quality is reflected in market prices and behavior (see, for instance, Cropper and Oates, 1992, for a review). Second, in particular in the context of tax jurisdictions competing for highly mobile factors (residents), the tax interaction terms make possible the case that some environmental protection (or other public goods provision) can be justified on the narrow grounds that it contributes to revenues.[19] Third, in a developing country setting, the scope for providing public goods that stimulate participation in the taxable economy may be significant.

The second factor that may invalidate Pigou's conjecture is β/μ (the inverse of the marginal cost of funds).[20] β/μ can be expected to be less than one – in support of Pigou's conjecture - but may be larger than one if the taxed goods on average are inferior goods in the sense that $\Sigma_j t_j x_{jI} < 0$. Then, the income effects from taxation cause consumers to shift demand so as to reduce the costs of funds.

We shall proceed with a few additional assumptions, to comment upon results in the so-called double dividend literature. The question examined is whether - in the context of costly revenue generation – the emission tax rate be set at a level higher than the first best rule (i.e. $\tau_1 = f_1 h\alpha$, where τ_1 the emission-presumptive rate on good 1, f_1 the emission factor). Bovenberg and de Mooij (1994) assume that wage income is used to purchase a clean and a dirty good and that a wage tax is the revenue instrument.

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[19] Tiebout's (1956) equilibrium in local public goods postulates *efficient provision* without a benevolent planner based solely on the non-separability terms: In Tiebout's model, landowners cum government have a revenue base capable of capturing *all* benefits.

[20] With heterogenous consumers, as Sandmo 1999 points out, the covariance between the vector β and the household consumption of taxed goods likely implies a tendency that redistributive considerations raise provision.

Moreover, there is separability in preferences between other market goods and leisure, and separability again between this aggregate and environmental quality (so $\Sigma_j t_j x_{je} = 0$). They then define as "Pigovian" the first best tax for the dirty good $\tau_1 = f_1 h\alpha$, to ask whether welfare would be improved by moving in a revenue neutral fashion to increase this tax or to decrease it. For a marginal reduction in the tax on the dirty good they find that the answer hinges upon whether labor supply will increase or decrease as a (broader) labor tax is reduced to substitute for a narrower tax on the dirty good. They show that the tax on the dirty good will be lower than the "first best" level under the assumption that labor supply is not in a backward-bending region. They then argue that an upward-sloping labor supply is to be assumed based on empirical studies.

We may use or own framework and an additional restrictive assumption to analyze this problem in optimum. Our result that the optimum Pigovian tax can be characterized in the presence of commodity taxes that satisfy the optimality conditions for the traditional, non-environmental tax problem is useful for this. For a tax on labor only to be optimal from a non-environmental perspective, we need to restrict preferences for the subaggregate of market goods, 1 and 2 to be homothetic (Sandmo, 1974). We can then bring with us from (6) above that marginal costs of abatement can be greater than the benefits if and only if β/μ is greater than one, and proceed to check under what conditions this can be the case.

The first order condition for the optimal labor tax for the traditional non-environmental problem is

(8) $$\frac{\beta}{\mu} = -\frac{t}{L}\frac{\partial L}{\partial w} + 1,$$

where L is labor (endowment minus leisure) and t is the tax on labor income.[21] Labor productivity is a constant, so $\partial L/\partial w = -dL/dt$. For the optimal tax problem which includes pollution, we know that (8) should be satisfied together with

(9) $$\tau_1 = f_1 h\alpha \frac{\beta}{\mu},$$

[21] Rearranging, $\beta/\mu = 1 - (t/w)\varepsilon_{Lw}$, so the cost of funds, μ/β, increases in the labor supply elasticity, ε_{Lw}, and in the tax level.

for the tax on the polluting good. From (9), we know that $\tau_1 > f_1 h\alpha <=> \beta/\mu > 1$. From (8), assuming a revenue requirement beyond $\tau_1 x_1$, so that *t>0*, we confirm the result that the marginal costs in optimum cannot be greater than benefits $h\alpha$ unless if the uncompensated labor supply curve is backward bending, $\partial L/\partial w < 0$ (i.e. unless if the income effect of a wage increase dominates over the substitution effect). However, the labor supply curve can be backwardbending only in a region for which proceeds from the labor tax are declining in *t*. The optimal labor tax rate is not found in such a region under our preference assumptions (since substitution from labor towards leisure means away from "dirty"). Thus, we may rule out *on theoretical grounds* the possibility that in optimum the environmental tax be set at a level higher than what the first-best parameters indicate, $f_1 h\alpha$. We may say that under these assumptions Pigou's conjecture applies and rejects the proposition that the environmental tax be set at higher levels than the benefits of pollution reduction.

When a public good such as the environment benefits production

In Eskeland 2000b, we make the variation that environmental quality also benefits production by reducing production costs, in addition to the pure public good benefiting consumers directly. Examples may be the brewer whose costs are lower when his water source is unpolluted, or the tourism industry that needs good air quality. We retain the assumption of constant returns to scale, so the benefits in terms of cost savings are not accruing to firms or their owners, but are passed on to consumers if they are not captured by government in the form of taxation. The rule for optimal provision corresponding to (6), written to accommodate heterogenous consumers and costly redistribution, is:

$$(10) \qquad -\frac{1}{f_{jb}} = \frac{{}_h \alpha^h \beta^h}{\mu} + \quad {}_j (h\overline{x_j} + x_j^P) c_{je} \, .$$

In (10), c_{je} is the marginal increase in unit costs of good j as pollution increases and $h\overline{x_j} + x_j^P$ is the total consumption of j by the *h* consumers and government. For a program which only has benefits in production, of course, the first sum in (9) is zero. Comparing (9) with (6), we can see that the generalization is in the spirit of a generalized Samuelsonian summation of marginal benefits, the benefits of reduced production costs

now added to the more familiar summation of benefits based directly on preferences (1). Interestingly, though, the benefits that originate in production costs are not “adjusted” with β/μ, the ratio of the marginal utility of income to the shadow price of public revenue. Thus, we conclude, public provision with benefits in production rather than as public goods (equation 1) defies Pigou's conjecture – and the double dividend debate - all together. Put in a different way, while Samuelson's (1954) rule for optimal provision of public goods applies only with adjustments in the context of costly revenue generation, the analogous rule for provision of collective factors of production (see Sandmo, 1972) applies directly even when revenue generation is costly.

This result, too, serves well to illustrate the links to Diamond and Mirrlees' result on efficiency in aggregate production. (10) is written in a form valid also with heterogenous consumers, and one might ask again why one should not value cost reductions differently according to who consumes the goods that benefit from a better environment. Again, the answer is that the social planner is assumed to have policy instruments with which consumer prices can be changed with specificity for each good. Thus, it is not attractive to make inefficient (for revenue or redistributive reasons) a program that saves costs for producers.

There is also a parallel to our case of nonseparability. In (7), we show how an adjustment to the rule for optimal provision occurs if provision interacts with the tax base. In (9), for the cost reductions to industries, interaction with the tax base is the whole story. Cost reductions to industries can be captured in their entirety without distortionary costs, by matching them with tax increases for the benefiting goods, so as to leave the all-inclusive consumer price unchanged. It is indeed another result implicit in Diamond and Mirrlees' (1971) analysis that public provision which benefits production should be subject to aggregate production efficiency, in this case meaning that the benefits be accounted for fully. For consumer provision in contrast, as with consumer abatement, the result is not hinted at by earlier findings.

Qualified by the assumptions, the findings have direct policy implications. To illustrate, if a road maintenance project were to save vehicle operators a dollar per passage, one might suggest to count the benefits as 50 cents with reference to the high distortionary costs of funding public budgets. The present analysis indicates that no such

adjustment should apply for the share of vehicles that are commercial or of government.[22] Finally, we should emphasize that it would be wrong to construe this principle as reflecting a judgment that production is more important than consumption; only consumption and consumer preferences matter in this model. Rather, it reflects assumptions implying that benefits accruing in production are easily taxable.

V. Conclusion

We have tried to summarize the lessons from a journey that included policy recommendations in a practical setting as well as development of policy principles. Working in an applied setting provides good discipline, helping not only to communicate principles better, but also to go back to the theory with reformulated questions.

It sounds odd to many theoreticians that economists had omitted to make the recommendation that a pollution control program emphasizing emission standards and "cleaner technologies" should be complemented by presumptive Pigovian taxes - to shift the economy towards "fewer polluting trips" as well. As we emphasized that this is a good principle in theory and also implementable in practice, we also quantified important aspects of demand management. First, we used results from technical studies to compute a marginal cost curve for emission reductions in the form of “cleaner cars and fuels”. Then, we estimated a demand model for cars and driving and used our rule for a matching tax to combine these two instruments in a cost effective way. The result indicates that the cost of pollution reductions in Mexico City increases by 44 percent if a program of emission standards and a presumptive Pigovian tax on gasoline is restricted to not employ the gasoline tax.

These results come about under the assumption that revenue and redistributive transfers bear no premia. Our subsequent theoretical analysis indicates that this approach to policy analysis is supported under a plausible set of more general assumptions. A positive shadow price of revenue influences the optimal environmental quality, and would typically reduce it (as in Pigou's conjecture for public expenditures). However, neither the shadow price of revenue nor redistributive considerations would change the shape of the program, since commodity taxes are assumed to be available, and they are

[22] Christiansen (1981) shows that benefits to a household, when they are represented by savings in terms of

better suited for redistribution and revenue generation than is a modification of a cost effective emission reduction program.

The qualifications to these generalizations are - roughly - the assumptions that support the recommendation of efficiency in aggregate production (Diamond and Mirrlees, 1971). Under these conditions, we find that firms, consumers and governments should be pushed in the same way, and equally hard, to reduce emissions, i.e. so that marginal costs of emission reductions are the same. Marginal costs of emission reductions shall also be the same across different polluting activities, or goods.

When abatement is untaxed, such pressure can be implemented by a uniform tax on emissions where they occur - combined with commodity taxes satisfying the optimality conditions for a traditional optimal tax problem without an environmental good. The emission tax will then not only induce optimal abatement - reducing emission coefficients in each activity - but also shift the economy optimally towards less polluting activities, complementing a commodity tax structure satisfying a formula that bear no evidence of the externality. If monitoring costs are such as not to allow emission taxes, but allow emission standards or abatement standards, then these standards combined with commodity taxes that include presumptive Pigovian taxes (the structure given by Sandmo, 1975) can implement the same allocation under favorable assumptions. This scenario is the more general scenario in which we support our Mexico City analysis, with the matching tax playing the role of the presumptive Pigovian part of the commodity tax structure.

The examination allowed us to shed light on other questions on the tour. Allowing for differences across consumers in access to pollution control technology, results are of two types. First, emission taxes, even though they are still first-best from an environmental perspective, they take on additional roles in lieu of the planner's objectives of revenue generation and redistribution. Second, without emission taxes, standards and presumptive Pigovian taxes will display qualities of "imperfect corrective pricing". In this case too, results under costly revenue generation prove to be fairly intuitive extensions of results developed under lump sum taxation.

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a market good (say, gasoline), shall be valued at the producer price.

A theme in our theoretical analysis is that environmental protection is different from government provided public goods only in the means of intervention, not in the more basic optimality principles, such as the wedge between marginal costs and benefits. This insight emerges now in the optimal tax model because we introduce abatement. This means that, in a setting with two public goods, one which is a negative environmental externality and another which is provided by government expenditure, the optimality conditions are the same. Intuition for this is given by noting that the difference between the two public goods in terms of revenue requirements may be substantial, but at the margin the relationships between additional provision and government revenue are identical. An area in which we benefit from this parallel is when we show that a question in the double dividend debate boils down to an old question about Pigou's conjecture for public expenditures. Pigou’s conjecture applies directly, to reject the proposition of an emission tax exceeding the marginal benefits.

REFERENCES

Alberini, Anna, Winston Harrington and Virginia McConnell. 1995. "Determinants of Participation in Accelerated Vehicle-retirement Programs." *The Rand Journal of Economics* 26: 93-112.

Alfsen, Knut H. 1992. "Use of Macroeconomic Models in Analysis of Environmental Problems in Norway, and Consequences for Environmental Statistics." *Statistical Journal of the United Nations* 9:51-72.

Atkinson, Anthony B. and Joseph E. Stiglitz. 1980. Lectures on Public Economics. McGraw-Hill Book Company, New York.

Atkinson, Anthony B. and N. H. Stern. 1974. "Pigou, Taxation and Public Goods." *Review of Economic Studies* 41(1):119-128.

Auerbach, Alan, J. 1985. "The Theory of Excess Burden and Optimal Taxation." In *Handbook of Public Economics,* edited by Auerbach and Martin Feldstein, Vol. 1, Chap. 2, North-Holland, New York.

Balcer, Yves. 1980. "Taxation of Externalities: Direct versus Indirect." *Journal of Public Economics* 13:121-129.

Baumol, William J. and Wallace E. Oates. 1988. "The Theory of Environmental Policy." Cambridge University Press, New York, Sydney.

Berndt, Ernst R. and G. Botero. 1985. "Energy Demand in the Transportation Sector of Mexico." *Journal of Development Economics* 17:219-38.

Bovenberg, A. Lans and F. van der Ploeg. 1994. "Environmental Policy, Public Finance and the Labour Market in a Second-Best World." *Journal of Public Economics* 55:349-390.

Bovenberg, A. Lans and Ruud A. de Mooij. 1994. "Environmental Levies and Distortionary Taxation." *American Economic Review* 84(4): 1085-1089.

Buchanan, J. M. and Gordon Tullock. 1975. " Polluters' Profit and Political Response: Direct Controls Versus Taxes." *American Economic Review* 65:139-47, March.

Christiansen, Vidar. 1981. "Evaluation of Public Projects under Optimal Taxation." *Review of Economic Studies* XLVIII: 447-457.

Cremer, Helmuth, Firouz Gahvari and Norbert Ladoux. 1998. "Externalities and Optimal Taxation." *Journal of Public Economics* 70: 343-364.

Cremer, Helmuth and Firouz Gahvari. 1999. "What to Tax: Emissions or Polluting Goods?" University of Illinois at Urbana-Champaign, Champaign, IL, February.

Cropper, M. L. and W. E. Oates. 1992. "Environmental Economics: A Survey." *Journal of Economic Literature* 30:675-740.

Dasgupta, P. and J. Stiglitz. 1972. "On Optimal Taxation and Public Production." *Review of Economic Studies* 39:87-103

Diamond, Peter A. 1973. "Consumption Externalities and Imperfect Corrective Pricing." *The Bell Journal of Economics and Management Science* 4(2): 526-538 (the journal is now published as Rand Journal of Economics).

Diamond, Peter A. and James A. Mirrlees. 1971. "Optimal Taxation and Public Production I: Production Efficiency." *American Economic Review* 61(1): 8-27 and 61(3):261-278.

Eskeland, Gunnar S. 2000a. "Externalities and Production Efficiency." Earlier version as Policy Research Working Paper Series, No. 2319. The World Bank, Washington, D.C, April.

_____. 2000b. "The Irrelevance of the cost of funds when a public good – such as the environment – benefits production." Development Research Group, World Bank, Washington, D.C. Processed.

Eskeland, Gunnar S., E. Jimenez and L. Liu. 1998. "Prices that Clear the Air: Energy Use and Pollution in Chile and Indonesia." *The Energy Journal* 19(3):85-106.

Eskeland, Gunnar S. and Tarhan N. Feyzioglu. 1997. "Is demand for polluting goods manageable: An econometric study of car ownership and use in Mexico." *Journal of Development Economics* 53:423-445.

Eskeland, Gunnar S. and Tarhan N. Feyzioglu. 1997b. "Rationing Can Backfire: The 'Day without a Car' in Mexico City." *World Bank Economic Review* 11(3):383-408.

Eskeland, Gunnar and Shanta Devarajan.1996. *Taxing Bads by Taxing Goods: Pollution Control with Presumptive Charges*. Directions in Development series, World Bank, Washington, D.C.

Eskeland, Gunnar S. 1994. "A Presumptive Pigovian Tax: Complementing Regulation to Mimic an Emissions Fee." *World Bank Economic Review* 8(3):373-394.

Eskeland, Gunnar S. and E. Jimenez. 1992. "Policy Instruments for Pollution Control in Developing Countries." *World Bank Research Observer* 7(2):145-169.

Fullerton, Don and Ann Wolverton. 1999. "The Case for a Two-Part Instrument: Presumptive Tax and Environmental Subisidy." In A. Panagariya, P. R. Portney and R. M. Schwab, editors, Environmental and Public Economics: Essays in Honor of Wallace E. Oates, Cheltenham, UK: Edward Elgar Publishing Ltd.

Fuss, M. A. 1977. "The Demand for Energy in Canadian Manufacturing." *Journal of Econometrics* 5:89-116.

Glomsrod, S., H. Vennemo and T. Johnsen. 1992. "Stabilization of Emissions of Carbon Dioxide: A Computable General Equilibrium Assessment." *Scandinavian Journal of Economics* 94(1):53-69.

Goulder, L. H., I. W. H. Parry, R. C. Williams III and D. Burtraw. 1999. "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting." *Journal of Public of Economics* 72:329-360.

Greenwald, Bruce C. and Joseph E. Stiglitz. 1986. "Externalities in Economies with Imperfect Information and Incomplete Markets." *Quarterly Journal of Economics* 101(2):229-264.

Harrington, Winston. 1997. "Fuel Economy and Motor Vehicle Emissions." *Journal of Environmental Economics and Management* 33:240-252.

Hazilla, Michael and Raymond J. Kopp. 1990. "Social Cost of Environmental Quality Regulations: A General Equilibrium Analysis." *Journal of Political Economy* 98(4):853-73.

Innes, Robert. 1996. "Regulating Automobile Pollution under Certainty, Competition, and Imperfect Information." *Journal of Environmental Economics and Management* 31(42):219-239.

Jorgenson, D. W. and P. J. Wilcoxen. 1993. "Reducing US Carbon Emissions: An Econometric General Equilibrium Assessment." *Resource and Energy Economics* 15:7-25.

King, Mervyn A. 1986. "A Pigovian Rule for the Optimum Provision of Public Goods." *Journal of Public Economics* 30(3): 273-291.

Konrad, K. and M. Schroder. 1991. "An Evaluation of Taxes on Air Pollutants Emissions: An Applied General Equilibrium Approach." *Swiss Journal of Economics and Statistics* 127(2):199-224.

Magat, W. A. and W. K. Viscusi. 1990. "Effectiveness of the EPA's Regulatory Enforcement: The Case of Industrial Effluent Standards." *Journal of Law and Economics* 33:331-360.

Meade, J. E. 1952. "External Economies and Diseconomies in a Competitive Situation." *The Economic Journal* 62(245): 54-67.

Pigou, Arthur Cecil. 1932. "The Economics of Welfare." Macmillan & Co, London, 4th edition (first edition was 1920).

Pindyck, R. 1979. *The Structure of World Energy Demand*. Cambridge, MA: MIT Press.

Ramsey, F. P. 1927. "A Contribution to the Theory of Taxation." *Economic Journal* 37(147):47-61.

Roberts, Marc J. and Michael Spence. 1976. "Effluent Charges and Licenses under Uncertainty." *Journal of Public Economics* 5:193-208.

Samuelson, Paul A. 1954. "The Pure Theory of Public Expenditure." *Review of Economics and Statistics* 36(4): 387-389.

_____ . 1951. "Theory of Optimal Taxation." Memorandum to the U.S. Treasury. Reprinted in *Journal of Public Economics*, 1986, 30:137-143.

Sandmo, Agnar. 1999. "Redistribution and the Marginal Cost of Public Funds." *Journal of Public Economics* 70:365-382.

_____ 1976. "Direct versus Indirect Pigouvian Taxation." *European Economic Review* 7:337-49.

_____ 1975. "Optimal Taxation in the Presence of Externalities." *Swedish Journal of Economics* 77 (1): 86-98 (the journal is now published under the name *Scandinavian Journal of Economics*).

_____ 1974. "A Note on the Structure of Optimal Taxation." *American Economic Review* 64(4):701-706.

_____ 1972. "Optimality Rules for the Provision of Collective Factors of Production." *Journal of Public Economics* l (1):149-157.

Schmutzler, Armin and Lawrence H. Goulder. 1997. "The Choice between Emission Taxes and Output Taxes under Imperfect Monitoring." *Journal of Environmental Economics and Management* 32:51-64.

Stiglitz, J. E. and Dasgupta, P. 1971. "Differential Taxation, Public Goods and Economic Efficiency." *Review of Economic Studies* 38(2):151-174.

Tiebout, Charles M. 1956. "A Pure Theory of Local Expenditures." *Journal of Political Economy* 64:416-424.

Tietenberg, Tom. 1992. "Environmental and Natural Resource Economics.3rd ed." HarperCollins Publishers, New York.

Weitzman, Martin L. 1974. "Prices vs. Quantities." *Review of Economic Studies* 41:477-91.

Whalley, John and Randall Wigle.1998. "Cutting Carbon Dioxide Emissions: The Effects of Alternative Policy Approaches." *The Energy Journal* 12(1):109-124.

Wijkander, Hans. 1985. "Correcting Externalities through Taxes on/Subsidies to Related Goods." *Journal of Public Economics* 28:111-125.