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# A Presumptive Pigovian Tax: Complementing Regulation to Mimic an Emissions Fee

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*If regulations are used to make cars and fuels cleaner, should gasoline taxes be used to manage demand for trips that pollute? Analysis of a well-composed program for Mexico City indicates that the emission reductions would cost 24 percent more if a tax on gasoline was not introduced.*

*A simple analytical framework is developed to analyze the use of abatement requirements to make cars cleaner, and a gasoline tax to economize on the use of cars. The two instruments should be combined to mimic the incentives that would have been provided by an emissions fee. Thus, cleaner cars and fewer trips are analogous to competing suppliers of emission reductions; the planner should buy from both so that marginal costs are equal. Applying that rule, the marginal cost of emission reductions is, simply, the gasoline tax rate divided by emissions per liter.*

This article is prompted by the practical challenge of reducing air pollution from transport in a metropolitan area such as Mexico City while keeping an eye on the welfare costs of doing so. A least-cost solution to such a problem could involve behavioral change, such as modified travel patterns, as well as a number of technical modifications, whether in the form of tune-ups and retrofitting of existing capital equipment or in the form of new configurations of machinery (for example catalytic converters) or improved fuels.

These details have not been of great interest to economists in the public finance tradition (with some notable exceptions) because a fee levied on individual emissions would provide perfect incentives. Firms and households exposed to such a fee would self-select, taking (only) those measures that are most effective from society's point of view, irrespective of whether they are technical modifications, changes in input mix, or changes in the consumption basket. Using such a fee, or tradable pollution permits, the detailed actions that can be

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taken to reduce pollution need be known only to the economy's microagents, because the market can help the planner find cost-effective abatement (Baumol and Oates 1988 provides good coverage of this topic).

If a social planner were to possess data on how much pollution each individual caused through the year, then a year-end tax bill based on emissions or related damages would provide appropriate incentives for pollution reduction. When continuous monitoring of individual emissions is not applied, however (and it is not yet feasible for motor vehicles), the planner needs to investigate which sectors are polluting, what options exist within those sectors, and how to best stimulate each option. This is the context in which the analysis of a program to control air pollution from motor vehicles in Mexico City takes place.

Real-world programs to control pollution rely almost entirely on abatement, or technical controls, aimed at reducing emissions per unit of production or consumption. Abatement measures, such as the use of (costlier but) cleaner fuels and catalytic converters, will then generally be induced by regulatory and price-based policies, the design of which may have a great impact on the efficiency of the program. One example is emission standards with periodic emissions testing. The effect of the policy will obviously depend on whether the test result is a reasonable proxy for emissions in use, which again will depend on technical, institutional, and behavioral conditions.[1] Technical standards, such as mandating the use of catalytic converters and unleaded gasoline, may be easier to monitor but are less flexible and less directly related to emissions and may thus be costlier. Both emission standards and technical standards may be enforced by policies imposing penalties or revoking privileges. Other inducement mechanisms may be lower taxes on cleaner fuels and on cars equipped for natural gas. The costs and benefits of these measures will depend on how well the planner knows the field and, in particular, on how much the planner knows about the individuals whose behavior is to change.

Even when well designed, a program that emphasizes technical controls may be improved in a variety of ways. The most obvious way would be to use the car's emissions factor (grams emitted per liter or per mile, as determined from biannual emission tests), multiply it by the odometer reading (as a proxy for the utilization of the "pollution plant" since the last test), and apply an emissions fee to the result. The fee could be paid upon testing, or it could be uniformly paid as a presumptive tax, at the gas station, to be refunded in part to the owners of vehicles that tested to be cleaner than presumed. The efficiency gains from such a reform would come through several channels. First, all owners would have a continuous incentive to drive less, and owners of the more polluting cars would have a greater incentive. Second, all owners would have continuous incentives to make their cars cleaner, but owners that rarely use their cars would be subject to

1. Lawson and others (1990) used a test technology different from those used in mandatory test programs, and surprise roadside tests, and found that the length of time since the last periodic emissions test had little influence on whether a car's emissions were within the compliance range.

less of this pressure. As a consequence, society would waste few resources cleaning cars that are rarely used. As an added benefit, the car market would facilitate the exchange of vehicles to make sure that households that use their vehicles intensively end up with the cleaner ones.

This article investigates the gains to be made from a less ambitious reform of a traditional program. A traditional program does little or nothing to discourage the use of goods that pollute. The article assesses the advantages of including such discouragement, without trying to differentiate this discouragement according to how clean the car is (or how easy it is to clean it). The proposed reform is a gasoline tax, presumptive of emissions. It is shown that a gasoline tax, even when uniformly applied, makes sense.

The practical motivation for suggesting such a modest reform is the general suspicion that administrative and technical systems for monitoring and enforcement are still weak and vulnerable, so that it is doubtful whether emission tests can be used as major tax-collecting devices. Of course, when monitoring technology and technical capacity so allow, the program can (and should) be improved. The most immediate direction would be to use emissions test results and utilization rates to collect an emissions fee, so as to increase pressure on high polluters and to reduce wasteful pressure on low polluters. The proposed uniform increase in the variable costs of polluters could also be a reform that would allow such refinements to gain momentum over time.

Section I briefly reviews the theoretical literature. Section II develops the theoretical background for analyzing cost-effectiveness from the perspective of very simple, general equilibrium, welfare economics. Section III applies the analytical framework to data from a program to contain pollution in Mexico City and shows how inclusion of a gasoline tax in the program would reduce the costs of attaining the targeted emission reductions. Section IV offers conclusions.

## I. Theoretical Background

The theory of optimal taxation has mainly been concerned with minimizing the distortionary costs of revenue-raising taxes (see, for instance, Mirrlees 1976). The broader normative public-finance literature has provided a case for an authoritative government and intervention through public expenditures, taxation, and regulation, with the two main rationales being market failure and concerns about income distribution (see Atkinson and Stiglitz 1980; Starrett 1988, for broad coverage). The result of greatest relevance for this study was provided by Pigou (1932), whose recommendation that pollution problems could best be taken care of by taxes gave rise to the term "Pigovian taxes" (the term "corrective taxes" is also used). The theory prescribes that taxes be applied so that individuals are confronted with the full marginal social costs of their activities. If taxes are applied this way, and if the definition of social costs includes such effects as the problems caused by pollution, then pollution control would be efficient in the sense that there would be no net benefits to society from different or further prevention of pollution or from more pollution. The position that authoritative intervention, for instance through Pigovian taxation, is necessary for efficiency when there are external effects was later challenged by Coase (1960). Coase argued that voluntary negotiations between those causing and those affected by an external effect could provide for efficiency. Later literature has emphasized that negotiations, as well as an intervening, poorly informed bureaucrat, may be costly and inefficient (see Farrell 1987 for a simple exposition and discussion).

Sandmo (1975) combines the motive of revenue generation with the need to discourage pollution when he analyzes how a revenue-motivated optimal tax structure would be modified when a negative external effect, such as pollution, is associated with one of the taxed commodities. He shows that traditional, distortion-minimizing revenue formulas will prevail but that a Pigovian element will be contained in the formula for the polluting good. As a special case, if the revenue requirement is sufficiently low, taxation of the polluting good may be sufficient so that revenues can be raised without causing distortions.

Other theoretical contributions concerned with Pigovian taxes have generally abstracted from the need to generate revenues through distortionary taxes. These theoretical contributions could be interpreted as effectively assuming that it is not costly to fund the public sector or, simply, that the topics can be analyzed separately. Sandmo (1975) may provide some support for such a separation, although the pollution-control agency would need to coordinate with the revenue-generating agency.

Many analysts have, however, been concerned with the distortionary effects of Pigovian taxes when the taxes do not perfectly correct the external effects. Notable among these are Sandmo (1976), Balcer (1980), and Wijkander (1985), all of whom ask whether taxes and subsidies levied on complements and substitutes can be helpful when taxation of the polluting good is either not feasible or not perfect. They find that such supportive instruments can be helpful when (a) the polluting good is used both in a polluting and in a nonpolluting activity (Sandmo 1976), (b) some users of the polluting good cause more harm per unit consumed than others (Balcer 1980), and (c) taxing the polluting good directly is not feasible (Wijkander 1985). These results can all be read as special cases of the point made by Greenwald and Stiglitz (1986) that market equilibria in economies with market failures are not constrained Pareto optimal and that a demand system, with all its own- and cross-price elasticities, can provide opportunities to seek Pareto improvements.

Designing pollution-control policies may involve more complex mechanisms than those discussed here, in particular when the costs of pollution reductions are better known to the individual than to the planner. The literature on incentives under asymmetric information and revelation mechanisms discusses whether optimal pollution control can still be induced (or whether the losses arising from the information asymmetry will be great).[2] Generally, the planner wants less pollution control from firms with high pollution-control costs. However, sending out such a signal would give firms incentives to exaggerate their control costs. The planner thus wants a mechanism that induces the firm to truthfully reveal its costs, or that induces self-selection based on true characteristics. Much of this literature centers on problems caused by small numbers of polluters, in which case the position of their individual control cost curves can be of great relevance for the desired total level of pollution.

For several reasons, however, it may be less important to construct mechanisms more complex than a straight fee when emissions are caused by many polluters—as with millions of vehicles causing urban smog. When there are many polluters, communication costs for sophisticated mechanisms may be higher. Also, the uncertainty with respect to each polluter's control cost will be of less relevance to the planner, unless the hidden parts of individual control costs are highly correlated (in which case more information through sampling of the population might be valuable). Dasgupta, Hammond, and Maskin (1980) show that the planner can do almost as well with knowledge about the population of polluters as with (additional) information about individual polluters when the number of polluters is large and the disturbance terms are uncorrelated. Hammond (1979: 263) points to an important feature of economies with many agents: "In a large economy, no agent has sufficient influence to be able to distort the terms of trade in his favor by distorting his true characteristics." When efficiency is not achieved in models of asymmetric information, constraints such as the participation constraint (that agents prefer to sign the contract with the principal) and the balanced budget constraint (that the contract neither generates nor requires funds) often play a role. In the model to be presented, in contrast, it is assumed not only that the planner has authoritative powers—and thus can impose new costs on polluters (the polluter-pays principle)—but also that a mechanism that generates or uses revenue is acceptable. Furthermore, risk aversion plays no role in the model.

In a traditional control program (which emphasizes making fuels and vehicles cleaner) the planner undertakes costly efforts to estimate the costs of pollution control for various groups of vehicles and users. These efforts are mostly based on surveys, sample tests, and engineering estimates and serve to narrow the planner's prior distribution of cost estimates for each of the groups. This information is used to estimate what the total of emission reductions should be and to design mechanisms for inducing change. Sometimes, although not always, a mechanism can be chosen that is sensitive to the particular circumstances of a vehicle or a vehicle owner in a subgroup (as when the price of conversion kits and the price of natural gas are used to make high-use vehicles self-select for conversion to natural gas).

2. See, for instance, Baron and Myerson (1982) or Besanko and Sappington (1987). For a review of results with emphasis on pollution control, see Laffont (1993).

A program consisting mostly of mandated abatement requirements has many potentially important weaknesses. The improvement proposed here—the uniform taxation of a major input or output of the polluting activity—merely removes one of these weaknesses, namely, that abatement requirements do not efficiently discourage demand for polluting goods. The gasoline tax is an indirect instrument that, through one-way communication, reveals privately held information about which trips can be sacrificed at a low social cost and encourages firms and individuals to sacrifice those. (The term "sacrifice of trips" is used figuratively for options that reduce pollution through reduced demand for the polluting good. Among other such options are more efficient cars.)

The analysis here makes the assumption that the pollution-control agency has all the existing knowledge about the status of vehicles and the efficiency of various abatement options. Removing this assumption would, obviously, open the door to further improvements through instruments that more closely mimic a true emissions fee. Consequently, the proposed program is poorer than a theoretically conceivable program in which, for instance, a pollution tax would reveal and exploit all relevant privately held information. How much poorer the program is depends on how important these remaining information gaps are, assuming that the agency exploits rationally the information that it holds. It is good to know, however, that the additional information upon which the proposed improvement relies—gasoline consumption—is readily available at the pump.

Lastly, in the theoretical literature the distinction between the optimal scale of polluting activities and optimal abatement has been treated only tangentially. The point has been made that pollution taxes are superior to abatement subsidies because the latter may lead to too much of the polluting activity (see, for instance, Baumol and Oates 1988). However, making polluters pay for abatement (as advocated by the Organization of Economic Cooperation and Development; see OECD 1975 and Opschoor and Vos 1989) does not imply optimal discouragement if they do not also pay for damages. Making polluters pay for damages would imply optimal discouragement; polluters would then choose to pay for optimal abatement. In the present study, two instruments are assumed available to the planner: an abatement requirement and a tax on a variable input (the one most strongly associated with pollution generation) in the polluting activity. Unless the emissions or the polluting good is taxed, the polluting activity is too large, even when polluters pay for abatement.[3] The use of more than one instrument to deal with only one negative external effect is driven by a monitoring problem. When monitoring of individual contributions to pollution is costly, indirect instruments should be used to influence the different choices that can affect pollution (see Eskeland and Jimenez 1992).

3. Some insight into the role that can be played by changes in the level of activity in polluting sectors is provided by Jorgenson and Wilcoxen (1990) and Hazilla and Kopp (1990). However, they explore changes in sectoral activity levels as result of abatement costs, rather than as a result of pollution taxes, input taxes, or output taxes.

## II. A Simple Model with Demand Management and Abatement

The model must not only allow for behavioral responses to policies that can influence demand, but must also provide a measure of the social costs of such demand manipulation. The models proposed in the literature on welfare economics are tailored to these purposes. Ideally, the model would have many consumers or groups of consumers. This would allow for analysis of the distribution of costs and benefits across economic agents, apart from efficiency aspects.

To focus on efficiency, the model used here is one with a representative consumer. Such a framework has two principal shortcomings. First, it cannot be used to analyze the effects on income distribution. The use of a representative consumer can be justified only by assuming that the effects of the air pollution control strategy on income distribution is not of major interest because, for instance, the planner can use other instruments that can cheaply transfer income between groups. Second, in practice consumers differ along other dimensions, for instance, by owning unevenly polluting vehicles. The model can best be interpreted as one in which a representative consumer owns a composite of the vehicle fleet in Mexico City.

The model employed here is separable along two lines in the direct utility function, as in Balcer (1980) and Wijkander (1985), and has a representative consumer, as in Sandmo (1976) and Wijkander (1985). Finally, it is assumed that generating public revenue is not costly in itself. This assumption is reasonable only if the requirement for public sector revenue does not exhaust the potential of instruments available for costless transfers to the public sector.

### *The Consumer's Problem*

Let consumers be numbered 1 through $n$ and let individual $j$'s emissions depend on the individual's consumption of the polluting good and the abatement applied. The individual's preferences are represented by a utility function, with utility depending on the quantities of polluting goods and nonpolluting goods consumed, as well as on the total amount of emissions from all $n$ individuals. It is assumed that the utility function satisfies the traditional regularity conditions: it is quasi-concave, continuous, and twice differentiable. Furthermore, it is assumed that the quantities consumed of polluting goods and nonpolluting goods, $x$ and $y$, respectively, are constrained to non-negative values, as is abatement, $a$, and that the individually optimal solution does not involve either of the corners $y = 0$ or $x = 0$. Furthermore, in this section, it is assumed that initial expenditures on abatement are very productive (abatement is produced at constant returns to scale, but its effect on emissions is declining), so that the corner $a = 0$ does not occur in the planner's optimum unless in combination with $t_x = 0$, where $t_x$ is the rate of tax on the polluting good. The latter assumption is relaxed in section III.

It is assumed that individual $j$ takes consumer prices as given and chooses a consumption vector that maximizes utility, $u$, under a budget constraint that requires that the total value of the individual's consumption not exceed the individual's income. Letting $\beta^j$ be the shadow price of $j$'s budget constraint, the Lagrangian of $j$'s maximization problem can be written

$$\mathscr{L}^j = u^j\left[y^j, x^j, \sum_{i=1}^{n} e^i(x^i, a^i)\right] - \beta^j\left[y^j + (p_x + t_x)x^j + p_a a^j - \left(I^j + \frac{1}{n}t_x \sum_{i=1}^{n} x^i\right)\right], \tag{1}$$

where superscripts denote individuals and $\Sigma e^i(x^i, a^i)$ is the sum of emissions, $e$, generated by all individuals. In the budget constraint, $(p_x + t_x)$ and $p_a$ are the consumer prices of the polluting good and of abatement, respectively, whereas $p_x$ and $p_a$ are the producer prices. The nonpolluting good is untaxed, and its price is normalized to one. Furthermore, the budget constraint reflects the assumption that tax revenues are redistributed to consumers as transfers, to be added to the consumer's lump-sum income, $I^j$. The consumer, if expanding the consumption of the taxed good, will share the generated tax revenues with all the other individuals. Thus, public and private income at the margin have the same social value, so that there is no need for costly revenue generation. For simplicity of exposition, it is furthermore assumed that an individual's abatement has little or no value to that individual compared with the price of the abatement. Thus, the consumer applies as little abatement as possible: zero or the level mandated by the planner. Then, as abatement is chosen by the planner, the first-order condition for consumer optimum is found by setting the partial derivatives of equation 1 with respect to $x^j$ and $y^j$ equal to zero:

$$u^j_{x^j}/u^j_{y^j} + u^j_{e^j}\, e^j_{x^j}/u^j_{y^j} = p_x + t_x - t_x/n, \tag{2}$$

where subscripts to the function symbols denote partial derivatives, and the equation has been solved for the shadow price of income for consumer $j$. Notice that there are superscripts for only one individual in the first-order conditions. We assume that individuals are equal, in order to be able to work with a representative consumer, and may thus eliminate individual superscripts.

Additional assumptions are that individuals do not take into account the effect of their own pollution on themselves and that they do not take into account that a share of their own tax payments will be returned to them. Both are either theoretically correct descriptions or minor approximations if $n$, the number of individuals who pollute each other and share public revenues (here assumed to be the same), is large (Sandmo 1975). Then, from the perspective of individual optimization, the second term and the term $t_x/n$ in equation 2 are both zero, so the first-order condition for individual optimum is

$$u_x/u_y = p_x + t_x. \tag{3}$$

Generally, the Marshallian demand functions $x(\cdot)$ and $y(\cdot)$ consistent with equation 3 will depend on the consumer's income, consumer prices, the mandated abatement, and the level of pollution. However, to simplify exposition and focus on the policy instruments, prices and income are suppressed. Also, the simplifying assumption that demand does not depend on the level of pollution gives the demand functions $x = x(a, t_x)$ and $y = y(a, t_x)$.[4]

### *The Planner's Problem*

The planner affects abatement through regulation, whereas consumption decisions are influenced by the regulation and by the tax rate levied on the polluting good. It is assumed that the technology is such that production costs (and thus producer prices) are constant, that is, not influenced by the manipulation of consumer prices. As is demonstrated in the literature, the analysis extends to the case with responsive producer prices as long as there are constant returns to scale (see, for instance, Diamond and Mirrlees 1971 or Atkinson and Stiglitz 1980: 373).

In advising a benevolent planner whose objective is to maximize consumer utility, the relevant resource constraint is that of the economy as a whole because it is assumed there is no need for distortionary taxation. The problem is formulated as one of maximizing the utility of the representative consumer, and the budget constraint can be written net of taxes and transfers. The Lagrangian of this problem, with mandated abatement and a tax on the polluting good as instruments, can be written

$$\begin{aligned} \mathscr{L} &= u\{y(a, t_x), x(a, t_x), ne[x(a, t_x), a]\} \\ &\quad - \gamma\, [y(a, t_x) + p_x x(a, t_x) + p_a a - I], \end{aligned} \tag{4}$$

where $u(y, x, ne)$ is substituted for $u(y, x, \Sigma_i e^i)$. Comparing equations 1 and 4, the difference between the individual's objective function and the planner's is that the individual does not take into account his effect on emissions, whereas the planner takes into account the effect of emissions on all individuals. A similar difference is present in the constraints of the two problems: whereas the individual looks at tax payments as costs, the planner takes into account that they are all redistributed. Thus, to the planner, taxes paid are not lost and involve costs only to the extent that they distort resource use.

An optimal program is characterized by the partial derivatives of equation 4 with respect to the abatement requirement and the tax rate both being equal to zero. Using also the partial derivatives of the resource constraint (which ties the demand responsiveness for the two consumption goods to each other), and

4. To see how the results extend, notice first that prices will be determined by the use of these policy instruments and that if producer prices are constant, $x_t = dx/d(p_x + t_x)$, and so on. Let $x = x(a, t_x, e)$, $y = y(a, t_x, e)$, and $e = e(x, a)$. Totally differentiating and solving, $dx/da$, $dy/da$, $dx/dt_x$, and $dy/dt_x$ can substitute for $x_a$, $y_a$, $x_t$, and $y_t$, and the subsequent analysis and results apply.

assuming that demand for the polluting good is not completely insensitive to its price ($x_t \neq 0$), we find that the optimal allocation is characterized by[5]

$$u_x / u_y + nu_e e_x / u_y = p_x \tag{5}$$

$$nu_e / u_y = \frac{p_a}{e_a}. \tag{6}$$

Equation 6 requires that the sum across individuals of the marginal rates of substitution be equal to the marginal rates of transformation, consistent with Samuelson's (1954) result for optimal provision of public goods. Air quality, or absence of pollution, is an ideal example of a public good according to Samuelson's definition that consumption of a public good is nonexclusive.

Using the fact that marginal rates of substitution in consumption will equal consumer prices (equation 3), the optimal allocation is induced by an appropriate abatement requirement and a tax to be levied on the polluting good equal to

$$t_x / (p_x + t_x) = -\, nu_e e_x / u_x. \tag{7}$$

Thus, the consumer price of the polluting good shall be such as to incorporate the social costs that its consumption imposes on others (notice that no such tax on the polluting good is desirable if emissions themselves are taxed).

Solving for $nu_e$, optimality requires that

$$t_x / e_x = -\, p_a / e_a. \tag{8}$$

Equation 8 states that the optimal tax rate on the polluting good, per unit of emissions from the polluting good, is equal to the direct marginal cost of abatement per unit of achieved emission reductions. This will prove a useful comparison in the next subsection, in the characterization of a cost-effective program.

The optimal program, as completely characterized by equations 5 and 6, could be implemented by one instrument: an emissions fee, if it were available. This fact is easily checked by replacing the instruments in equation 4 with a tax levied on emissions and modifying the individual budget constraint accordingly.

### *Cost-effective Pollution Control*

In the optimal program, abatement and demand management are pursued to the point where marginal benefits equal marginal costs. If benefit estimates are unavailable, or in dispute, it is helpful to ask how a specified target for emissions

5. In general, if consumption of the polluting good is completely insensitive to its price (meaning that the adjustments to price changes will be in the consumption of nonpolluting goods only), then $c_a / e_a = nu_e$ characterizes the optimal program, whereas $t_x$ is not determined by pollution-control objectives, because it has no effect on pollution.

(or emission reductions) can be achieved at lowest possible costs.[6] The following shows how the concept of cost-effectiveness, emphasizing the costs of manipulating demand, fits into a traditional framework of welfare analysis.

Starting from an arbitrary set of policies—an abatement requirement, $a$, and tax rate, $t_x$—welfare and emissions will be given as functions of $a$ and $t_x$: $w(a, t_x) = u\{y(\cdot), x(\cdot), e[a, x(\cdot)]\}$ and $e(a, t_x) = e[a, x(\cdot)]$. The estimated marginal effect on welfare from a small change in the tax rate, per unit of associated reductions in emissions, is found by partial differentiation and division:

$$\frac{\partial w}{\partial t_x} \Big/ \frac{\partial e}{\partial t_x} = \frac{u_y t_x}{e_x} + nu_e. \tag{9}$$

In conventional terminology, the first element in equation 9 is the marginal cost of a change in the tax rate, and the second is the marginal benefit. Following the same procedure, but this time differentiating with respect to the abatement requirement, the marginal impact on welfare of an adjustment in the abatement requirement, per unit of associated reductions in emissions, is

$$\frac{\partial w}{\partial a} \Big/ \frac{\partial e}{\partial a} = \frac{(t_x x_a - p_a)u_y}{e_x x_a + e_a} + nu_e \tag{10}$$

where similar comments apply for the two elements.

Equations 9 and 10 are valid expressions for the net marginal impact on welfare of a change in the tax rate and the abatement requirement, respectively, even when the instruments are not applied cost-effectively or optimally. Furthermore, should the use of one of the instruments be constrained to some value, then the optimal policy (as opposed to cost-effective pollution control), conditional on the actual application of one instrument, is characterized by the available (unconstrained) instrument's net marginal impact on welfare being equal to zero.

Composing a cost-effective program requires the comparison of marginal costs of emission reductions across instruments. It is now easily seen that a comparison of the two instruments—abatement and taxation—is robust to imprecision in the benefit estimate, because the benefit estimate is added in the same way to the expressions for the marginal impact on welfare.

The cost expression in equation 9 is very simple: marginal costs depend only on the tax rate on the polluting good (assuming that other goods are priced at marginal costs) and on the marginal impact on emissions of consuming the polluting good (grams of pollutants emitted per liter of gasoline con-

6. Quantifiable estimates of environmental benefits can be hard to come by, both in physical terms (for example, improved visibility or reduced mortality) and in value terms (for example, willingness to pay for improved visibility or reduced mortality). For a recent, general discussion, see Cropper and Oates (1992). Briefly, on what is applicable to Mexico, see Margulis (1991). For a methodology based on health effects, see Ostro (1994).

sumed).[7] Thus, the marginal cost of using tax rate changes to reduce emissions does not depend on the elasticity of demand for polluting goods. This result is illustrated in figure 1, which is drawn for a given level of abatement and consequently a given $e_x$. The welfare cost (emission benefits excluded) of a tax change, $dt$, is the trapezoid $abcd$, approximated by the rectangle $tdx = tx_t dt$ for small tax changes. Emission reductions, $de$, will equal $e_x dx = e_x x_t dt$, and $x_t$ cancels out in the ratio between the two, that is, $(dw/dt)/(de/dt) = t/e_x$, which is the expression for marginal costs. Thus, the part of the gasoline demand curve that lies above the supply curve can be seen as a supply curve for emission reductions (emissions per liter of gasoline, $e_x$, is shown as an alternative unit of measurement along the $x$ axis). This result does not say that the amount of emission benefits offered by a given tax change is independent of the demand elasticity. It says that the marginal welfare costs, per unit of obtained emission reductions, are independent of the demand elasticity. As an example, if the elasticity were small, the emission reductions would be small, but so would be the costs from sacrificed consumption, because changes in consumption would be small. The result should be of no surprise. A basic result of welfare economics says that efficiency is ensured when agents face the marginal social costs and benefits of their actions. In the absence of other distortions, that result does not depend on demand elasticities.

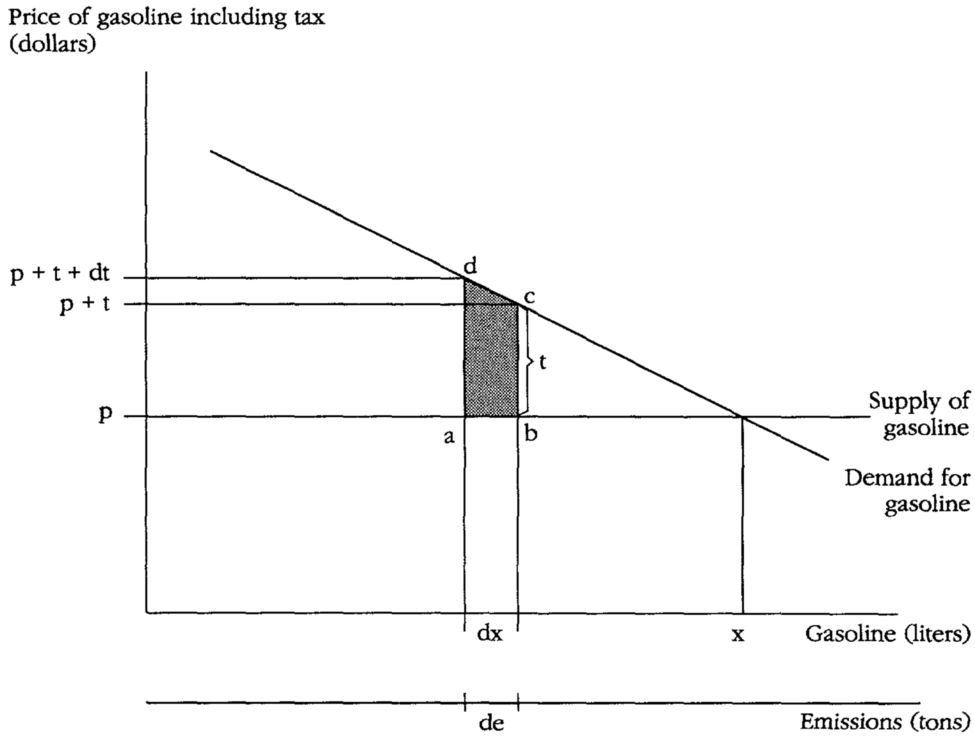
In comparison with equation 9, the expression for marginal welfare costs of abatement requirements, equation 10, is considerably more complicated. In particular, the responsiveness of demand to stricter abatement requirements, $x_a$, remains a determinant both of the welfare costs (in the numerator) and of the emission reductions (in the denominator). Somewhat paradoxically, the cost of emission reductions through abatement depends on the demand responsiveness, whereas the cost through changing the tax rate, the demand management instrument, does not.[8]

Figure 1 also shows, however, that the cost of achieving a given emissions reduction is higher, the lower the demand elasticity. This result carries over to the case in which abatement is available. With abatement available, the implication is that the cost of not applying a gasoline tax is higher, the higher the

7. The assumption that the responsiveness of emissions to small changes in gasoline prices will be proportional to the responsiveness of gasoline consumption, that is, that $e_x(a, x)x_t = kx_t$, is probably fair, although conservative (Krupnick 1992 provides some analysis). Proportionality is assumed in the main emissions projection models, such as the U.S. Environmental Protection Agency's Mobile 4 and AP-42 models. In this analysis, the use of different fuels and the relative prices of fuels are suppressed so that the results apply to a general price level for automotive fuels. In practice, relative prices between fuels may not be available for manipulating demand between fuels. Technical considerations may give the planner preferences for a specific match between car type and fuel type. (The concern in Mexico City was to reserve limited supplies of unleaded gasoline for cars with catalytic converters.)

8. Several authors have addressed the issue that abatement requirements also affect emissions through demand responsiveness, but I have not seen noted that this responsiveness affects welfare costs as well. An effect explored in the literature is that the higher costs of new cars decelerate replacement of older, dirtier cars (Crandall and others 1986; Berkovec 1985). Equation 10 does not include such effects on fleet demographics, which will, to some extent, wash out in the long run.

Figure 1. *The Welfare Cost of an Increase in the Tax on Gasoline*




demand elasticity. As an example, if abatement is cheap and demand inelastic, a cost-effective program would take only small emission reductions from demand reductions, so losses in a program that failed to stimulate demand reductions would not be large. One may notice, here, an important distinction between Pigovian and revenue-motivated taxes. For Pigovian purposes, it is particularly important to tax goods if they are elastic in demand, because one seeks reductions in demand. For revenue generation, one seeks to tax goods inelastic in demand, to minimize demand distortions.

Minimizing the welfare costs of targeted emission reductions, one would utilize the two instruments (the gasoline tax and mandated abatement) so that their marginal costs are equalized (just as one would procure goods from two suppliers). Setting the marginal-cost expressions, equations 9 and 10, equal to each other, some elements cancel out, and a cost-effective program is characterized by

$$t_x / e_x = - p_a / e_a \, . \tag{11}$$

Equation 11 is the solution to the maximization of welfare subject to an emissions constraint. Constrained maximization would, in addition, yield a shadow price equal to the two expressions in equation 11 on the emissions constraint. The indirect method used here also derives the marginal cost for the two instruments when they are not exploited cost-effectively (equations 9 and 10). Equations 9 through 11 illustrate that the attractiveness of a tax on the polluting good does not depend on the availability of benefit estimates. The mere application of mandated abatement reveals that welfare costs can be saved by taxing polluting goods.

To interpret this result in light of a first-best program, notice that a program with direct taxation of individual emissions (or with tradable emission permits) optimally combines discouragement of the polluting activity with incentives to make the activity cleaner. Mandated abatement, instead, needs to be accompanied by instruments discouraging activity levels to minimize welfare costs of emission reductions. Also, the left side of equation 11 is the marginal cost measure for the tax on polluting goods, and the right side is the simple, or direct, marginal cost for abatement expenditures. Thus, this simplistic measure of cost-effectiveness, often used in applied studies, is valid, but only if the polluting good is taxed accordingly (otherwise, equation 10 gives a different measure, which is the correct one). Equation 11, which is a complete characterization of a continuum of cost-effective programs, is equal to equation 8, which, together with equation 6, gives a complete characterization of the optimal program. Thus, the optimal program is a special case among cost-effective programs.

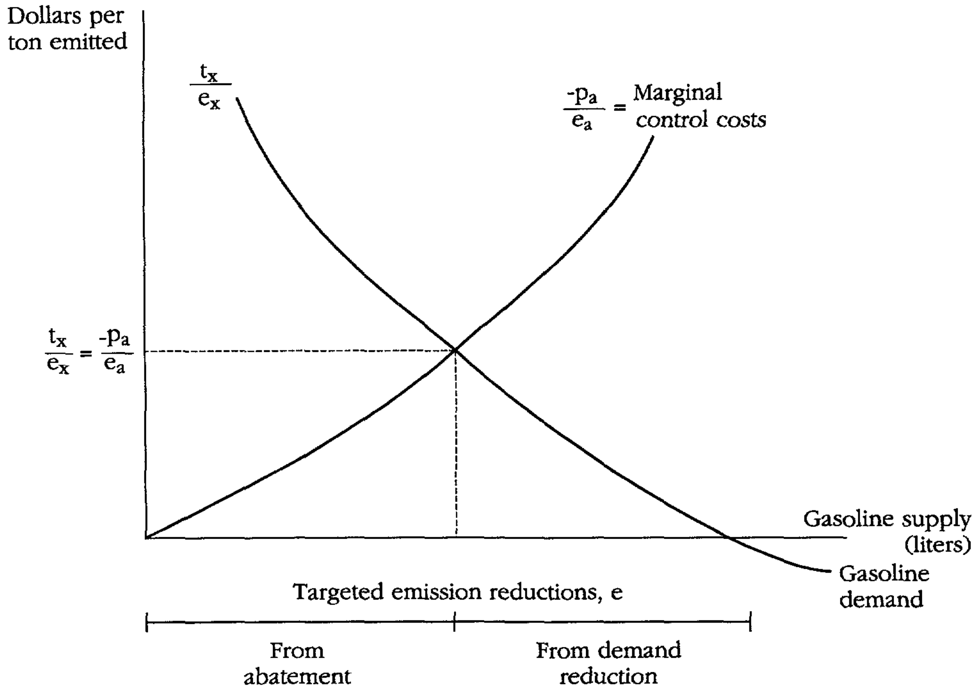
Figure 2 illustrates a cost-effective program. The horizontal line is the amount of emission reductions targeted. The marginal cost curve for emission reductions through abatement expenditures, equation 10, is drawn from left to right (for simplicity, it is assumed that $x_a = 0$). The part of the gasoline demand curve that lies above the marginal cost of supply, recalculated to be quoted per gram of implied emissions, is a supply curve for emission reductions provided by the other instrument, the gasoline tax (equation 9). A cost-effective program is found where the two curves intersect. For any other combination of abatement and tax rate that satisfies the target, the difference between the two marginal cost curves can be saved by substituting, at the margin, the cheaper for the more expensive instrument, holding emissions constant.

There is another way of exploiting the results of this section, however. Equation 11 states that knowledge of the marginal costs per unit of emissions reduced through technical controls implies knowledge of the gasoline tax rate with which it should be combined for the program to be cost-effective. This perspective is applied in the following application to data on pollution-control options in Mexico City.

## III. Application to an Air Pollution Control Program

In an analysis of emissions control options for motor vehicles in Mexico City, technical control options were ranked according to incremental costs per unit of

Figure 2. *Abatement and Demand Reduction in a Cost-Effective Program*




weighted emission reductions (table 1).[9] The list is thus sorted in the sequence in which measures would be implemented if the ambition level of the control program (or, equivalently, the willingness to pay for emission reductions) were gradually increased. However, demand responsiveness is not incorporated in the figures, which simply show the direct incremental costs of abatement divided by the increment in emission reductions, $-p_a/e_a$. The figures in table 1 are, however, valid estimates of marginal costs if the abatement initiatives are accompanied by a gasoline tax that is optimal, conditional on the extent of abatement (equation 11). Such a matching gasoline tax is shown in the fourth column.[10]

9. The term "weighted emission reductions" refers to the prioritization of air pollution control programs that address several kinds of emitted pollutants simultaneously. In the World Bank's analysis of the Mexico City program, weights attempted to reflect both the desirability of achieving ambient standards and the contribution of each emitted gram of a particular pollutant to total ambient concentrations of pollutants. The following weights were applied: lead, 85/g; nitrogen oxides, 4.7/g; respirable dust, 2.3/g; dust, 0.9/g; sulphur oxides, 1.4/g; carbon monoxide, 0.04/g; and nonmethane hydrocarbons, 1.8/g (see Weaver 1991).

10. For simplicity, these calculations assume that the abatement requirement does not affect demand, that is, that $x_a = 0$, and that the cost of abatement, $-p_a/e_a$, is unaffected by the gasoline tax. The latter assumption may be valid even when sizable changes in instrument use are considered, but the assumption

An example may illustrate the calculations in table 1. If the measure called "Mandate '1993 standards' for passenger cars" was the costliest applied in a program, then the cost of abatement to be matched by the gasoline tax would be \$669 per weighted ton of emissions. With this and all the cheaper measures in effect, emissions per liter for the fleet as a whole would average 60 weighted grams, and the gasoline tax should be 4 cents a liter, as calculated by equation 11.[11] These tax rates represent optimal discouragement of gasoline use, given the burden placed on gasoline users to make their use cleaner. Any combination of technical controls with a lower gasoline tax than suggested implies that, keeping total emissions unchanged, consumers could be better off by spending less on abatement and sacrificing more trips in return.

The tax rate per liter of gasoline in table 1 increases less than proportionally with the costs of applied technical measures. The explanation for this is that the technical measures reduce emissions per liter, so the tax base for a presumptive Pigovian gasoline tax declines with increasing control costs. Therefore, there are several reasons why the gasoline tax becomes an increasingly expensive instrument the more aggressive the program is. One is that each liter carries fewer grams of emissions as successive control measures are undertaken, so the sacrifice of a liter in consumption offers less in terms of emission reductions the cleaner the average vehicle is. Another is that, the higher the rate of the gasoline tax, the more valuable are the trips that households and firms have already sacrificed.

An estimate of the elasticity of gasoline demand is needed to estimate the emission reductions resulting from the gasoline tax. Berndt and Botero (1985) estimated demand equations based on pooled regional (1973–78), as well as national (1968–79), time-series data for gasoline sales in Mexico. On the basis of several models, they concluded with price elasticity estimates in the range of −0.2 to −0.7.[12] Eskeland and Feyzioglu (1994), using an improved

that abatement requirements affect demand in the same way that output taxes do would be more appropriate, particularly in the long run (abatement requirements affect fixed costs of vehicle ownership more than they affect short-term variable costs). This alternative assumption would increase the emission reductions offered at any of the suggested policy combinations and thus not change the way the curve is shifted to the right when a matching gasoline tax is included in the program.

11. For the 1993 standard, annualized toxicity-weighted emissions are calculated to be 0.036 tons a year, whereas the baseline alternative would give 0.191 tons a year, so the emissions reduction is calculated to be 0.155 tons a year. Annualized costs, including fuel savings but also a higher maintenance bill, are calculated to be \$104. The 1993 standard thus offers emission reductions at \$104/0.155 = \$669/ton. To calculate the matching gasoline tax, observe that when emission controls cheaper than and including \$669 a ton are applied, the emissions coefficient is calculated to be 60 grams a liter, that is, ($t_x$ dollars a liter/60 grams a liter) $\times$ $10^6$ grams a ton = \$669/ton, which implies that $t_x = (669 \times 60)/10^6 = 0.04$.

12. Some other empirical studies indicate the same range. Pindyck (1979) uses pooled data and finds that for OECD countries, the price elasticity exceeds −0.4 when the time for adjustment is four years or more; for Brazil and Mexico, estimates are −0.12 for the short run and −0.55 for the long run. Sterner, Dahl, and Franzen (1992) report estimation of various models for 21 OECD countries (time series and pooled), with an average of −0.25 for short-run elasticities and −0.8 for long-run elasticities.

Table 1. *Mexico City: Abatement Measures and Matching Gasoline Tax Rates*

| *Abatement measure* | *Cost of weighted emission reductions (U.S. dollars per ton)* | *Cumulative weighted emission reductions (thousands of tons)* | *Cumulative costs of abatement (millions of U.S. dollars)* | *Matching gasoline tax (cents per liter)* |
|---|---|---|---|---|
| Retrofit trucks for liquid petroleum gas | −379 | 90 | 0 | −4.4 |
| Retrofit minibuses for compressed natural gas | −248 | 148 | 0 | −2.8 |
| Retrofit trucks for compressed natural gas | −225 | 231 | 0 | −2.4 |
| Recover gasoline vapor | −80 | 275 | 0 | −0.8 |
| Provide light buses with new engines | 140 | 299 | 3 | 1.4 |
| Bring minibuses to "1992 standards" | 181 | 391 | 20 | 1.7 |
| Mandate inspection and maintenance of high-use vehicles | 209 | 545 | 52 | 1.8 |
| Mandate "1993 standards" for gasoline trucks | 264 | 632 | 75 | 2.1 |
| Mandate "tier-1 standards" for taxis | 322 | 641 | 78 | 2.5 |
| Provide R-100 buses with new engines | 482 | 651 | 83 | 3.7 |
| Replace taxis to conform to "1993 standards" | 510 | 714 | 115 | 3.7 |
| Test emissions for passenger cars | 651 | 771 | 152 | 4.4 |
| Mandate "1993 standards" for passenger cars | 669 | 883 | 227 | 4.0 |
| Provide special diesel | 699 | 893 | 234 | 4.2 |
| Lower vapor pressure to 7.5 | 836 | 904 | 243 | 4.9 |
| Provide regular unleaded gasoline | 923 | 954 | 289 | 5.1 |
| Decentralize inspection and maintenance of passenger cars | 1,034 | 1,018 | 356 | 5.3 |
| Replace gasoline trucks | 1,114 | 1,096 | 442 | 5.0 |
| Require 5 percent MTBE[a] in regular gasoline | 1,201 | 1,116 | 467 | 5.3 |
| Lower vapor pressure in premium unleaded to 7.5 | 1,313 | 1,128 | 482 | 5.6 |
| Pave roads (1000 km) | 1,335 | 1,136 | 498 | 5.7 |
| Require "1991 standards" for passenger cars | 1,367 | 1,180 | 508 | 5.4 |
| Reduce sulphur to 0.1 percent in diesel | 1,371 | 1,187 | 569 | 5.3 |
| Require "tier-1 standards" for passenger cars | 1,629 | 1,201 | 578 | 6.2 |
| Conform to U.S. specifications for diesel fuel | 2,097 | 1,207 | 601 | 7.9 |
| Require 11 percent MTBE[a] in regular gasoline | 2,447 | 1,219 | 613 | 9.0 |
| Require 5 percent MTBE[a] in premium gasoline | 13,487 | 1,222 | 643 | 49.0 |
| Require 11 percent MTBE[a] in premium gasoline | 14,728 | 1,226 | 686 | 53.2 |

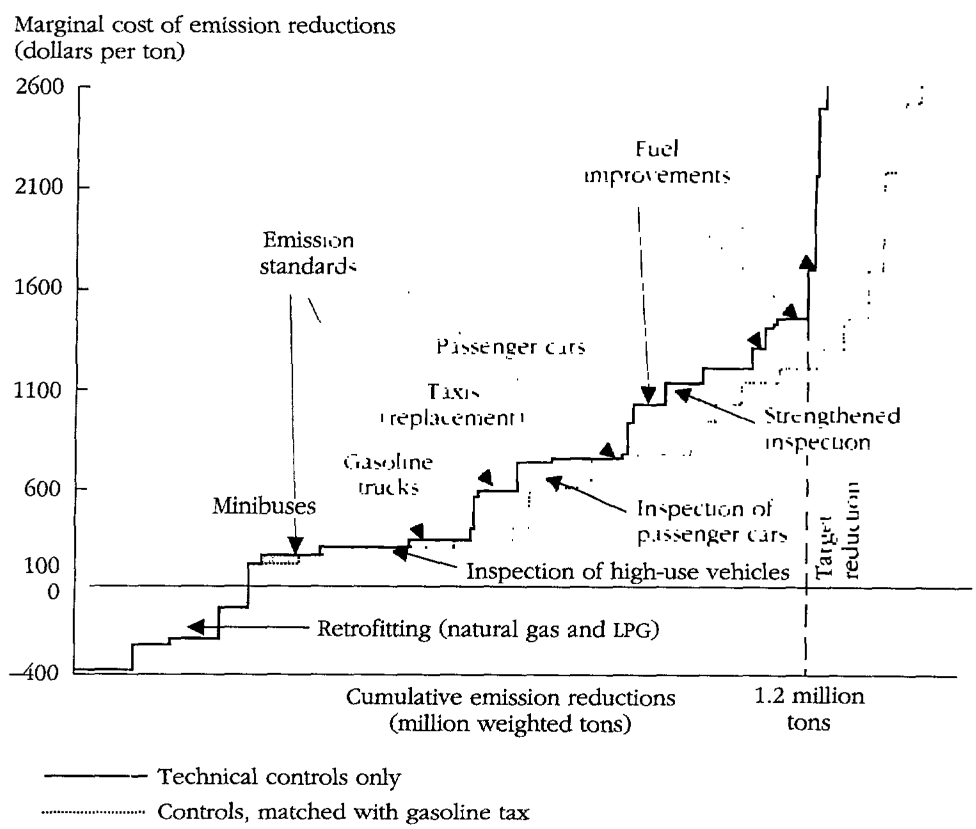
a. MTBE is a fuel oxygenator, as an alternative to lead for raising octane levels.
*Source:* World Bank 1992.

methodology and more recent data, estimate short- and long-term elasticities for total gasoline consumption of −0.79 and −0.8, respectively. Thus, the most important difference in terms of estimated parameters is a higher short-term elasticity; the longer-term effects are quite similar. To estimate the effects on the 1995 emissions inventory, a price elasticity of −0.8 is employed.

Because the gasoline tax will induce demand to contract, more emission reductions will be provided at every cost level, and the result will be a more moderately sloped control cost curve. The two control cost curves are shown in figure 3, with the area between the curves representing the difference in total costs between a strategy based solely on technical controls and a strategy including demand management with the help of a gasoline tax.

Under these assumptions, a gasoline tax of 6.2 cents a liter (26 percent, ad valorem) reduces demand by about 20.8 percent for a program targeted to reduce weighted emissions by 1.2 million annual tons by 1995. Applying such a

Figure 3. *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.

tax thus allows for 20.8 percent additional emission reductions at a willingness to pay of $1,629 a ton. Not one of the abatement measures offers emission reductions of that magnitude. Alternatively, settling for a target of 1.2 million tons in emission reductions would make unnecessary the use of measures escalating in costs from $1,114 to $1,629 a ton. The cost savings would be an estimated $111 million annually, or 19.2 percent of the estimated total control costs.

The following can highlight the interdependency between the two sets of instruments. When control costs reach $1,629 a ton, average emission coefficients are reduced by 70 percent, reducing the base for the presumptive emissions tax on gasoline to 30 percent of its precontrol level. Thus, at a willingness to pay of $1,629 a ton, the optimal gasoline tax rate would be 20, rather than 6.2, cents a liter if the gasoline tax was the only available instrument.

A higher gasoline tax could be justified by a number of alternative assumptions, but not (as shown in section II) by a higher (or lower) demand elasticity. First, because the cost curve for technical controls is assumed to be steep for reductions exceeding 1.2 million tons, a further rise in the gasoline tax is one of the very few instruments that are effective if further reductions are needed. Second, reduction in usage also has benefits in terms of reduced congestion, noise, and accidents, none of which are accounted for in this analysis. It might be tempting to add that attaching a separate value to the transfer of funds from the private sector to the public sector would also justify a higher rate and that such transfers are to be valued in an economy that has suffered severely under strained public finances. However, such a change in modeling assumptions would motivate broadly based taxes on all goods without necessarily raising the part of the rate levied on gasoline that is motivated by the emissions control objective. (But the use of Pigovian taxes would reduce the distortionary costs of revenue generation; see Sandmo 1975). Although the present model has been developed under the assumption that generating public revenues is not costly and thus cannot be used to gauge the importance of revenue generation, it might be of interest that the tax rate indicated by the narrowly focused model would generate an estimated $350 million in annual revenue in Mexico City alone.

## IV. Concluding Remarks

Can demand management instruments such as a gasoline tax play a role in a cost-effective pollution control program? An analytical framework was presented that allows the comparison of demand management instruments with mandated abatement requirements. The framework provided the following results:

- Adding mandated abatement requirements to a program consisting of indirect taxes—or vice versa—will improve the program.

- The set of programs in which abatement and demand management are combined in a cost-effective fashion is characterized without knowledge of the demand elasticity for gasoline (equation 11).
- The cost associated with not including gasoline taxes in the tool kit for the control program is larger, the higher the demand elasticity.

To investigate the practical significance of these findings, the framework was applied to a recently analyzed program of technical interventions to reduce air pollution from urban transport in Mexico City. It was found that a tax of 6.2 cents a liter (26 percent, ad valorem) would be suitable to complement abatement in a program aimed at reducing emissions from the 1995 vehicle fleet by about 70 percent. Using a demand elasticity of $-0.8$, the inclusion of a gasoline tax in the program would make the targeted emission reductions attainable at 19.2 percent lower social costs, including the welfare costs of demand manipulation. The low level of the tax is partly explained by the fact that abatement will, by then, have reduced average emission coefficients by 60 to 70 percent, so marginal emissions per liter, the base of a presumptive Pigovian tax on gasoline, are also diminished.

The recommended tax could have been higher if higher emission reductions were targeted or if reduced congestion, accidents, and road damage were valued as well. For a city with a persistent problem of air pollution, the tax rate could decrease over time if reductions in emission coefficients so warrant. Alternatively, the tax rate could increase over time if the increase in demand for the polluting good is such that increasingly expensive measures must be undertaken.

After recent policy-induced increases in gasoline prices of 40 to 50 percent, implicit tax rates in Mexico are higher than those suggested above. The higher tax rate may well be justified by the reasons mentioned, as well as by the fact that average emission coefficients are still much higher than those assumed above for 1995. More important, the actual setting of tax and price policy in Mexico is one of a multitude of objectives and interests, including the important one of funding public budgets. The model presented here is far too modest in scope to judge a complex tax structure in a more general context.

## References

The word "processed" describes informally reproduced works that may not be commonly available through library systems.

Atkinson, Anthony, and J. E. Stiglitz. 1980. *Lectures on Public Economics*. Maidenhead, U.K.: McGraw-Hill.

Balcer, Yves. 1980. "Taxation of Externalities, Direct versus Indirect." *Journal of Public Economics* 13:121–29.

Baron, David P., and R. B. Myerson. 1982. "Regulating a Monopolist with Unknown Costs." *Econometrica* 50(4):911–30.

Baumol, William J., and W. E. Oates. 1988. *The Theory of Environmental Policy*. Englewood Cliffs, N.J.: Prentice-Hall.

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

Berkovec, James A. 1985. "New Car Sales and Used Car Stocks: A Model of the Automobile Market." *Rand Journal of Economics* 16(2, Summer):195–214.

Besanko, David, and David E. M. Sappington. 1987. *Designing Regulatory Policy with Limited Information.* New York, N.Y.: Harwood Academic Publishers.

Coase, Ronald. 1960. "The Problem of Social Costs." *Journal of Law and Economics* 3:1–44.

Crandall, Robert W., H. Gruenspecht, T. Keeler, and L. B. Lave. 1986. *Regulating the Automobile.* Washington, D.C.: Brookings Institution.

Cropper, Maureen L., and Wallace E. Oates. 1992. "Environmental Economics: A Survey." *Journal of Economic Literature* 30 (June):675–740.

Dasgupta, Partha, Peter Hammond, and Eric S. Maskin. 1980. "On Imperfect Information and Optimal Pollution Control." *Review of Economic Studies* 47:857–60.

Diamond, Peter A., and James A. Mirrlees. 1971. "Optimal Taxation and Public Production, I: Production Efficiency and II: Tax Rules." *American Economic Review* 61:8–27, 261–78.

Eskeland, Gunnar S. 1992. "Attacking Air Pollution in Mexico City." *Finance and Development* 29(4, December):28–30.

Eskeland, Gunnar S., and Tarhan Feyzioglu. 1994. "Is Demand for Polluting Goods Manageable? An Econometric Model of Vehicle Ownership and Gasoline Demand in Mexico." Policy Research Working Paper 1309. World Bank, Policy Research Department, Washington, D.C.

Eskeland, Gunnar S., and Emmanuel Jimenez. 1992. "Policy Instruments for Pollution Control in Developing Countries." *The World Bank Research Observer* 7(2, July):145–69.

Farrell, Joseph. 1987. "Information and the Coase Theorem." *Journal of Economic Perspectives* 1(2):113–29.

Greenwald, Bruce C., and Joseph E. Stiglitz. 1986. "Externalities in Economies with Imperfect Information and Incomplete Markets." *Quarterly Journal of Economics* 101:229–64.

Hammond, Peter. 1979. "Straightforward Individual Incentive Compatibility in Large Economies." *Review of Economic Studies.* Symposium on Incentive Compatibility, XLVI (2), No.143, 263–82.

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

Jorgenson, Dale W., and Peter J. Wilcoxen. 1990. "Environmental Regulation and U.S. Economic Growth." *Rand Journal of Economics* 21(2, Summer):314–40.

Krupnick, Alan. 1992. "Modelling Issues in the Control of Air Pollution from Transport." Processed (submitted for the World Bank Research Working Paper Series).

Laffont, Jean-Jacques. 1993. "Regulation of Pollution with Asymmetric Information." *Document de travail.* Institut D'Economie Industrielle.

Lawson, Douglas R., P. J. Groblicki, D. H. Stedmand, G. A. Bishop, and Paul L. Guenther. 1990. "Emissions from In-Use Motor Vehicles in Los Angeles: A Pilot Study of Remote Sensing and the Inspection and Maintenance Program." *Journal of the Air and Waste Management Association* 40:1096–1105.

Margulis, Sergio. 1991. "Back of the Envelope Estimates of Environmental Damage Costs in Mexico." Policy Research Working Paper 824. World Bank, Latin America and the Caribbean Technical Department, Washington, D.C.

Mirrlees, J. A. 1976. "Optimal Tax Theory: A Synthesis." *Journal of Public Economics* 6:327–58.

OECD (Organization for Economic Cooperation and Development). 1975. *The Polluter Pays Principle.* Paris.

Opschoor, J. P., and Hans Vos. 1989. *The Application of Economic Instruments for Environmental Protection in OECD Member Countries.* Paris: Organization for Economic Cooperation and Development.

Ostro, Bart. 1994. "Estimating Health Effects of Air Pollution: A Methodology with an Application to Jakarta." Policy Research Working Paper 1301. World Bank, Policy Research Department, Washington, D.C. Processed.

Pigou, A. C. 1932. *Economics of Welfare.* London: Macmillan.

Pindyck, Robert S. 1979. *The Structure of World Energy Demand.* Cambridge, Mass.: MIT Press.

Samuelson, P. A. 1954. "The Pure Theory of Public Expenditure." *Review of Economics and Statistics* 36:387–89.

Sandmo, Agnar. 1975. "Optimal Taxation in the Presence of Externalities." *Swedish Journal of Economics* (now the *Scandinavian Journal of Economics*) 77:86–98.

———. 1976. "Direct versus Indirect Pigovian Taxation." *European Economic Review* 7:337–49.

Starrett, David A. 1988. *Foundations of Public Economics.* Cambridge Economic Handbooks. Cambridge University Press.

Sterner, Tomas, C. Dahl, and M. Franzen. 1992. "Carbon Tax Policy, Carbon Emissions, and the Global Environment." *Journal of Transport Economics and Policy* (May):109–19.

Weaver, Christopher S. 1991. "Proposed Pollutant Weights for the Mexico City Air Pollution Control Program." Annex 4 in World Bank (1992). Processed.

Wijkander, Hans. 1985. "Correcting Externalities through Taxes on Subsidies to Related Goods." *Journal of Public Economics* 28:111–25.

World Bank. 1992. "Mexico Transport Air Quality Management in the Mexico City Metropolitan Area." Sector Study, March 9, 1992, 10045-ME. World Bank, Publications Unit, Washington, D.C. Processed.