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TAXES, FUEL CONSUMPTION, AND CARBON DIOXIDE EMISSIONS

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SUMMARY

The consumption of fossil fuels is a major source of carbon dioxide that contributes to the greenhouse warming of the earth's atmosphere. This report is a preliminary study of whether taxes should be used in industrialized countries to reduce this consumption.

Following the introduction, the report has five principal sections. First, it elaborates a general framework for the analysis and evaluation of proposals to tax fossil fuels. Second, it gives a basic introduction to the concept of "price elasticity of demand"; economists use elasticity figures to indicate the responsiveness of a good's consumption to changes in its price. Third, the report goes on to discuss some common difficulties economists face when they try to estimate and interpret elasticities. Fourth, it surveys some of the more highly-regarded elasticity estimates for fossil fuels provided by researchers in the last decade. And fifth, building on the previous discussion, the report concludes with a preliminary assessment of the merits of an increased gasoline tax in the U.S..

The report's principal conclusions are as follows:

A Framework for the Analysis of Taxation Proposals

-- Fossil fuels can be hierarchically categorized by physical type, consuming sector, and end-use service provided. Given data limitations, the most feasible categorization is by fuel type (principally oil, natural gas, and coal) and consuming sector (usually identified as residential, industrial, commercial, and transport).

-- When deciding whether or not to work for a tax on a fuel in one of these categories, policy makers should weigh five factors: 1. the contribution of the fuel to the greenhouse problem; 2. the propensity of consumers to conserve this fuel when its price increases, either by changing the rate of use of the technologies that consume the fuel or by substituting other factors of production for the fuel; 3. the propensity to substitute for the fuel other fuels whose combustion contributes less to the greenhouse effect, 4. the policy feasibility of the proposed tax; and 5. the social benefit of the tax. The propensities to conserve and substitute (2 and 3) are encompassed by the price elasticity of demand for the fuel in question.

The Basics of Price Elasticities of Demand

-- The own-price elasticity of demand for a commodity is the percentage change in demand for the commodity given a one percent change in its price. The cross-elasticity of demand for a commodity is the percentage change in demand given a one percent change in another commodity's price.

-- Price elasticities are derived from mathematical models that describe energy consumption as a function of the price of the fuel, the price of fuel-consuming technology, income, time, and numerous other variables.

-- An own-price elasticity figure for a good applies to only one point on the good's demand curve, and a demand curve with a constant elasticity is concave.

-- Economists distinguish between "short-run" and "long-run" elasticities. The short-run price elasticity of demand for a fuel is a measure of people's ability to change their consumption habits in the period (usually taken to be one year) immediately following a price increase. The long-run elasticity additionally takes into account changes in fuel-consuming capital stock (over a period of up to twenty or thirty years) through replacement with more efficient technologies or technologies that consume other fuels.

-- We are concerned mainly with long-run elasticities because greenhouse warming is a long-run problem that requires permanent changes, not just in habits of fuel consumption, but also in the economy's capital stock.

-- When faced with a price increase in a particular fuel, consumers can respond in four possible ways: 1. In the short run, they can change the rate at which they use the technologies that burn the fuel. 2. Also in the short run, they can sometimes change the mix of fuels or factors of production that are inputs into these technologies. 3. Over the longer term, people can replace their fuel-consuming capital stock with technologies that use a cheaper fuel or that use the fuel more efficiently. 4. Also over the longer term, people can change their measure of "welfare" so that it is less dependent on the particular services provided by the fuel in question.

-- This fourth possibility is rarely considered by economists. But, in the end, we may not be able to achieve the needed reductions in fuel consumption solely through responses of types 1 through 3. We may have to think seriously about actively revising our criteria of welfare, that is, of the "good life."

-- This fourth type of response involves, essentially, changing the position and shape (and in turn the elasticity) of the demand curve for the services provided by a given fossil fuel.

Problems with the Estimation and Interpretation of Elasticities

-- The percentage size of the responses of types 1 through 3 above, given a certain price increase for a certain fuel, can be predicted using the own-price and cross-elasticities for the fuels and factors of production in question.

-- It is commonly assumed that estimating and interpreting these elasticities is a fairly straightforward task. Unfortunately, this is not the case, and, although there have been countless studies of the effects of price on energy consumption, little consensus has emerged on the price elasticities of demand for energy sources.

-- We should take special heed of Douglas Bohi's cautionary note: "If policy makers turn to research in this area for guidance, they will be confronted with a range of numbers that is frequently so wide it offers little direction. These disparities can affect the enthusiasm for a given analytical position, or they can be used to support widely disparate positions."

-- Variations in elasticity estimates arise from two main sources: differences in the sample data and differences in the econometric methodologies used to derive estimates from the data.

-- Models of energy consumption fall into four general categories: structural, reduced-form end-use, reduced-form static, and reduced-form dynamic. Each has its strengths and weaknesses. The magnitude of an elasticity estimate, as well as its reliability and validity, will be influenced by the type of energy model the researcher uses. When we interpret elasticities, we should therefore keep in mind the important differences between these models.

-- We should also be aware of a number of other issues relating to the magnitude, reliability, and validity of elasticity estimates, including problems of aggregation across energy sources, consumers, and end-uses; problems of separating the supply and demand effects of price increases; problems arising from markets in disequilibrium because of government regulation; and issues relating to the form of the functions used to describe energy demand.

-- It appears, in general, that formal econometric modeling has been unduly emphasized in energy analysis, and that more resources must be devoted to hard empirical research into actual energy consumption behavior. Some researchers contend that numerous crucially important determinants of energy demand are not incorporated in existing formal models, including institutional limits on choice, the nature of communication in a society about energy issues, and the symbolic meaning of appeals for energy conservation in a given culture. In the main, it appears that economists are operating with a narrow and impoverished view of human rationality.

Current Estimates of Price Elasticities of Demand

-- A review of the current literature on long-run own-price elasticities of demand for fossil fuels by sector suggests that there is a great deal of uncertainty about the figures for most fuel-sector categories. The exceptions are residential electricity and natural gas (where the consensus estimates are, respectively, -0.7 and -0.3) and

transportation gasoline (-0.8).

-- There are two principal reasons why we should take special interest in the gasoline elasticity. First, this elasticity is one of the few fuel-sector elasticities which has been thoroughly and effectively researched by economists and on which they have reached a fair consensus. Second, from the point of view of reducing the emissions of carbon dioxide, we are more interested in conservation (resulting from changes in technology use-rates and interfactor substitution) than in interfuel substitution. And when we look at the price elasticity for gasoline, we know we are looking at largely a conservation effect; whereas with the elasticities of other fuels, we are less sure how much is a genuine conservation effect and how much is simply the result of the substitution of one fossil fuel for another.

-- For these latter fuels, in order to separate the two effects, it is necessary to consult a complete formal model of the economy's energy consumption that includes information about fuel and factor shares in addition to own-price and substitution elasticities. Formal models have been used in this way, but their results must be regarded with some skepticism.

An Assessment of an Increased Gasoline Tax

-- It is a common misperception that the cost of a tax on a commodity is borne entirely by the consumer. But the distribution of the burden is actually shared between the producer and consumer according to the elasticities of the commodity's supply and demand curves. Therefore, the tax leveled on a commodity such as gasoline must normally be larger than the desired increase in price, because some of the tax will be absorbed by the producer and will not appear in the retail price.

-- An increased gasoline tax in the U.S. merits the support of policy makers for the following reasons: 1. Gasoline consumption in the U.S. accounts for between 2% and 3% of total global greenhouse forcing by anthropogenic greenhouse gases. 2. As noted, demand for gasoline exhibits a relatively high elasticity of -0.8, and we can interpret this as largely a conservation effect. 3. A gasoline tax in the U.S. seems somewhat more politically feasible than other possible energy taxes, although the American political and economic culture presents a very hostile environment for any tax proposal. 4. While a gasoline tax is generally thought by economists to be regressive, these effects can be at least partially mitigated.

-- There appear to be two general ways of arriving at a judgment about the size of the tax. First, we can try to estimate the total value of the external costs that we wish to internalize through the tax. But there seems to be no truly satisfactory way of doing this. Second, we can decide how much we want to reduce carbon dioxide emissions, and then, using our elasticity figure of -0.8, we can calculate the price increase required to bring about this reduction.

-- If the -0.8 figure is accurate, a gasoline tax in the U.S. that is sufficient to raise the price by 100% would induce a 43% decrease in consumption. But we should remember that the -0.8 figure applies only to a single point on the demand curve, and there is reason to suspect that it does not apply at higher prices.

-- Furthermore, when we sum up the life-cycle costs of high-efficiency automobiles, we find that the average gasoline consumer may not have much financial incentive to purchase a car with a fuel efficiency of over 40 miles per gallon, even when the gasoline price is more than twice current levels. Thus, the -0.8 elasticity figure may also be misleading because researchers obtained the data for this estimate while fuel economies were far below 40 miles per gallon and consumers had a reason to invest in efficiency.

-- Empirical research is needed to determine whether or not the -0.8 figure will continue to hold even when automobile efficiencies surpass the 40 mile per gallon mark.

-- Because the price elasticity of demand for gasoline may be less than -0.8, a gasoline tax should be coupled with two other policies: an increased gas-guzzler tax (with moving thresholds and rebates for fuel efficient vehicles) and improved vehicle efficiency standards (that apply effectively to light trucks and that allow sufficient lead time for efficiency improvements to move from research and engineering to production).

I. INTRODUCTION

The combustion of fossil fuels is a major source of carbon dioxide that contributes to the greenhouse warming of the earth's atmosphere. This report is a preliminary study of whether taxes should be used to reduce this fuel consumption.

The report emphasizes information and analysis that is probably not readily available to policy makers. At the most general level, it lays out a framework to guide our analysis of the efficacy, fairness, and feasibility of taxes on fossil fuels; this framework should be of use in future research. More specifically, the report summarizes the range of estimates (provided by econometric modelers during the last decade) of price elasticities of demand for the principal fossil fuels in the principal sectors of the economy.[1] These elasticities are derived from macroeconomic models of energy consumption and cannot be fully understood independently of the models and their underlying assumptions. Therefore, the following pages include a review of the nature and appropriate interpretation of price elasticities in energy economics.

The latter part of this report considers in some detail the merits of a higher gasoline tax in the United States. This tax is evaluated in light of its effectiveness in reducing carbon dioxide emissions, political feasibility, and impact on wealth distribution; and it is briefly compared with other policy instruments, including a gas-guzzler tax, mandated end-use efficiency standards, and pollution options.

[1]The price elasticity of demand for a good is the percentage change in the good's consumption resulting from a one percent change in its price.

Principally for reasons of time, several important issues are not dealt with here. First, this report does not consider the utility of taxes in reducing fuel consumption specifically in developing economies. While data on the effects of price on fuel demand are plentiful for certain sectors and fuels in the OECD nations, without exception data are very scarce for developing countries. Furthermore, noncommercial biomass, which is not susceptible to taxation, makes up a large fraction of fuel consumption in these societies. For these reasons, estimating the effects and feasibility of fuel taxes would require considerable additional research.[2]

Second, this report does not examine the possible deleterious macroeconomic effects -- on inflation, unemployment, and national income -- of fuel price increases. This is a massive, tangled, and contentious issue that would require much time to understand and effectively summarize.[3]

Finally, this report does not undertake an analysis of the possible responses of electric utilities to taxes on fossil fuels, although in industrialized economies the combustion of fossil fuels by utilities is a major source of carbon dioxide. These

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[2]Readers interested in examining more closely the situation in developing countries should refer to Pindyck (1979, chapter 7), Dunkerley et al. (1981, especially chapter 5), Manibog (1984), Moavenzadeh and Geltner (1984, chapter 5), Sathaye and Meyers (1985), Wood and Baldwin (1985), Blitzer (1986), Dorian and Clark (1987), Meier and Munasinghe (1987), Metwally and Arab (1987), Dayo and Adegbulugbe (1987), Siddayao et al. (1987), Sathaye et al. (1987), and Gouda (1988).

[3]Useful articles on these issues include Gibbons (1984), Gordon (1984), Sweeney (1984), Huntington (1985), Berndt and Wood (1987), Solow (1987), Doblin (1988), Jorgenson and Fraumeni (1981), and Jorgenson (1984, 1986, 1988a and b). Jorgenson's work is particularly important here because he suggests that higher energy prices will lead to a lower rate of productivity growth in industrialized economies. In other words, higher energy prices, if appropriate countermeasures are not taken, could actually impede the development of the energy-saving technologies needed to reduce fossil fuel consumption. Jorgenson's view is disputed by some economists; Douglas Bohi at Resources for the Future (who is currently writing a book on energy and macroeconomic policy) has said in conversation that Jorgenson is "an outlier" on the question of energy prices and productivity. But Jorgenson's research is widely regarded as very thorough and deserving of close attention.

utilities operate within extraordinarily complex regulatory and financial regimes that make it very difficult to estimate the responsiveness of their fuel consumption to price.[4] This issue needs research far beyond the scope of this report.

II. A FRAMEWORK FOR THE ANALYSIS OF TAXATION PROPOSALS

Although the following analytical framework is preliminary, it can help us judge the merits of various taxation proposals; towards the end of this report, this framework is used to evaluate the proposal to increase the U.S. gasoline tax.

Policy makers trying to use taxes to reduce the greenhouse effect need answers to the following questions: Which of the many possible taxes or tax increases should they work to achieve? More specifically, from which of these taxation options can they expect (probabilistically) the biggest return (in preventing global warming) per dollar of policymaking effort invested?

To answer these questions, we can begin by using the following hierarchical procedure to categorize the relevant energy sources:

1. First, we can categorize fossil fuels by their physical type; for example, we can distinguish between oil, coal, and natural gas.[5] We also need to categorize electricity according to whether it is generated by the combustion of one or other type of fossil fuel.

2. Then we can divide each of these types of fuel and electricity into further categories according to the economic sector that consumes this energy, that is,

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[4]Professor Richard Tabors at MIT is currently conducting some very interesting research on the use of combined-cycle (natural gas) technologies to reduce utilities' emissions of carbon dioxide. He should be contacted directly for further information about his work.

[5]If we wish to implement a "carbon tax," then we should distinguish between physical types of fuel on the basis of the amount of carbon released per unit of useful energy contained in the fuel.

whether the final consumer is the commercial, residential, industrial, or transportation sector. This gives us categories such as "residential oil" and "industrial electricity produced from the combustion of natural gas."

3. And finally, we might further divide these energy categories by the end-use service this energy provides in a given sector. Thus we derive the category of "residential oil used for space heating."

Ideally, a thorough study would disaggregate fuels by using all three categorization schemes.[6] For instance, we might seek the price elasticity of demand for electricity used for illumination in the industrial sector. But such extremely disaggregated data are not available, so this report uses only the sectoral and fuel-type categorizations -- giving, for example, the coal, oil, gas, and electricity elasticities for each sector.[7] However, there are still serious data constraints here, especially outside the US.

Once we have completed our categorization, we can determine whether it would be worthwhile to work for taxes on a given fuel (or type of fossil fuel-generated electricity) by evaluating the tax proposal according to the following five variables:

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[6]Of course, many other categorization schemes are possible. For example, fossil fuels could be grouped according to their point of origin; in particular, we might distinguish between domestically produced and imported fossil fuels in order to levy an import fee or tariff. This policy option will be discussed later.

[7]These will be called "fuel-sector elasticities." If we assume there are four basic energy sources and four final consumer sectors, then we have sixteen possible fuel-sector elasticities. (Of course, there is no demand within some of these fuel-sector categories, for example "coal for transportation.") In addition, as will be noted shortly, we will likely find useful the price elasticities of demand of utilities for the three basic fossil fuel energy sources (oil, coal, and natural gas) that they consume to produce electricity.

1. The contribution of the fuel's combustion to the total "greenhouse forcing" of climate by anthropogenic carbon dioxide.[8]

2. The propensity to conserve this fuel when its price is increased. Conservation can come either from a decrease in the rate of use of the technology that consumes the fuel or from the substitution of non-energy factors of production (specifically, capital and labor) for the energy that the fuel provides.

3. The propensity to substitute for this fuel less environmentally deleterious fuels. (Variables 2 and 3 in this list are encompassed by the fuel's price elasticity of demand.)[9]

4. The policy feasibility of imposing taxes on this fuel; and,

5. The social benefit of the suggested tax (other than that from the lower production of greenhouse gases).[10]

We can numerically estimate values for the first three variables, but for the last two we might best use some simple ordinal scale (e.g. "high," "medium," and "low"). Policy makers should work for a tax on a particular fuel if it has a high "score" on each of these variables. Fuels that score well in all five categories offer

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[8]"Forcing" is a term used by climate scientists to describe the contribution of human-released gases to the greenhouse effect. These gases include carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide.

[9]Regarding variables 2 and 3, the situation is a little more complicated for electricity generated by utilities burning fossil fuels. In such situations, utilities are intermediate consumers of energy, in the sense that they convert the chemical energy of coal, oil, or natural gas into electrical energy for final consumption by industries, businesses, and residences. Conservation and substitution can take place at the utility stage as well as the final consumer stage. For example, even if a final consumer is willing to bear an increased electricity price without substantially decreasing demand (i.e., the consumer's price elasticity is low), the utility may still decrease its demand for a heavily taxed fossil fuel by increasing the efficiency of its generating processes (conservation) or switching to a less taxed fuel (interfuel substitution).

Therefore, it may be efficacious to impose taxes at either or both stages. We thus need estimates of utilities' price elasticities for the various fossil fuels they burn, and we also need estimates of the final consumers' price elasticities for the resulting electricity.

[10]We should be careful here not to assume that our version of the "social good" is objective or even widely-accepted. While many policy makers would likely see as socially beneficial a tax on a fuel that had a progressive effect on income distribution, some might argue that the tax structure is already too progressive because it provides insufficient incentive for entrepreneurship and investment.

more hope for useful policy initiatives. On the other hand, policy makers should devote less effort to achieving taxes on a fuel that has a low score on one or more of the variables (i.e., it contributes little to the problem, there is little likelihood of conservation or benign substitution, it would be politically impossible to impose a tax, or the tax would have undesired social effects.)

This is really little more than common sense. It certainly is not a precise procedure or formula for ranking proposals to tax fossil fuels in order to reduce emissions of carbon dioxide. Good quantitative data for 1 through 3 will be hard to find, and estimates for 4 and 5 will be very subjective. But this framework should be a useful heuristic to guide our analysis in the following pages.[11]

III. THE BASICS OF PRICE ELASTICITIES OF DEMAND[12]

Two Approaches to Energy Modeling

Researchers interested in determining the potential for energy conservation in an economy generally use either one of two modeling approaches. The end-use approach, exemplified by Goldemberg et al. (1987), can be described as "bottom

[11]An issue not addressed by this analytical framework, nor addressed in detail in this report, is the appropriate stage (in the temporal sequence of stages from the extraction and production of a given fossil fuel, through its refinement and distribution, to its final consumption) at which a tax is most effective. By including categorization according to end-use service, this framework implies that taxes are most effective when imposed on final consumption rather than at an earlier stage. In the end, economics may not guide this decision; rather the stage at which a tax is imposed may be decided by bureaucratic and institutional requirements for the effective management of the tax.

[12]Good introductory discussions of price elasticities can be found in Griffin (1979, pp. 17-25), Pindyck (1979), Bohi (1981, Chapter 2), Bohi and Zimmerman (1984, pp. 105-113), and Edmonds and Reilly (1985, pp. 57-68).

up": the researcher first identifies the many services provided by energy-consuming technologies in an economy; he then builds a hypothetical alternative economy in which each of these services is provided using the most energy-efficient technology that is both currently available and cost-effective.[13] In contrast, the econometric approach of Hogan (1988, 1989), Pindyck (1979), Griffin (1979), and many other researchers, is more "top down": they use aggregated empirical data to test mathematical models of the relationships between energy consumption, income, price, output, population, and certain other variables.[14] While the first approach is undoubtedly useful in identifying the outer limits of possible energy conservation in an economy, it cannot help us estimate the consumption reduction produced by specific levels of taxes on sources of energy. Such estimates -- of, in particular, the price elasticity of demand for the various sources of energy -- are derived from the latter, econometric models of energy consumption.

Price Elasticity of Demand

The price elasticity of demand for a commodity is the percentage change in demand for the commodity given a one percent change in its price. The commodity's demand is "inelastic" with respect to price if this figure is between 0

[13]Of course, the criteria we use to judge a technology's "cost-effectiveness" are subject to broad debate. For instance, any assessment of the life-cycle cost of a technology will crucially depend on an estimate of the discount rate, but such estimates are often disputed. For a brief description of three criteria of cost-effectiveness, see Goldemberg et al. (1987, p. 54, Box 3).

[14]This distinction between the "bottom-up" end-use approach and the "top-down" econometric approach is drawn from Goldemberg et al. (1987, pp. 70 and 113). Stern (1984, p. 8) similarly identifies these two general approaches (except that he uses the term "engineering process" rather than "end-use") and adds a third -- the system-dynamics approach -- which is less constrained by empirical data and therefore of little use to us here.

and -1.0, "unitary elastic" if equal to -1.0, and "elastic" if between -1.0 and negative infinity.[15]

As a ratio of percentages, price elasticity is independent of the unit of measure, which makes for easy interpretation and comparison across economies. But, when we consider the effects of price increases on energy demand -- such as those induced by taxes -- we should note that an elasticity figure is best interpreted as applying to only **one** point on the demand curve. Edmonds and Reilly (1985, p. 65) note that "elasticity is a concept developed primarily for application to single points on a demand schedule, or at most for small segments of the demand schedule." Moreover, it is important to remember that because elasticity is a ratio of percentages, a straight, diagonal demand curve (as is commonly used in the simple supply/demand diagrams of economists) exhibits a range of elasticities from negative-infinity to 0, with a magnitude of -1 at the halfway point; and a demand curve with a constant elasticity of -1 will be concave (see Figures 1 and 2).

Given all this, price elasticities should be interpreted carefully. If gasoline, for example, has an elasticity of -.8, then a one percent increase in gasoline's price will produce a .8 percent decrease in consumption. But we **cannot** therefore conclude that a 100% increase in price will lead to an 80% decrease in consumption. Rather, assuming the demand curve for gasoline exhibits constant elasticity (which means that all points along the curve have the same elasticity), a 100% increase in price

[15]There is a terminological problem in the literature here. Conventionally, economists refer to an elasticity figure as "greater than" another when the former figure indicates demand is more elastic than the latter. Thus an elasticity of -1.0 is "greater than" an elasticity of -0.5. Of course, what economists are actually referring to here is the absolute value of the elasticity figure. This report holds to conventional usage.

will produce a 43% decrease in demand. This is because the demand curve is concave, and every additional percent increase in price produces a smaller decrease in consumption than the last. A simple mathematical procedure is used to calculate the percentage decrease in consumption given a certain price elasticity and a certain increase in price. The Table 1 provides a selection of results.

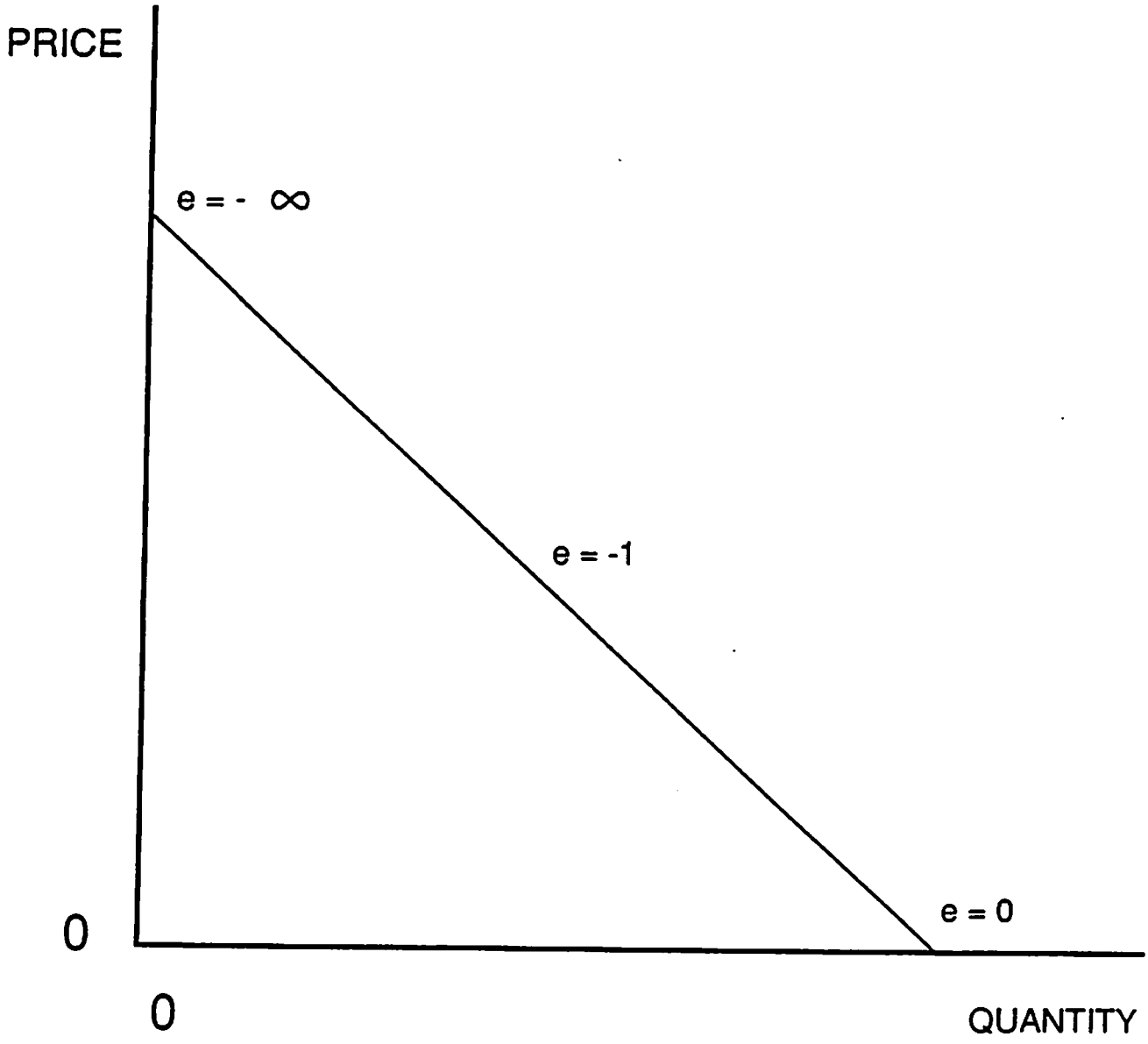

Figure 1. Price Elasticities along a Linear Demand Schedule

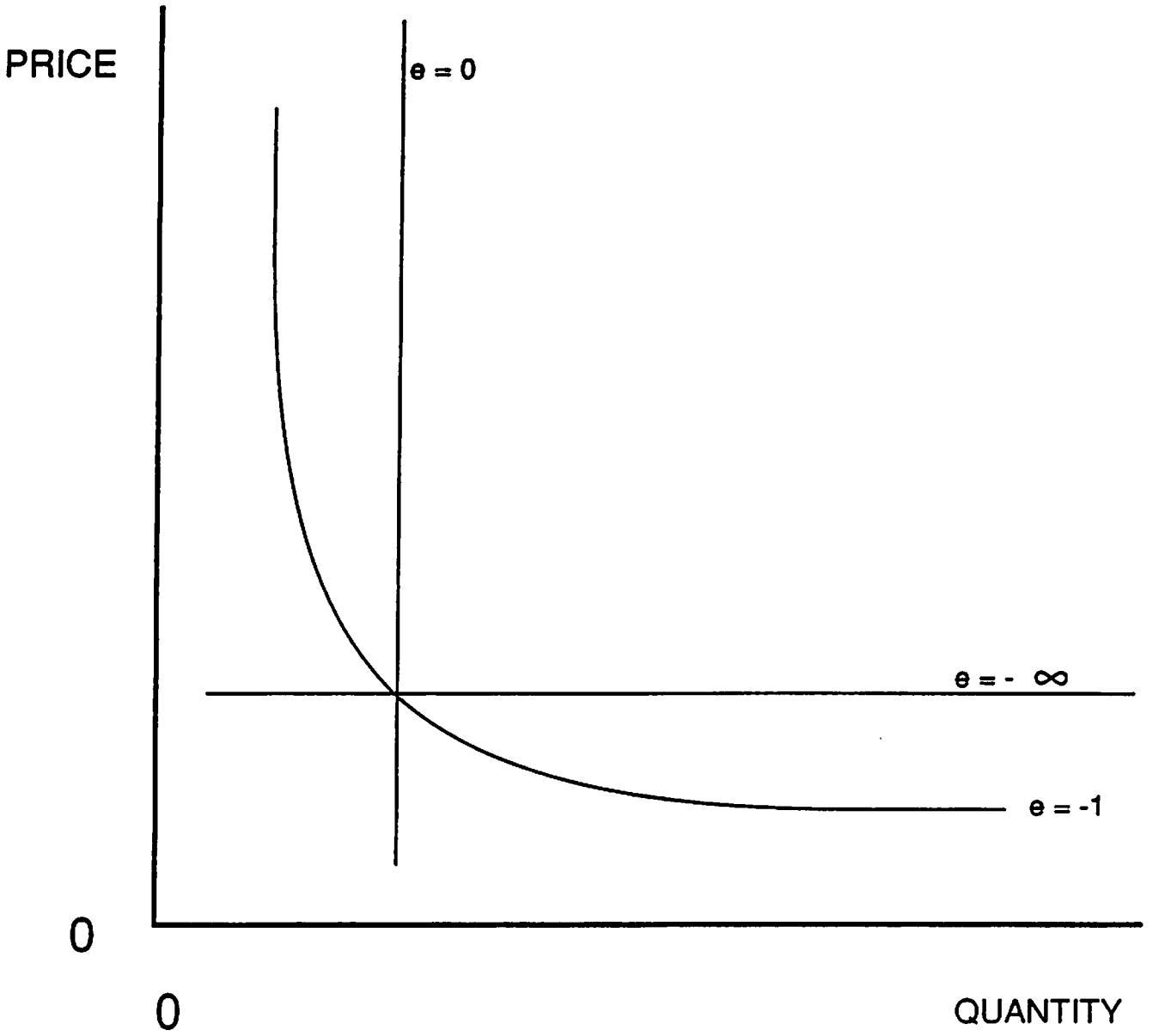

Figure 2. Perfectly inelastic, perfectly elastic, and unitary elastic demand curves

Table 1.
Selected Elasticities, Price Increases, and Consumption Decreases

Elasticity	Price Increase	Consumption Decrease
-.2	50%	8%
	100%	13%
	200%	20%
	400%	28%
-.5	50%	18%
	100%	29%
	200%	42%
	400%	55%
-.8	50%	27%
	100%	43%
	200%	58%
	400%	72%
-1.0	50%	33%
	100%	50%
	200%	67%
	400%	80%
-1.2	50%	39%
	100%	56%
	200%	73%
	400%	86%

As a rule of thumb, if the elasticity is -1.0, then the consumption decrease will equal one minus the ratio of the old price to the new price. Thus for a price increase of 200%, the consumption decrease is 1 - 1/3 or approximately 67%. Remember that all of the above figures for consumption decrease assume that the demand curve exhibits **constant** elasticity. We will find later in this report that there is reason to question this assumption.

Own-price and Cross-Elasticities

Economists commonly distinguish between "own-price" elasticity (which we have discussed above) and "cross-elasticity." The former, as noted, is the percentage change in a good's consumption arising from a one percent change in its price. The latter is the percentage change in a good's consumption given a one percent change in **another** good's price. If, for instance, a one percent increase in the price of residential natural gas produces a .5 percent increase in the demand for residential electricity, then we say that the cross-elasticity of residential electricity with respect to residential natural gas is .5. In this case, we say that electricity is a "substitute" for natural gas, because a price increase in the latter produces an increase in demand for the former; this means that people substitute natural gas to obtain some of the services provided by electricity. If, however, an increase in the price of natural gas leads to a **decrease** in the demand for electricity, then we say that electricity is a "complement" of natural gas; for some reason the two goods need to be consumed together, and the consumption of one increases or decreases with the consumption of the other.

Issues of substitutability and complementarity are very important when we consider the potential for energy conservation and for changes in energy consumption patterns. This is because energy, as Edmonds and Reilly put it, is the "purest of intermediate goods." People do not value energy directly; rather they value energy because it provides services that are valued.[16] Ideally, as long as the same services are provided at the same cost, the consumer should be indifferent as

[16]Thus economists often say that the demand for energy is a "derived demand."

to the particular mix of energy sources used to provide these services. Moreover, the consumer should be equally indifferent to the particular mix of factors of production (energy, capital, and labor) used. If there are, therefore, substantial differences in the prices of energy sources or in the prices of the factors of production, there may be wide latitude (depending on technological limitations) for substitution between energy sources and between energy, capital and labor. In our examination of the effects of taxes on fossil fuel consumption, we are thus interested not only in the own-price elasticities of fuels, but also in their cross-elasticities with respect to other, less-polluting energy sources, and in the cross-elasticities between factors of production.

Short-run and Long-run Elasticities

If the price of a particular fossil fuel increases, people may respond immediately be changing the way they use the technologies that consume this fuel. Over the longer term, consumers may replace their current technologies with those that consume less of the fuel, or another cheaper fuel, yet provide the same services. For example, a sudden jump in the price of gasoline may, in the short run, induce people to drive fewer miles and organize car pools. Over the longer term, however, it is likely drivers will replace their cars with those that get more miles per gallon. This is the basis for economists' distinction between "short-run" and "long-run" energy price elasticities. The short-run price elasticity of demand for a fuel is a measure of people's ability to change their consumption habits in the period (usually taken to be one year) immediately following a price increase. The

long-run elasticity additionally takes into account changes in fuel-consuming capital stock (over a period of up to twenty or thirty years) through replacement with more efficient technologies or technologies that consume other fuels.[17] In this report, we are interested in long-run elasticities because greenhouse warming caused by carbon dioxide emissions is a long-run problem that requires permanent changes, not just in habits of consumption, but also in the economy's capital stock.

Four Responses to a Fuel Price Increase

In general, then, when faced with a price increase in a particular fuel, consumers of the fuel can respond in one or a combination of the following ways:

1. In the short-run, they can change the rate at which they use the technologies that burn the fuel. For example, an automobile owner can drive less, and factory managers can shut down their production lines.

2. Also in the short-run, people can change the mix of fuels or factors of production that are inputs into these technologies. For instance, factory managers may be able to substitute labor for energy as an input into the production process, without changing the technology in the factory. This is commonly called **ex post** flexibility in the mix of inputs, because it is a change in consumption that occurs **after** the installation of equipment (see Hogan, 1989, p. 60, and Fuss, 1977).

3. Over the longer term, people can replace their fuel-consuming capital stock with technologies that use a cheaper fuel or that use the fuel more efficiently (i.e., that require less fuel per unit output of good or service). If the new technology is more fuel-efficient, one of two things may be occurring. On the one hand, the new technology may allow non-energy factors of production (labor, capital, or materials) to be substituted for energy; in other words, a decrease in the consumption of energy may be offset by an increase in the consumption of other factors of production. On the other hand, the new technology may permit a reduction in energy consumption without an increase in the consumption of other factors. In either case, the ratio of the amount of energy to other factors -- what economists call the "energy intensity" of production -- is reduced.

Changes in equipment that allow substitution of another fuel or that increase

[17]It also takes into account longer-term changes in consumption behavior, such as moving closer to work (in the case of gasoline consumption).

the fuel-efficiency of production are examples of **ex ante** flexibility in the mix of inputs, because they are changes in consumption that occur **at the time of** the installation of new equipment, not after its installation.

4. Over the longer term, people can change their measure of "welfare" so that it is less dependent on the particular services provided by the fuel in question.

Changing Our Preferences

This fourth possible response is rarely considered by economists, who usually treat judgments about welfare and utility as external to their models. These judgments are left up to the consumer, who expresses his preferences in the marketplace, and the consumer is sovereign, unassailable. It is not the economist's job to question these preferences; rather he simply takes them as given, incorporates them into his models, and derives predictions of the consumer's economic behavior.

But by leaving such judgments (about the criteria of welfare) external to their models, economists imply that these criteria fall outside the purview of policy: governments must simply accept the preferences of their citizens; their principal role is to provide the appropriate conditions for markets that can efficiently allocate resources according to these preferences.

Furthermore, there is often the subtle implication that when consumers come together and express their preferences (i.e., their individual criteria of welfare) in a market, the prices and choices arising from this market interaction reflect a set of **objective** criteria of welfare. The outcomes of market interaction are simply beyond reproach; they are an objective "good." And invariably this objective "good" is closely associated with a high level of material and energy consumption. Thus

Griffin (1979, pp. 13-21) implies that any tax-induced conservation of energy (that moves the energy market away from its normal equilibrium of supply and demand) results in an objective welfare loss:

> . . . even if reduced energy consumption does not lead to lower GNP, real standards of living are lowered. Reduced energy consumption implies both smaller, less comfortable homes and autos and the substitution of labor-intensive activities for those performed by energy.

Griffin seems to regard the criteria used to judge welfare and standard of living as immutable and objective. He seems to be saying that big houses and cars and low labor-intensity production will always be regarded as good things. But clearly he is wrong: we can quite easily imagine people changing their preferences so that these things are **negatively** valued. In fact, such preference changes have already occurred in the many sub-groups in Western society that emphasize sustainability, material simplicity, and ecological preservation. People in the "green" community, for example, commonly **prefer** living in older, less spacious housing, driving smaller cars, and washing their own dishes.

It is one of the principal contentions of this report that, in the end, we may not be able to achieve the needed reductions in fuel consumption solely through the kinds of responses described in points 1 through 3 above. We may have to think seriously about actively revising our criteria of welfare or, more prosaically, of the "good life."

This fourth kind of response should not be confused with the incorporation of external costs into the price of a good or service. Economists note that often certain costs of the production of a commodity are not included in its price; for example, it might be argued that the current price of gasoline does not reflect the

long-term social costs of greenhouse warming (or even, for that matter, the long-term economic costs). These are "external" costs borne by the commons and the public at large. And one way of incorporating these external costs in gasoline's price is through a tax.

But "internalizing" these external costs through a tax does not involve changing the criteria of welfare -- the preferences -- of consumers. The preferences stay the same, only the cost of satisfying them changes. They may still **prefer** big cars over small cars, but the tax makes them less affordable and therefore less obtainable. If we think of a demand curve for the particular service provided by big cars, what a tax does is simply slide the equilibrium price and quantity **up** the demand curve. A tax does not change either the position or shape of the demand curve.

The fourth kind of response involves, essentially, changing the position and shape (and in turn the elasticity) of the demand curve for the services provided by a given fossil fuel. For instance, if we could convince people who currently like the services provided by space heaters and air conditioners that living in a cooler house in winter and a warmer house in summer is not really that bad,[18] then we would be shifting inward the demand curve for the services provided by space heaters and air conditioners. Moreover, to the extent that these consumers would be willing to forgo those services much more readily as their price increases, then the elasticity of the demand curve has increased.

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[18]We might even convince them that this is **preferable** to life in a completely temperature-controlled environment, because one becomes more aware of the weather and seasons beyond the house's walls.

Technology and the Long-run Price Elasticity of Demand

A final point worth noting in this section is that the potential for the second and third kinds of responses to a fuel price increase is mainly determined by available technology. In other words, the **ex ante** and **ex post** cross-elasticities for fuels and factors of production are, in the main, technologically determined. Furthermore, once we recognize the important role of technology in determining elasticities of demand, we see that we really should distinguish between two kinds of estimates of "long-run" elasticity. On the one hand, we can estimate the long-run price elasticity of demand for a fuel assuming that interfuel and interfactor substitution is governed by technologies that **currently exist**. In other words, we estimate long-run elasticities assuming no further technological change from the present moment, but current capital stock can be replaced with the best currently available technology that substitutes cheaper fuels or other factors of production. On the other hand, we can estimate long-run elasticities assuming that technological change continues and that new, currently unforseen, possibilities will arise for interfuel and interfactor substitution.[19]

[19]It seems that economists usually lump together these two kinds of elasticities without much thought. A more sophisticate treatment is provided by the well-known Institute for Energy Analysis/Oak Ridge Associated Universities global energy-economy model produced by Edmonds and Reilly and later used by the MIT Energy Laboratory (1983). This model separates price-induced and non-price-induced technological change, with the former included in the estimate of long-run price elasticity of energy demand, and the latter incorporated in the model as a separate variable stated in terms of percent per year improvements in energy efficiency.

IV. SOME PROBLEMS WITH THE ESTIMATION AND INTERPRETATION OF PRICE ELASTICITIES OF DEMAND

In Section III, we found that the consumers of a fuel that is subjected to taxation may respond in a variety of ways. They may change the rate at which they use their existing stock of fuel-consuming technology, and/or they may substitute cheaper fuels or non-energy factors of production in either the short-run (by changing the mix of inputs into existing technology, which is **ex post** flexibility) or the long-run (by changing the technology itself, which is **ex ante** flexibility).[20]

The size of these changes, given a certain price increase, can be predicted using the own-price and cross-elasticities for the fuels and factors of production in question. We might think that the task of generating reliable estimates of these elasticities is relatively straight-forward: a researcher simply needs to gather information on the changes in the consumption of a fuel that have followed changes in its price or in the prices of other fuels. And our researcher is fortunate that there have been two huge increases in petroleum prices within the last twenty years -- in 1973-74 and 1979-80 -- that should provide ample data on price and consumption changes. Moreover, once we have these elasticity estimates in hand, we might think they are easy to interpret: an elasticity of a certain magnitude means, using a simple calculation, that a given price increase will lead to a consumption decrease of a certain magnitude.

Unfortunately, the story is not so simple. Although over the last fifteen years there have been countless studies of the effects of price on energy consumption,

[20]Also, as discussed, consumers may change the criteria they use to gauge the value of the services provided by the fuel. We will return to this issue in the conclusion of this report.

little consensus has emerged on the price elasticities of demand for energy sources. This has frustrated many researchers. In 1977, the U.K. Department of Energy concluded that "elasticities are as elastic as rubber bands," while the Energy Modeling Forum (1980) asserted that:

> . . . contrary to popular conception, the energy demand elasticity cannot even be defined consistently without explicit specification of several factors. The point of measurement, method of aggregation, price change composition, time frame, taxes and regulations assumed can significantly affect the calculated value of aggregate elasticity.

And in the opening pages of his thorough review of numerous attempts to estimate elasticities, Bohi (1981, p. 1-2) warns:

> A cursory review of empirical studies of energy demand shows a startling lack of consensus on price elasticities. The estimates vary considerably from one study to the next, in one case suggesting that price is very important and in the next that it is not; sometimes implying that income is the controlling factor while other times suggesting price is dominant; or sometimes indicating that interfuel substitution is important and other times that it is not. If policy makers turn to research in this areas for guidance, they will be confronted with a range of numbers that is frequently so wide it offers little direction. These disparities can affect the enthusiasm for a given analytical position, or they can be used to support widely disparate positions.

Policy makers should take special heed of Bohi's last two sentences here. As will be clear from the discussion in this section and the one that follows, in most of the possible fuel-sector categories there is either very little information on which to base estimates of elasticities or the range of estimates is very broad. In these cases, econometric research gives us no useful policy guidance. Yet, because elasticity estimates appear to have the hard edge and precision of science, there is a danger that policy makers will seize upon any available estimate that seems to be congruent with already favored policy prescriptions. It will be instructive and perhaps a bit chastening, therefore, to review in some detail the difficulties

associated with the estimation and interpretation of price elasticities. These figures are helpful but very limited tools of policy development. Policy makers need a clear understanding of what they can reasonably do with elasticity figures; that is, they need to know which claims they can and cannot reasonably make using a given estimate.

Two Sources of Variation in Elasticity Estimates

Useful reviews of these issues can be found in Pindyck (1979, chapter 2), Bohi (1981, chapter 2), Kouris (1983), and Bohi and Zimmerman (1984). Bohi (1981, p. 2) notes that "the differences among statistical estimates of price elasticities arise from two basic sources: differences in the economic and institutional conditions reflected in the sample and differences in the procedure applied to the data to derive the estimates." Thus elasticity estimates vary, first, because there are variations between samples in energy-consuming habits and technologies and variations in the institutions governing energy markets. Such variations are to be expected across both space and time; they may hinder our understanding of the potential response to a fuel price increase, and they often have real policy importance.

But a more troubling source of variation in elasticity estimates is the diversity of approaches used by economists to model energy consumption. Variations arising from this source are artifacts of researchers' methodologies. These variations have policy importance to the extent that they make more difficult the prediction of the response to price changes, but they do not reflect any policy-relevant difference in the **real** world. Bohi writes:

Every econometric study of demand begins with the same basic economic concepts. It is the estimation procedure that produces divergence. A choice has to be made about the type of model to use, the kinds of data that are appropriate, and the estimation technique that fits the model and data.

Energy Consumption Models

To understand this second source of variation, let's review the basics of energy modeling. As noted previously, the demand for energy is "derived demand": we do not want the energy itself, rather we want the services it provides for us. Invariably, energy needs to be combined with capital to provide these services, so the demand for energy is interdependent with the demand for this capital. According to Bohi and Zimmerman (1984, p. 108), the consumption of a specific fuel in an economy with a certain capital stock can be mathematically stated as follows:

$$Q_i = \sum_{k=1}^{m} R_{ki} A_{ki} \qquad 1$$

Here, the consumption of fuel **i** is the sum of the fuel consumed by each type of capital stock, **A**. R_{ki} can be interpreted as the utilization rate of the **k**th type of equipment of the **i**th fuel. This equation allows the separate specification of the demand functions for **R** and **A**, which is characteristic of "structural" models of energy demand. These separate functions might be stated as follows:

$$A_i = f(P_i, P_j, P_a, Y, X); \quad i \neq j. \qquad 2$$

$$R_i = g(P_i, Y, Z). \qquad 3$$

The first of these two equations says that the demand for the type of equipment that uses fuel **i** is a function of the price of **i**, the price of alternative fuel **j**, the price of the equipment **a**, income **Y**, and certain other variables encompassed by **X**. The second equation gives the utilization rate as a function of the price of fuel **i**, income **Y**, and certain other variables included in **Z**.

Bohi and Zimmerman note that "the interdependence of these two functions illustrates the joint nature of the decision process and indicates that both the capital stock and the utilization rate are endogenous factors of energy demand." If the data for such an analysis are available, and if the modeler has enough time, such structural models give us the most complete understanding of patterns of energy consumption in an economy. But data frequently are **not** available, and full structural models demand vast modeling resources, so economists often compromise by reducing the complexity and requirements of their models.

For instance, when modelers know something about the kinds of energy-consuming equipment in the capital stock, but little about its price, they may develop a "reduced-form end-use" model. Here, the amounts and types of equipment are held constant in the model and left unexplained, while the model concentrates on the determinants of the equipment utilization rate given the existing capital stock.[21] Alternatively, if modelers do not have adequate information on equipment stock

[21]See Fisher and Kaysen (1962). Bohi and Zimmerman note that: "Both the structural and reduced form end-use models are also commonly referred to as 'conditional demand' models since the short-run results are conditional upon a given capital stock."

either, functions 2 and 3 above can be collapsed into a single "reduced-form equation" using equation 1. Thus, if we modify equation 1 to:

$$Q_i = h(A_i, R_i) \qquad 1'$$

in which A_i and R_i are vectors of individual equipment types using fuel i, then we can substitute equations 2 and 3 into equation 1' (dropping P_a) giving:

$$Q_i = k(P_i, P_j, Y, X, Z); \quad i \neq j. \qquad 4$$

This is a reduced-form equation, from which price elasticities of demand are readily available. While this approach is both more feasible (given data limitations) and less unwieldy than structural models, we have lost considerable information. In particular, because equation 4 tells us nothing about the relationship between **R** and **A** (utilization rate and equipment stock), we can no longer clearly distinguish between short-run and long-run responses to fuel price increases. For this reason, equation 4 is called a "static" model.

There are ways of reintroducing a short-run/long-run distinction into these models. Frequently, economists rely upon their data to separate short from long-run effects: they assume that time-series data from within a country reflect short-run adjustments, while cross-sectional data from many countries give us information on the potential for long-run changes in energy consumption. However, there are

reasons to be suspicious of this approach.[22]

Another method of separating short and long-run effects is to say that current consumption of a fuel is an incremental change over past consumption, where the increment is determined by the **desired** consumption given the current price (i.e., consumption after full adjustment of capital stocks) and a certain adjustment coefficient. Thus if Q_t is current consumption, Q_t' is desired consumption after adjustment of capital stock, and **d** is the adjustment coefficient, then:

$$Q_t = Q_{t-1} + d(Q_t' - Q_{t-1}); \qquad 0 < d < 1. \qquad 5$$

This "reduced-form dynamic model" introduces a lagged value of past consumption as an explanatory variable;[23] but, of course, everything still depends on the estimates of **d** and Q_t'. These can be obtained by taking Q_t and Q_t' as equivalent and substituting equation 4 into 5 (Bohi and Zimmerman, p. 110; Bohi, 1981, p. 19); the estimate of **d** is obtained by selecting the coefficient that produces the best agreement with the data. But the results are somewhat ad hoc. As Bohi (1981, p. 21) writes: "It is a matter of choosing the result that best fits the data,

[22]The deep assumption in a cross-sectional analysis is that the countries' capital stocks have had enough time to adjust fully to prevailing fuel prices. But price changes are continually occurring in most countries, and their economies may never be at equilibrium; so we have no way of determining if the price effect we observe is truly long-run. Furthermore, the structure and determinants of demand are likely to vary substantially across countries, and this raises questions about whether we can apply the same model to data from different countries, as is required by a cross-sectional approach. Finally, cross-sectional analysis will tend to exaggerate fuel price elasticities to the extent that energy-intensive industries (such as smelting) locate in countries with low fuel prices.

[23]The seminal books discussing lagged adjustment models are Koyck (1954) and Houthakker and Taylor (1970). The lagged model described here is suggested in the latter work and is generally known as a "partial" adjustment model.

rather than using the data to test a hypothesis about the nature of the adjustment process." Moreover, in general, these "lag-adjustment" models -- while perhaps the most popular type of model in the elasticity-estimating business -- are very sensitive to certain underlying assumptions.[24]

We have, then, four general types of macroeconomic model of energy demand: structural, reduced-form end-use, reduced-form static, and reduced-form dynamic. Each has its strengths and weaknesses, as Bohi and Zimmerman (p. 110) conclude:

> The structural model incorporates the greatest amount of theoretical information about the nature of energy demand behavior and empirical detail. It is also the most cumbersome to estimate. End-use models retain the distinction between capital stock and the utilization rate and can provide estimates of separate end-use elasticities, but are limited to conclusions about the short run. The reduced-form static model provides the least amount of information, but it is relatively simple to estimate. The flow adjustment or reduced-form dynamic model expands on the static version in a potentially useful way, but the distinction between short and long-run adjustments is generally based on an arbitrary specification of the adjustment process. The choice is governed by the objective of the analysis, the availability of capital stock information, and the ease with which the model is employed.

The magnitude of an elasticity estimate, as well its reliability and validity, will be influenced by the type of energy model the researcher uses. When we interpret elasticities, we should therefore keep in mind the above differences between energy models, and interpret the estimates accordingly. But we should also be aware of a number of other issues relating to the magnitude, reliability, and validity of elasticity

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[24]Bohi (1981, p. 20) writes: "Even minor changes in equation form, variable definition, and sample period tend to produce major changes in estimates of the coefficient of the lagged dependent variable. Consequently, estimates of long-run elasticities tend to be highly erratic."

It is also important to note here that an elasticity of demand will not necessarily be the same for a price decrease as it is for a price increase. Elasticities, in other words, may be "asymmetric," and this can present problems for lagged adjustment models (see Gately, p. 97-98).

estimates, including problems of aggregation across energy sources, consumers, and end-uses; problems of separating the supply and demand effects of price increases; problems arising from markets in disequilibrium because of government regulation; and issues relating to the form of the functions used to describe energy demand. These will be considered briefly now.

The Aggregation Problem

The first issue all researchers mention is the problem of aggregation; this problem divides into three parts according to whether the researcher wants to aggregate across energy sources, consumers, and/or end-uses. Ideally, as proposed in Section II above, researchers would use disaggregated data at each of these levels.[25] But invariably the data for such three-fold disaggregation are not available. Furthermore, it is not clear that we would want a **fully** disaggregated model of an economy's energy consumption, even if we could produce one, because the result would be so finely textured (with so many individual elasticities) as to be unmanageable. At some arbitrary point, the researcher must stop subdividing the three categories (of fuel, consumer, and end-use) into finer and finer classifications.

So some degree of aggregation is inescapable. At the level of energy sources, a fully aggregated model would relate energy consumption as a whole (perhaps divided by consuming sector) to price, income, and other variables. This is

[25]Data are usually obtain from the national statistical yearbooks of individual countries, and various publications of the OECD (especially the International Energy Agency), the U.N., and the EEC. In the U.S., publications of the Energy Information Administration of the federal Department of Energy are particularly useful.

not an uncommon approach, and it can yield some insights. But as Kouris (1983, pp. 74-76) notes, it is not at all clear what we should use as our standard for comparing and aggregating diverse fuels. The options include aggregation by thermal content (e.g. Btu's), by average cost, by marginal cost, and by the "useful" energy content of the fuel in a given technology. None of these alternatives is entirely satisfactory, but many researchers have concluded that aggregation by thermal content is the least problematic approach. It seems best, however, to avoid aggregation across energy sources entirely by making at least a crude distinction between types of fuels (e.g. oil, natural gas, and coal).[26]

At the level of the consumer, even if data are disaggregated into the residential, commercial, industrial and transport sectors, we are still grouping very diverse consumers within each one of these broad categories.[27] This is especially true in the industrial sector, where, as Bohi and Zimmerman note (p. 111), "different plants in the same industry use different production processes and industry groupings combine widely different commodities and processes." Each plant or industry grouping that uses a different production process has a different demand function, and the aggregation problem, essentially, is one of arriving at a valid aggregation of these demand functions.[28] This problem is not easily solved; even a

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[26]In full models of an economy's energy consumption, even if fossil fuels are not identified separately, it is especially important to separate electric from non-electric energy sources (see Moghimzadeh, 1986, p.68).

[27]Consumers are usually also grouped according to region or country, as in the cross-sectional type of analysis mentioned above.

[28]Bohi (1981, p. 28) writes: "Each application possesses different demand characteristics, with some that are fuel-specific and requiring substantial modifications of the capital stock, and others with considerable flexibility in fuel switching."

marginally satisfactory solution requires implausible assumptions about the similarity of the income elasticities of demand[29] for individual consumers within the economic sector in question.

Disaggregation at the level of end-use is virtually impossible given current data limitations. Bohi (p. 28) asserts that "even with the finest detail micro data, one must aggregate over different end uses to obtain a measure of the price responsiveness of each fuel." In general, there is good reason to be suspicious of the quality of the data available for the consumer and end-use levels of aggregation. Bohi goes on:

> The most accurate and complete information is available for electricity consumption, because of data reporting requirements established for public utilities. But even here serious measurement problems arise. Consuming sectors are defined in the data by the rate structure paid by users. Residential users pay residential rates, commercial users pay commercial rates, and industrial users pay industrial rates. However, consumers in one sector may pay rates identified with another sector, depending on the level of consumption. In addition, some categories are established by arbitrary definitions. For example, individually metered dwellings and gang-metered buildings with fewer than five households are typically classified as residential, while sales to buildings with more than five households are classified as commercial. The basic information is supplied by individual utilities and, to make matters worse, the definition of class varies from utility to utility.

And,

> The most serious information gaps are in the area of petroleum products, where, . . . for transportation fuels, systematic records are kept of sales by product only, with no distinction by consuming sector or type of use. Gasoline sales are not distinguished by automobile versus other purposes, or by private versus commercial consumption. Fuel oil sales do not distinguish residential space heating from commercial and industrial uses.

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[29]The income elasticity of demand is the percentage change in demand for a commodity given a one percent change in income.

Aggregation errors are a serious threat to the validity and reliability of elasticity estimates. Since they are difficult to understand, predict, and quantify, researchers tend to ignore the possibility of such errors, and instead focus on problems of sampling and equation specification. In general, the greater the aggregation the more questionable the elasticity estimate. We can also predict that the greater the aggregation, the higher the price elasticity of demand, because aggregation provides "greater opportunity for systematic variation in consumption behavior that is correlated with, yet unrelated to, price variation" (Bohi, 1981, p. 31).

The Identification Problem

A further problem that researchers must confront in their attempts to model energy demand (and estimate elasticities) concerns the separation of the supply and demand effects of a fuel price increase. Economists commonly call this the "identification problem." At any one time, the price of commodity reflects the interaction of both supply and demand functions. If we could assume, say, that the demand function for this commodity was stable, then changes in the commodity's price would reflect shifts in the supply function and the price-quantity data points would demarcate the demand function. But such an assumption is usually unwarranted: price changes often reflect shifts in both the supply **and** demand functions (see Figure 3).

Theoretically, if the supply curve for a fuel is perfectly elastic,[30] then any increase or decrease in the fuel's price must be a result of a shift in the supply

[30]Perfect elasticity of supply means that suppliers do not change the price for a fuel as demand for it increases; this is characterized by a horizontal supply curve.

curve, not a shift in the demand curve. Thus any subsequent decrease in quantity demanded can be interpreted as a result of the price increase, and this allows us to demarcate the demand curve. But a situation of perfect elasticity of supply is unlikely, and to the extent that this assumption is embedded in many energy models, their results are suspect. More pragmatically, researchers sometimes try to circumvent the identification problem by developing simultaneous equation models of supply and demand, but it is not clear that this approach is appropriate in energy modeling (see Bohi and Zimmerman, 1984, p. 111-112). "Many demand studies," Bohi writes, "ignore the problem of separating supply and demand effects or simply pass over the problem with a warning that price elasticity estimates may be biased as a result."

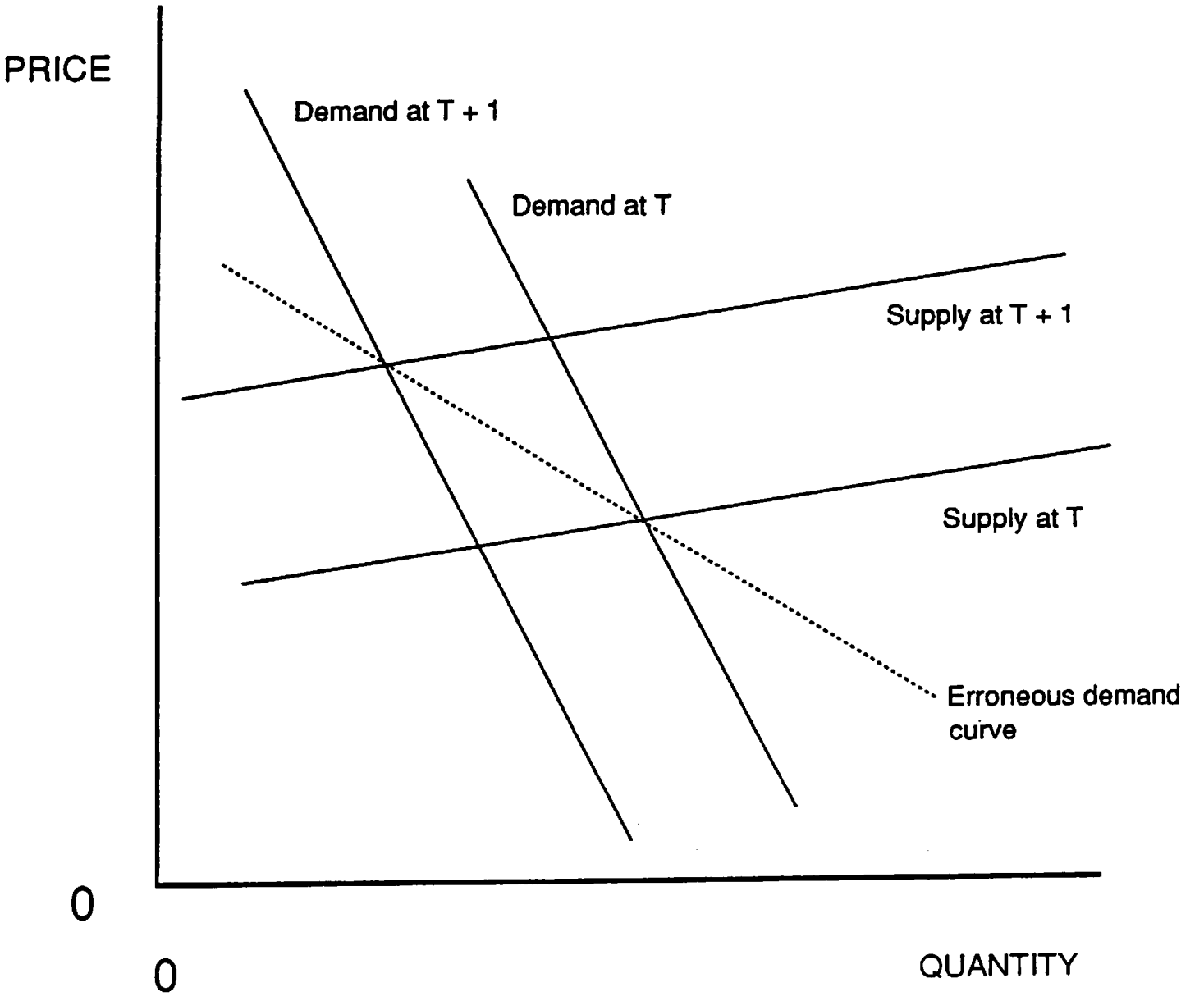

Figure 3. An Example of the Identification Problem

Misspecification of the demand curve may result if an inward shift in the demand curve occurs at the same time as an upward shift in the supply curve.

Identification of demand effects is made even more difficult by the fact that in many energy markets, especially those for natural gas and electricity, customers must make consumption decisions not on the basis of a single price but, rather, on the basis of a complex rate schedule. Often, for example, the price of the fuel goes down in steps as consumption increases.[31] Despite considerable empirical research, it is not clear whether consumers make their consumption decisions according to their average price of consumption, the marginal price of their next unit of consumption, or some measure of the entire rate structure.

Regulation and Energy Market Disequilibrium

Government intervention in energy markets also makes estimating elasticities difficult. Price controls and pollution regulations often prevent a market from coming to equilibrium, and any given price-quantity data point cannot therefore be taken to lie on the normal supply and demand curves. This makes it "difficult if not impossible to infer from observable data the true characteristics of unrestricted behavioral relationships. Furthermore, models based on, or deduced from, equilibrium market conditions are not appropriate" (Bohi, p. 43).

Although apparent in petroleum markets, in the U.S. this problem is particularly acute with natural gas and coal, and it seems to have been widely neglected in the modeling of these markets. Natural gas price controls, for example, produced an excess of supply before 1965 and an inadequate supply afterwards.

[31]What this means, essentially, is that the consumer faces a supply curve with a negative elasticity. For most goods, the supply curve has a positive elasticity; that is, an increase in quantity demanded produces an increase in price. But a negative elasticity introduces an identification problem similar to a positive elasticity.

Both before and after 1965, "price and quantity consumed would not reflect the true demand for natural gas because of supply constraints. Market price was not allowed to close the gap between supply and demand" (Bohi, p. 44). Beginning in 1967, coal consumption by utilities was significantly affected by air pollution regulations. As these regulations were introduced, adjusted, interpreted, and differentially applied over the subsequent decades, the coal market was kept from equilibrium. It is worth quoting Bohi at length here:

> The regulations have contributed to a large disparity between the price for Btu of coal and other fuels compared with the preregulation period. The disparity means that existing coal-fired plants have a large fuel cost advantage compared with alternatives and that large increases in the relative price of coal will not reverse the advantage. Existing coal-fired plants will tend to operate to capacity and will be unaffected by major swings in relative fuel prices. Short-term demand will not be price responsive. Long-term demand will not be fully responsive either, because of delays and impediments to new investment. The fuel cost advantage of coal reflects more than a simple internalization of the cost of air pollution control devices because the costs involve more than pollution control equipment and because these costs have not yet become well defined and stable. The demand for coal remains in a state of disequilibrium because the institutional constraints are still in disequilibrium. (p. 44-45)

Equation Form

The final matter that should seriously affect our interpretation of elasticity estimates is the form of the equations used to describe energy demand. "The choice of equation structure," Edmonds and Reilly (p. 61) write, "can be critical in the determination of elasticities, especially if one wishes to measure elasticities at prices or incomes lying beyond the range of historical observations." They claim that it is not well understood that "despite all of the work which has been undertaken in recent years to establish general functional forms capable of

describing any arbitrary matrix of elasticities at a point, functions impose themselves on the data away from the point of estimation, and in forecasting -- and especially very long-term forecasting, it is the area beyond historical observation that is most interesting."

The issues surrounding equation structure are elaborate and arcane, but in general there are three options available to modelers: linear, double logarithmic, or translog functions. The most commonly used is the double logarithmic form,[32] but important questions have recently been raised about the appropriateness of this mathematical approach. Pindyck (1979, p. 22) comments:

> The double logarithmic demand function is convenient in that price and income elasticities are constant and given directly by the estimated coefficients of the price and income variables. This function, however, cannot be derived as an exact representation of any well-behaved utility function. If in fact this restricted representation of demand is not a correct specification of consumer behavior, the elasticities resulting from its estimation may be biased.[33]

The translog functional form is more "flexible" in that it imposes fewer restrictions on the utility and production functions that underlie the supply and demand equations. The translog form, however, faces its own limitations. In particular, it cannot incorporate the previously mentioned lagged adjustment

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[32]An example of a double logarithmic function, provided by Bohi, is:

$$\log Q = a + b \log P + c \log Y + d \log Z$$

where Q is the quantity demanded, P is its price, Y is income in the case of final consumption or output in the case of intermediate demand, and Z is a vector of other variables.

[33]One of the principal objections to this functional form is that it requires constant own-price elasticities for all levels of price and income; furthermore, it stipulates that cross-price elasticities for all energy sources stay constant and equal under such changes. Those researchers who wish to avoid these implications often use a linear equation structure, but this approach is burdened by other restrictive assumptions.

processes, and therefore it provides only a static model of an economy's energy consumption; in other words, it does not allow us to distinguish effectively between short and long-run price elasticities. Furthermore, flexibility is achieved at the price of a much larger number of parameters, which, because of the need to preserve degrees of freedom, limits the number of determinants of demand that can be included in the equation.

The Limits of Formal Energy Modeling

Given all of the above caveats and qualifications, there is good reason to question the real utility of mathematical models of energy consumption and the elasticity estimates derived from them. These models are built upon a large number of explicit and implicit assumptions, many of which are, if not simply wrong, at least suspicious. Stern (1984), in cooperation with the Panel on Energy Demand Analysis of the National Research Council, has provided an excellent critique of formal energy modeling. His overarching argument is that formal modeling has been unduly emphasized in energy analysis, and that many more resources must be devoted to hard empirical research into energy **behavior**. He advocates a "problem-oriented" approach to energy policy issues. Such analysis is "by definition unsystematic, being addressed to specific questions rather than to the accurate description of an entire social or economic system. An issue or policy option is raised, and information is gathered and analyzed by the best available methods to clarify the issue or the policy implications" (p. 18). Techniques of use in this problem-oriented approach include better analysis of existing data, more extensive

surveys of energy behavior, natural and controlled social experiments, and more exacting evaluation of the consequences of past and present energy programs.

More specifically, Stern contends that numerous crucially important determinants of energy demand are not incorporated in existing formal models. These include institutional limits on choice, beliefs about future fuel prices and availability, the nature of communication within a society about energy issues, the symbolic meaning of appeals for energy conservation in a given culture, and the public's psychological reaction to news of fuel shortages. While from a technical point of view, it may be impossible to include some of these factors in formal models, the problem here, principally, is that economists are operating with narrow and impoverished understandings of human rationality and social behavior. These understandings are grounded in economic theory and reinforced by the limited availability of quantitative data. Stern writes:

> When policy analysts equate a model with reality, they begin to define issues in the terms most central to the model and to ignore the variables the model ignores. Among these ignored variables are many important behavioral factors for which quantitative data do not exist and that are not prominent in economic theory, for example: incompleteness of information, mistrust, the symbolic meanings of action, personal attitudes, social values, political conflict, and organizational routine. The phenomena that result from such influences are, of course, encompassed by formal demand models, but they appear under other labels and so may be misconceived in important ways.

And, more directly on the matter of elasticities:

> In energy demand models, behavioral variables are usually subsumed under broad concepts that are vague with respect to their behavioral basis. The concept of own-price elasticity, for example, describes the fact that, other things being equal, the quantity demanded of something is inversely related to its price. But the concept says nothing about how the information embodied in price enters a consumer's awareness or about how awareness of price affects action. Thus, the concept of elasticity bypasses the behavioral phenomena that underlie the response to price; the behavioral questions are begged. Because the concept of elasticity is behaviorally atheoretical,

> elasticity estimates cannot predict whether unanticipated conditions, such as news of an impending major oil shortage, will change the ways consumers respond to price signals. A focus on price elasticity also ignores factors that can mediate the effects of price, such as the quality or trustworthiness of available information or the ways that information is communicated. (pp. 13-14)

In a similar vein, Feldman (1987) notes that the public's energy conservation behavior cannot be explained by standard economic models that rely upon estimates of the consumer's discount rate and concern for monetary savings. He finds that a lack of cynicism on the part of consumers[34] and a concern for what is socially acceptable are more important predictors of conservation behavior than the monetary factors incorporated in formal models. In particular, it appears that consumers do not use a clear discount rate: people exhibit "a basic lack of ability to impute value to an object and to conserve that value in the face of apparent changes over time" (p. 34). He concludes:

> Avoided costs and implicit discount rates are probably not useful concepts for describing the behavior of the general public, however useful they may be for analyzing the behavior of commercial and industrial decision makers. We would do well to avoid building our models and preparing our advertising campaigns based upon the assumption that the energy consumer operates -- or can operate -- as a rational investor. (p. 39)

We have now surveyed the basics of formal energy modeling, and we have gained a general understanding of the very real limitations of this approach. We can now go on to review some of the latest estimates of price elasticities of demand for fossil fuels.

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[34]That is, "the belief that conservation efforts make a difference and that individuals can control their wants, their energy use, and their energy costs."

V. CURRENT ESTIMATES OF PRICE ELASTICITIES OF DEMAND FOR FOSSIL FUELS

Most of us have the intuitive conviction that aggregate energy demand is affected by price, because we know that our own energy consumption depends, in part, on price. For example, following the oil price shocks of 1973 and 1979, most of us changed our driving and auto-purchasing behavior in order to reduce our gasoline consumption. The annual figures for American, European, and Japanese oil consumption from 1970 to 1987 show the aggregate consequence of the many small behavioral changes in response to these price shocks.

Table 2
Oil Consumption in Millions of Barrels Per Day

	1970	1973	1974	1975	1978	1979	1980	1981	1982	1983	1984	1985	1987
United States													
Gasoline	6.33	7.25	6.96	7.06	7.85	7.51	7.09	6.91	6.83	6.92	7.06	7.09	7.52
Total	14.56	17.14	16.43	16.20	18.89	18.46	17.71	16.55	15.83	15.74	16.10	16.06	16.81
Western Europe													
Gasoline	2.39	3.04	2.97	2.90	3.33	3.35	3.19	3.05	3.07	3.14	3.15	3.15	3.36
Total	12.38	14.80	13.81	13.15	14.18	14.54	13.39	12.60	12.11	11.85	11.84	11.74	12.26
Japan													
Gasoline	0.71	0.99	0.96	0.91	1.06	1.07	0.98	0.92	0.90	0.92	0.94	0.95	1.02
Total	3.97	5.42	5.31	5.04	5.49	5.55	5.39	5.12	4.58	4.39	4.57	4.36	4.45

(Source: World Oil Trends: 1988-89 Edition.)

But to what extent is this common intuition (that energy consumption is sensitive to price) supported by empirical and modeling findings? What are the best estimates of the price elasticities of demand for the various fuel-sector categories?

In the energy econometrics community, it seems to be generally accepted that Bohi (1981) and Bohi and Zimmerman (1984) are the most thorough and

balanced reviews of the varied studies of energy elasticities in developed countries.[35] As we have seen, both of these surveys begin with a detailed analysis of the many problems bedeviling energy modeling. Bohi (1981) then reviews elasticity research that uses largely pre-1973 data, while Bohi and Zimmerman (1984) update this survey by assessing the numerous research projects of the late 70s and early 80s.

While both of these surveys merit careful reading, the latter report provides the best assessment of the price elasticity figures that are cited in the **current** scholarly literature.[36] The conclusions of both reports are sure to disappoint people looking for a consensus among energy economists about the price responsiveness of fossil fuel consumption. Table 3 presents Bohi's summary (p. 159), while Table 4 presents that of Bohi and Zimmerman (p. 147). Readers of the tables in this section should keep in mind that any price elasticity figure encompasses two effects: **conservation** of the fuel through a decrease in the rate of use of the technology that consumes the fuel or through substitution of non-energy factors of production; and **substitution** of other fuels. It is not possible, using the elasticity figures alone, to identify what proportion of a change in consumption is due to one effect or the other.

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[35]Another excellent review of the issue is provided by Kouris (1983). See also the report of the Energy Modeling Forum (1980).

[36]Readers may be surprised to learn that the best review of the elasticity literature is over five years old. Following the 1979 oil price shock, there were many studies of elasticities, which Bohi and Zimmerman assessed in their 1984 paper. Since that time, the rate of research on elasticities has decreased, and it appears that none of this newer research should lead us to revise the general assessment offered by Bohi and Zimmerman.

Table 3.
Bohi's 1981 Summary of Own-Price Elasticities by Sector and Fuel

Sector and Fuel	Estimates in the literature		Conclusions about the estimates	
	Short-run	Long-run	Short-run	Long-run
Utilities:				
Natural Gas	-0.06	-1.43	-0.06	Uncertain
Fuel Oil	-0.10	-1.50	-0.10	Uncertain
Coal (steam)	-0.09 to -0.46	-0.67 to -1.15	-0.09	Uncertain
Residential:				
Electricity	-0.06 to -0.49	-0.45 to -1.89	-0.2	-0.70
Natural Gas	-0.03 to -0.40	-0.17 to -1.00	-0.10	-0.50
Fuel Oil	-0.13 to -0.3	-1.10 to -1.76	Uncertain	Uncertain
Commercial:				
Electricity	-0.17 to -0.25	-1.00 to -1.60	Uncertain	Uncertain
Natural Gas	-0.03 to -0.40	-0.17 to -1.00	Uncertain	Near -1.0
Fuel Oil	-0.07 to -0.2	-1.10 to -1.76	Uncertain	Uncertain
Industrial:				
Electricity	-0.04 to -0.22	-0.51 to -1.82	Uncertain	Between -0.5 and -1.0
Natural gas	-0.07 to -0.21	-0.45 to -1.50	Uncertain	Uncertain
Fuel Oil	-0.11 to -0.22	-0.80 to -2.82	Uncertain	Uncertain
Coal (steam)	-0.10 to -0.49	-0.49 to -2.07	Uncertain	Uncertain
Transportation:				
Gasoline	-0.11 to -0.41	-0.36 to -0.77	-0.2	-0.7 or more elastic

Table 4.
Bohi and Zimmerman's 1984 Update of Own-Price Elasticities

	Electricity Short/long	Natural Gas Short/long	Fuel Oil Short/long	Gasoline Short/long
Residential	-0.2/-0.7	-0.2/-0.3	Uncertain	N/A
Commercial	Uncertain	Uncertain	Uncertain	N/A
Industrial	Uncertain	Uncertain	Uncertain	N/A
Transport	N/A	N/A	N/A	-0.2/less elastic than -1.0

Table 3 shows us that in most fuel-sector categories the literature contains a wide range of estimates of price elasticities. It also shows us that, in Bohi's judgement, there is strong reason to doubt the accuracy of these estimates. That judgement has not changed in Bohi and Zimmerman's later survey of the literature; of the ten relevant fuel-sector categories, in only three are the authors prepared to present specific elasticity estimates. While they acknowledge that their comparative judgments are "highly subjective," these judgments are based on "a number of specific criteria." They write: "In addition to the usual measures of statistical significance and conformity among studies, results from studies that use highly disaggregated data, that model the structural elements of demand behavior, and that are generally consistent with the economic theory of demand are considered more reliable." They continue:

> Perhaps the most disconcerting conclusion to be drawn from [Table 4] is the large amount of uncertain results. Outside of residential demand for electricity, the quality of the information obtained from years of study ranges from weak to very poor. Information on commercial and industrial energy demand is weakest, and research conducted in recent years adds little to that reported earlier [in Bohi, 1981].

Given the extent of uncertainty, the authors are reluctant to make any claim about trends in elasticities from the pre-1973 to the post-1973 period. If we compare the analysis in the two reports, the most that might be said is that Bohi and Zimmerman are slightly more generous in their estimate of the long-run elasticity of gasoline than was Bohi in 1981. While Bohi concludes in 1981 that the figure is "larger than -0.7," the 1984 analysis suggests that it is "slightly less than unity." However, in a recent telephone conversation Bohi was a bit less equivocal, stating that the price elasticity of demand for gasoline is "about -0.7."

In general, Bohi and Zimmerman's measured and skeptical assessment of the results of formal energy modeling seems quite justified. There are so many things we do not understand about energy consumption and about possibilities for change, there are so many important factors left out of the energy models, and there are so many arbitrary assumptions embedded in these models, that policy makers would be well-advised to use elasticity estimates as only the roughest of heuristics.

However, researchers other than Bohi and Zimmerman have been less restrained in proposing elasticity estimates. Liu (1983), for example, gives estimates of own-price elasticities and cross-elasticities of demand for natural gas in the residential, commercial, and industrial sectors by DOE region in the United States. He concludes that natural gas demand by region is "highly elastic," with own-price elasticities often greater than -2.0.

Many economists have estimated price elasticities for energy demand by sector, aggregating across fuels. The Energy Modeling Forum (1980) recommended that such aggregate elasticities be provided at three levels of energy demand --

primary, secondary, and delivered -- but most figures given by economists are for "final demand" or delivered energy. Generally, economists contend that elasticities increase as one moves along the temporal sequence from primary to delivered energy.[37] For instance, Nordhaus (1977b) gives the following figures:

Table 5.
Nordhaus' 1977 Estimates of Final Demand Elasticities by Sector

Sector	Long-run Elasticity	Best Guess	Implicit Elasticity for Primary Energy[38]
Residential	-0.71 to -1.14	-0.9	-0.3
Industrial	-0.30 to -0.52	-0.7	-0.4
Transport	-0.36 to -1.28	-0.8	-0.2

It is also common for researchers to aggregate across fuels and sectors, producing price elasticities for energy consumption in the economy as a whole.[39] For example, along with the above sectoral elasticities, Nordhaus (1977b) estimates that the economy-wide long-run price elasticity for energy (final demand) falls within a range of -0.66 to -1.55, with a best guess of -0.8. Prosser (1985) derives a much more conservative aggregate elasticity of -0.37.

Let's turn now to three highly-regarded studies of energy consumption in developed economies that estimate elasticities of demand for fuels.

[37]This is because a given price increase in monetary terms at the primary level (when passed through to the final stage) is a larger percentage of the primary price than the final price (assuming that one unit of the primary fuel produces, on refinement, roughly one unit of the final fuel.)

[38]To obtain this estimate, the "best guess" figure is divided by the "ratio of retail price to crude price" (Nordhaus and Yohe, 1983, p. 122).

[39]Such estimates are particularly useful within large econometric models of energy consumption, such as those that project future carbon dioxide emissions (see, for example, Mintzer, 1987).

In the residential and industrial sectors for selected OECD countries, Pindyck (1979) uses translog functions to interpret pooled time-series cross-section data (up to 1974) "as a means of identifying long-run elasticities."[40] But for certain sectors and countries, insufficient data forces him "to work with much simpler models of demand" that may be quite inaccurate.

Pindyck calculates both "partial" and "total" elasticities. Partial elasticities "refer to a specific demand relation and measure demand effects caused by a change in a given price when all other arguments in this relation are assumed to be constant" (Longva et al, 1988, p. 299). Total elasticities, however, measure demand effects caused by changes in all the variables in the energy model as it reaches a new equilibrium. Longva et al. go on: "Total price elasticities . . . include the substitution possibilities both in production and consumption, i.e. they indicate the ability of the economy as a whole to adjust to changes in prices," and thus they tend to be higher. While there are strong arguments for using total elasticities, they are more difficult to calculate and are not the kind most commonly provided by researchers. However, every attempt has been made to cite only total elasticities in this report.

The estimates listed in Table 6 are drawn from different parts of the diverse discussion in Pindyck's book; they do not fall as cleanly into categories as the estimates of Bohi and Zimmerman.

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[40]Note that Pindyck does not use **dynamic** translog functions to capture the distinction between short-run and long-run elasticities, although he suggests (pp. 37-40) that such approaches are feasible given sufficient resources. Rather he relies upon cross-section data to tap long-run behavior. As indicated above, Bohi, Zimmerman, and numerous other researchers believe that the introduction of lagged variables in translog functions produces serious internal inconsistencies in energy models.

Table 6.
Pindyck's 1979 Estimates of Own-price Aggregate and Fuel-sector Elasticities

Sector	Long-run Elasticity	Preferred Estimate
Residential:		
Aggregate	-1.05 to -1.15	-1.10
Electricity	Positive to -0.68	0 to -0.4
Natural gas	-1.28 to -2.09	-1.70
Fuel oil	-1.10 to -1.38	-1.0 to -1.25
Coal	-1.00 to -1.12	-1.0 to -1.25
Industrial:		
Aggregate	-0.75 to -0.84	-0.80
Electricity	-0.54 to -0.63	
Natural gas	-0.41 to -0.67 for U.S. and Canada	
	-1.37 to -2.34 for Europe and Japan	
Fuel oil	-1.03 to -1.12 for U.S. and Canada	
	-0.06 to -0.56 for Europe and Japan	
Coal	-1.89 to -2.24 for U.S. and Canada	
	-1.29 to -2.15 for Europe and Japan	
Transportation: (simultaneous equation model)		
Gasoline	-0.50 (5 years) -0.84 (10 years)	-1.31 (25 years)
(lagged adjustment model)		
Gasoline	-0.10 to -0.38 for U.S. and Canada	
	-1.61 for Europe	
Diesel fuel	-1.06 to -1.09 for U.S. and Canada	
	-0.62 for Europe	
Jet fuel	-1.44 to -1.82 for U.S. and Canada	
	-0.33 to -0.43 for Europe	

In his commentary on these findings, Pindyck is fairly optimistic about the possibility of energy conservation in response to higher prices. "One of our most important results," he writes, "is that the own-price elasticity of aggregate energy use in the residential sector appears to be much larger in the long run than had been thought previously" (p. 118). He continues:

> This means that the use of taxes or other policies to raise retail fuel prices (such as deregulation in the U.S. and Canada) can be a very effective means of reducing or limiting energy consumption, given that enough time is allowed to pass to let demand adjust fully.

Similarly, in the industrial sector, "the own-price elasticity of aggregate industrial energy demand appears to be significantly larger than had been thought previously and energy and capital appear to be substitutable rather than complementary factors of production" (p. 179). And in the transportation sector, the price elasticity of gasoline "is in the vicinity of -1, so that higher gasoline prices could be a very effective means of reducing consumption, although a number of years would have to pass for the effects to take place" (p. 233).

Analyzing data from OECD countries, Griffin (1979) uses a model similar to that of Pindyck but checks its results against those produced by a simple fuel-share model. He assumes that variations in energy consumption between countries show long-run responses while the within country samples show short-run responses. Griffin's long-run estimates appear in Table 7.

Table 7.
Griffin's 1979 Estimates of Own-price Aggregate and Fuel-sector Elasticities

Sector	Long-run Elasticity
Utilities:	
Natural gas	-0.98
Fuel Oil	-4.27
Coal	-0.86
Industrial:	
Aggregate (nine country sample)	-0.80
(eighteen country sample)	-0.40
Electricity	-0.56
Natural Gas	-1.22
Fuel Oil	-0.89
Coal	-1.21
Residential:	
Aggregate	Slightly less elastic than -1.0
Electricity	-0.72
Natural Gas	-2.61
Fuel Oil	-0.86
Transportation:	
Gasoline	-1.34 to -1.50
(portion attributable to change in utilization rate)	-0.64

Aggregating across sectors, Hogan (1988, 1989) has developed an important energy model that employs data from the period during and after the two oil price shocks. He uses translog functions that incorporate lagged variables (contrary, it seems, to the recommendation of Bohi and Zimmerman) and that clearly distinguish between **ex ante** and **ex post** flexibility in the substitution of inputs. He finds that **ex post** substitution is relatively unimportant, but that there is significant potential for **ex ante** substitution, given enough time: "Responses to price changes take time," he writes (1989, p. 54). "Although there is overwhelming evidence of great flexibility in the use of energy and other inputs, the most important changes in energy

utilization depend upon changes in energy-using equipment." This recent study, as well as his previous ones, indicate "the importance of the slow process of adjustment, large long-run elasticities, and sharp differences between electric and non-electric energy demand."

Hogan presents the following tables of **ex ante** price elasticities for the United States and Japan.[41] Note that coal falls in the "other" category.

Table 8.
Hogan's 1988 Ex Ante Price Elasticities for the United States

	Electric	Natural Gas	Heavy Oil	Other	Light Oil	Transport Fuel	Capital/ Labor
Electric	-1.42	0.19	0.04	0.03	0.18	0.04	0.94
Natural Gas	0.60	-1.30	-0.06	-0.14	0.88	-0.25	0.28
Heavy Oil	0.60	-0.27	-1.98	0.37	1.25	-0.25	0.28
Other	0.60	-3.97	3.07	-5.94	6.20	-0.25	0.28
Light Oil	0.60	0.72	0.19	0.10	-1.64	-0.25	0.28
Trans. Fuel	0.04	0.00	0.00	0.00	0.00	-0.89	1.01
Cap./Labor	0.03	0.00	0.00	0.00	0.00	0.04	-0.08

Table 9.
Hogan's 1988 Ex Ante Price Elasticities for Japan

	Electric	Natural Gas	Heavy Oil	Other	Light Oil	Transport Fuel	Capital/ Labor
Electric	-1.64	0.31	0.01	0.07	0.76	-0.16	0.65
Natural Gas	1.18	-2.26	0.04	-0.13	0.23	0.27	0.67
Heavy Oil	1.18	2.29	-24.93	-0.13	20.65	0.27	0.67
Other	1.18	-0.57	-0.01	-0.13	-1.41	0.27	0.67
Light Oil	1.18	0.09	0.15	-0.13	-2.24	0.27	0.67
Trans. Fuel	-0.23	0.01	0.00	0.00	0.02	-0.98	0.81
Cap./Labor	0.02	0.00	0.00	0.00	0.00	0.02	-0.07

[41]The following tables are matrices of substitution elasticities. They should be read as follows: A one percent change in the price of one of the inputs across the top of the matrix produces the indicated percentage change in the consumption of the inputs listed down the left hand side. Thus, for the United States, a one percent increase in the price of natural gas produces, in Hogan's model, a .19 percent increase in the consumption of electricity. (These inputs are, therefore, substitutes.) Own-price elasticities are along the diagonal from the top left to the bottom right of the matrix.

Hogan's matrices are interesting in a number of respects. First, as we should anticipate, for both the United States and Japan, energy sources tend to be substitutes for each other rather than complements. In terms of factors of production, energy seems to substitute for capital and labor, while there is no clear evidence that capital and labor substitute for energy (as indicated by the zeros that predominate across the bottom of both matrices). The very high own-price elasticity for heavy oil in Japan and cross-elasticity for heavy oil with respect to light oil are artifacts of the very small share of the Japanese energy market taken up by heavy oil in Hogan's model.

In general the own-price elasticity for transportation fuel (gasoline and diesel) is much smaller than that for the other sources of energy. It is reasonable to assume, and Hogan has confirmed this in conversation, that the transport own-price elasticity reflects mainly a **conservation** effect, whereas the other own-price figures reflect more interfuel substitution. Currently, in the U.S. and Japan there are no widely-used road-transport technologies that consume fuels other than gasoline and diesel. Substitution of other fuels for gasoline and diesel, if it takes place, must occur through the use of significantly different technologies that provide some of the services of road technologies, such as rail and mass transit. While some of this substitution undoubtedly occurs, the match between the services provided by the latter transport technologies and road technologies is often not good. Therefore, we can assume that the decrease in consumption produced by an increase in the price of transport fuel is a consequence of a change in the rate of utilization of road-

transport technologies (with limited substitution of non-road technologies that consume other fuels) and/or the substitution of non-energy factors of production for the fuel (i.e. an increase in the efficiency of the road-transport fleet).[42]

The Importance of the Price Elasticity of Demand for Gasoline

We can now see that there are two principal reasons why we should take special interest in the transport fuel elasticities -- in particular that of gasoline -- provided by the above studies. First, as Bohi and Zimmerman indicate, the gasoline elasticity is one of the few fuel-sector elasticities which has been thoroughly and effectively researched by economists and on which they have reached a fair consensus. Second, from the point of view of reducing the emissions of carbon dioxide, we are more interested in conservation than in interfuel substitution. And when we look at the price elasticity for gasoline, we know we are looking at largely a conservation effect; whereas with other fossil fuel price elasticities -- such as those for natural gas or heavy oil -- we are less sure how much is a genuine conservation effect and how much is simply the result of the substitution of one fossil fuel for another. In order to separate the two effects, it would be necessary to consult a complete formal model of the economy's energy consumption that included information about fuel and factor shares in addition to own-price and substitution

[42]For those fuels (and associated technologies) where interfuel substitution is easier, Sherif ("Dynamic Properties. . .", undated, p. 8) has used the Energy and Price Modeling System of the Canadian Department of Energy, Mines, and Resources to separate conservation and substitution effects. He concludes that in general "the substitution effect is larger than the conservation effect" for these fuels and that "the impact of aggregate price changes is weaker on total demand than on each of the individual fuels." On the Canadian experience with energy conservation, see also Sherif (1986) and Sahi and Erdmann (1981).

elasticities.

This point needs special emphasis. If we are interested in the effects of taxes on carbon dioxide emissions, elasticity figures (with the exception of that for gasoline) are of little use by themselves. We need to know how much of the decrease in a fossil fuel's consumption is a consequence of conservation and how much is a consequence of interfuel substitution. Furthermore, since the substituted fuels release different amounts of carbon dioxide per unit of energy produced, we need to know **which** fuels are substituted and in what proportions. This information can be obtained only from a full formal model of the economy's energy consumption. Formal models have been used in this way;[43] but even when this has been done, for many of the reasons stated in the previous section, these models' results must be regarded with skepticism.

VI. A PRELIMINARY ASSESSMENT OF AN INCREASED GASOLINE TAX IN THE UNITED STATES

The General Economic Effect of a Tax

Before reviewing the specific proposal to tax gasoline, we should consider the advantages and disadvantages of taxation compared to another obvious method of limiting fuel consumption: rationing. Referring to Figure 4, if the current

[43]See, for example, the important work on global carbon dioxide emissions, energy consumption, and carbon taxes by Nordhaus (1977a, 1980), Seidel and Keyes (1983), the MIT Energy Laboratory (1983), Nordhaus and Yohe (1984), Edmonds and Reilly (1983, 1985), and Edmonds et al. (1986). Keepin (1986) provides an excellent review of the strengths and weaknesses of this work. Lazzari (1987) examines the impact on the U.S. economy of a general energy tax that can serve as a rough analog for a carbon tax.

consumption of a commodity is Q1 and policy makers want to reduce it to Q2, they could simply impose rationing to achieve their goal. But the rationing agency is immediately faced with the problem of allocating Q2 units of the commodity among Q3 uses.[44] The uses of the commodity that need to be restricted are those between Q2 and Q3, but the agency cannot accurately identify these uses. Any such centralized authority will have only the roughest idea which uses of the commodity are more valued by consumers than others.

This problem can be solved by applying a tax to the commodity and letting the market allocate the commodity to the highest valued uses. If a tax of the appropriate amount is added on top of price P3, the excess demand for the commodity disappears. The tax has "identified" and curtailed only the less-valued uses from Q2 to Q3. At the price P3 + Tax, uses of the commodity with a value lower than P3 + Tax leave the market (see Griffin, p. 15). Because taxation allows for effective allocation between uses, it is said to be more "efficient" than rationing. This does not mean, of course, that problems of equity are also resolved. The economically efficient allocation of resources according to market valuation is not necessarily a just allocation, especially given the large disparities in wealth that commonly characterize the participants in a commodity market and the resulting disparities in their ability to satisfy their preferences.

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[44]According to the supply curve, suppliers can provide the Q2th unit of the commodity at price P3; but at price P3, the demand for the commodity is Q3. Note that a negatively sloped demand curve, as in this diagram, indicates that consumers experience a decreasing marginal utility for the commodity: each extra unit is valued slightly less than the last. So the Q3th unit is less valuable than the Q2th.

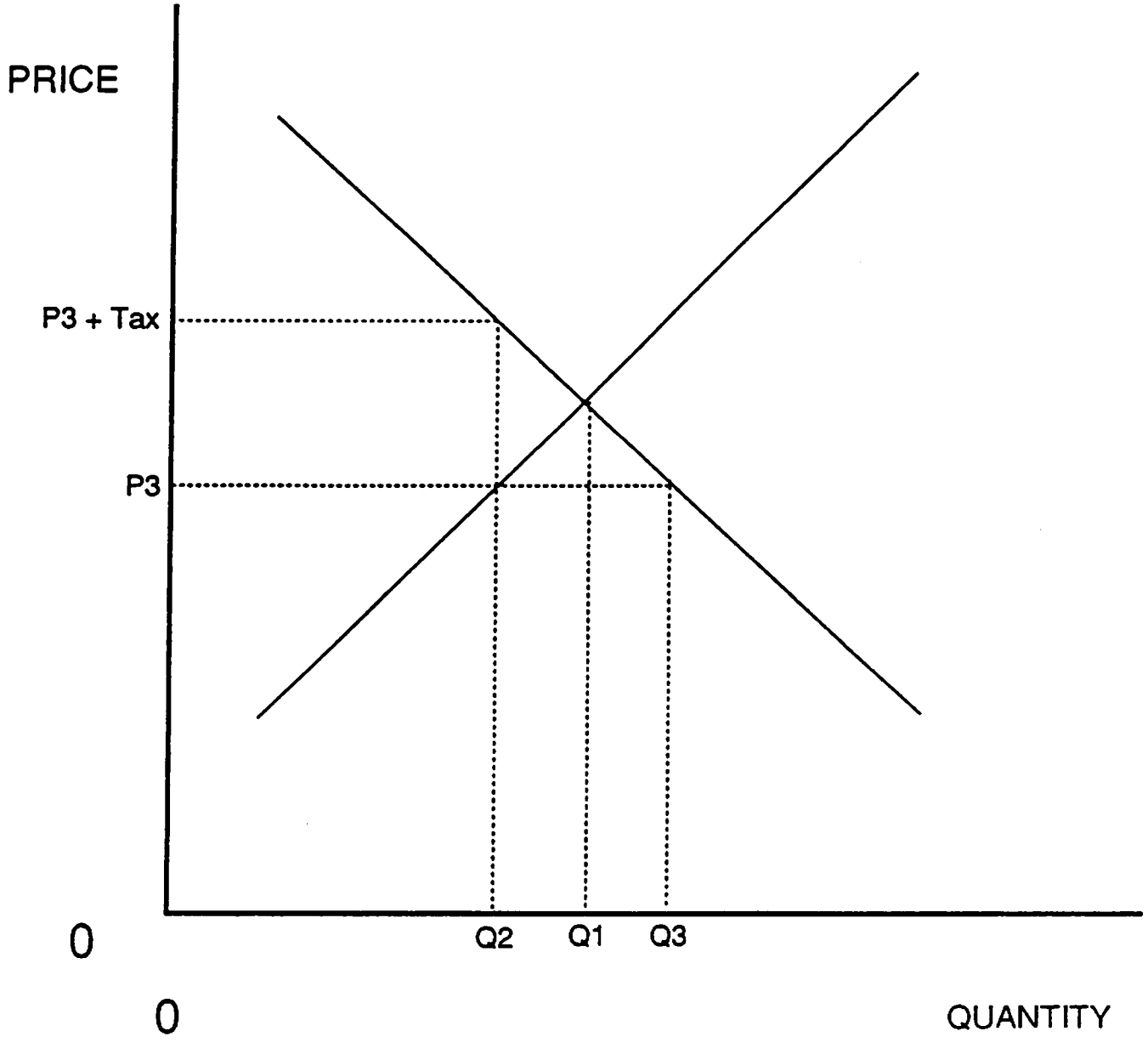

Figure 4. Taxes, Rationing, and Economic Efficiency

Figure 5 depicts the effect of a tax on the producer and consumer. It is a common misperception that the cost of a tax on a commodity is borne entirely by the consumer. But the distribution of the burden is actually shared between the producer and consumer according to the elasticities of the supply and demand curves. Figure 5 is the same as Figure 4, except that the tax has been identified as an upward shift in the supply curve: for every quantity Qx of the commodity that suppliers were willing to provide at price Px, the price is now Px + Tax. The equilibrium of supply and demand shifts from D to A; the quantity purchased decreases from Q1 to Q2; and the equilibrium price rises from P1 to P2, which, it is important to note, is **less** than the amount of the tax. Thus the after tax price received by the producer drops from P1 to P3; in other words, the producer must pay a portion of the tax on each unit of the commodity sold.

The government's total tax revenue is indicated by the whole shaded rectangle ACP3P2. This tax burden is jointly shared by consumers (rectangle ABP1P2, lightly shaded) and producers (BCP3P1, darkly shaded).[45] Thus, for example, if the current price of gasoline is $1.00, and if the government imposes a $1.00 a gallon tax, the price will not increase to $2.00 a gallon, unless demand is perfectly inelastic or supply is perfectly elastic, which we know they are not. Rather the price will increase to, say, $1.80 a gallon. In other words, 80 cents of the tax will be passed on to the consumer, while 20 cents will be absorbed by the producer and distributor of the gasoline. The extent to which the tax is passed on to

[45]Economists frequently note that there is an extra burden imposed by a tax, often called the "deadweight loss," which is indicated in Figure 5 by the triangle ADC. Lazzari writes: "This loss to consumers and producers is not gained by the government as revenue." See Griffin (1979, pp. 17-21) for an interpretation of this as a "welfare loss" to society.

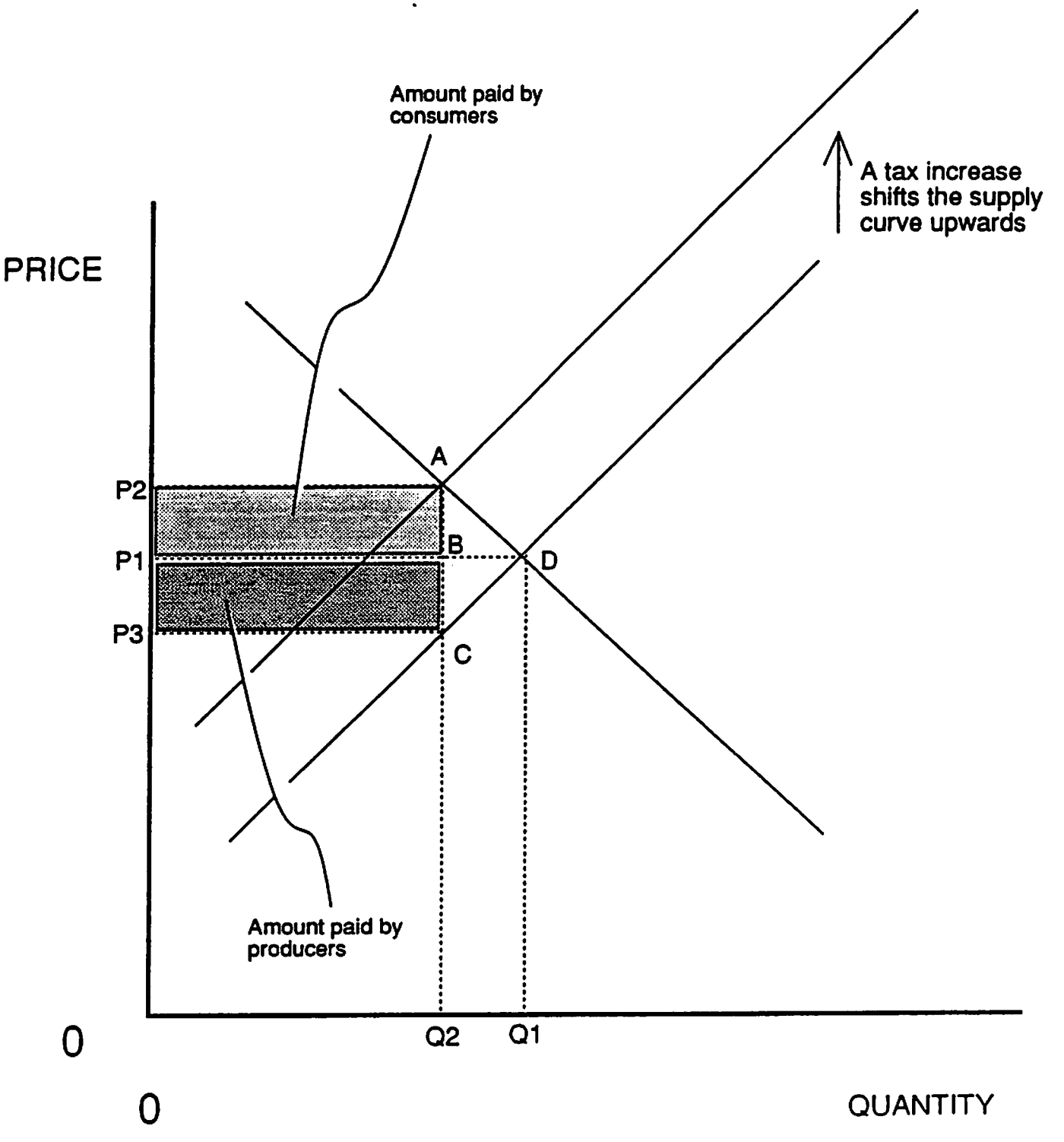

Figure 5. The Economic Effect of a Tax
(Lazzari, 1986)

consumers is determined by the interaction of the supply and demand curves; in general, the more inelastic the demand for a commodity, and the more elastic the supply, the greater the portion of the tax passed on. In his comments on the effects of a gasoline excise tax imposed on the refiner, Lazzari (1986, p. 6) comments:

> Due to consumer sensitivity to higher prices, the refiner cannot, under the most typical conditions, fully shift the tax forward. Part of the gasoline excise tax would probably not be shifted forward, but rather would be paid either by the refiner in the form of lower after-tax price and profits, or would be paid by factors of production (capital and labor) in the form of lower factor payments (i.e. shifted backwards). Thus, after paying the tax, the price a refiner receives is less than the before-tax price. Yet, by raising gasoline prices to consumers, the refiner would prevent the tax from being borne 100 percent by the industry and its factor resources.[46]

Should Policy Makers Support a Gasoline Tax?

The discussion at the end of Section V led us to focus our attention on the long-run own-price elasticity of gasoline demand in the industrialized nations. There seems to be a general consensus among researchers that this figure is about -0.8.[47] While the two oil price shocks of the last twenty years have led many economists to conclude that gasoline demand is more price responsive than previously assumed, few would say that it is more elastic than -1.0.[48]

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[46]This comment would apply equally to a tax imposed at the retail level.

[47]For example, Lazzari (1986, p. 13) suggests this is a "reasonable mid-range figure."

[48]Covering eighty studies, Dahl (1986) provides perhaps the most exhaustive survey of research on the price elasticity of gasoline; then, using an arithmetic average of the studies' elasticity figures, she calculates the long-run elasticity as -1.12. But Khazzoom (1988, pp. 63-72) points out that there are strong reasons to question the methodology Dahl uses to produce this figure. After carefully examining Dahl's survey and the research of other economists, Khazzoom uses a long-run figure of -0.783 in his own calculations.

The United States has the lowest gasoline tax of any Western industrialized country. Going by the criteria identified in Section II of this report, such a tax would seem to merit particular attention from U.S. policy makers. First, on the matter of this fuel's contribution to the greenhouse problem, gasoline consumption in the industrialized world is a major source of anthropogenic carbon dioxide: in the United States, for example, transportation contributes about 31% of total U.S. emissions, and gasoline-powered travel, in turn, contributes about 60% of these transportation emissions.[49] Given that the U.S. is responsible for about a quarter of total human releases of carbon dioxide, gasoline combustion in the U.S. by itself contributes about 5% of global carbon dioxide emissions. This, in turn, accounts for approximately 2% to 3% of the total greenhouse forcing by anthropogenic greenhouse gases.[50]

Second, regarding the consumer's propensity to conserve gasoline and/or substitute other fuels for it, from our review of recent econometric research we know that, while the demand for gasoline is not price elastic, it still exhibits a relatively high elasticity of about -0.8. Moreover, we know that there is little present interfuel

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[49]"Transportation" encompasses, principally, passenger travel and freight haulage by road, air, water, pipeline, and rail. In 1985, total U.S. energy consumption in the transportation sector was about 20.76 quadrillion Btu's, of which about 11.3 quads (54%) went to passenger road travel in automobiles, light trucks, and buses, and about 4.11 quads (19.5%) went to freight haulage by road in light and heavy trucks. In the U.S., bus travel makes up less than 2% of total passenger miles by road, and automobiles and light trucks are almost exclusively gasoline-powered. Therefore, we can estimate that about 53% of energy consumption in the transportation sector is due to gasoline-powered passenger travel. Since some freight is hauled by light truck, it seems reasonable to estimate that close to 60% of U.S. transport energy (and, equivalently, close to 60% of U.S. transport carbon dioxide) comes from gasoline combustion. (Statistics adapted from Davis et al., 1988).

[50]As mentioned earlier in this report, anthropogenic greenhouse gases include carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide. Although the latter three gases are released in much smaller quantities than carbon dioxide, they trap infrared radiation much more effectively within the atmosphere, and therefore, in combination, account for about 50 percent of total greenhouse forcing.

substitution in automobiles and light trucks,[51] and that the substitution of non-road technologies (consuming different fuels) is constrained. Therefore, we can interpret this -0.8 as representing largely a conservation effect. And we can say with some confidence that a sizeable tax on gasoline would likely induce significant conservation through changes in automobile use rates and efficiencies (the substitution of capital for energy). It is important to note that, in light of our current econometric knowledge of energy consumption in industrialized countries, we **cannot** reach a similarly firm conclusion about **any** other fossil fuel.

Third, on the matter of the policy feasibility of the tax, a gasoline tax in the United States seems somewhat more feasible than other possible energy taxes. Although the American political and economic culture presents a very hostile environment for any tax proposal, commentators frequently note that a reduction in gasoline consumption would have many beneficial effects besides a reduction in carbon dioxide emissions -- such as decreased dependency on imported crude and lower regional pollution -- and arguments referring to these effects could be used to promote a gasoline tax.[52] Furthermore, the institutional mechanisms are already

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[51]There is, of course, a small amount of substitution between gasoline and diesel. More importantly, however, there may be substitution possibilities in the next decades that could significantly affect carbon dioxide emissions. In British Columbia, for example, a large-scale market test is being conducted of the acceptability of natural gas as an automobile fuel. But whether this can be considered a less deleterious fuel than gasoline depends not only on the carbon emitted per unit of usable energy, but also on the cumulative greenhouse forcing of the natural gas (methane) released during its preparation and distribution to auto-fueling stations. Other substitutes for gasoline might include electricity and hydrogen (a very successful hydrogen-powered car has recently been tested by BMW in West Germany), but these may be produced by processes that release a great deal of carbon dioxide. If methanol derived from coal is used widely to fuel automobiles, total carbon dioxide emissions will rise.

[52]There may also be a temptation to argue that such a tax could help reduce the federal budget deficit. However, if this policy were followed, the tax could have a strong recessionary effect. It might be preferable to return the funds raised directly to the economy.

largely in place for such a tax; in comparison with a carbon tax, a gasoline tax would require relatively little new bureaucratic apparatus or public education.[53] To make it more saleable to the American public, the tax could be coupled with an oil import fee; such a fee could be used to set a floor-price, for instance $25 per barrel, for both imported and domestic petroleum.[54] This arrangement would reinvigorate the economies of oil-producing regions in the U.S., a prospect which would help ensure these regions' political support for the policy package. The import fee could also be promoted as likely to reduce the vulnerability of the U.S. to the whims of radical Middle East suppliers.[55]

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[53]As of 1986, the Federal tax on gasoline was 9 cents per gallon and on diesel 15 cents per gallon. The gasoline tax is collected from the refiner or importer, while the diesel tax is imposed at the retail level.

[54]On the matter of an oil import fee, see Lazzari (1986), Gelb and Lazzari (1986), Gelb (1987), Hausker (1988), Tussing and Van Victor (1988), Broadman and Hogan (1988), and Nesbitt and Choi (1988). Lazzari (1986) has produced an especially useful theoretical and econometric comparison of the economic impact of an increased gasoline tax versus an oil import fee. He notes:

> The gasoline excise tax imposes a larger absolute burden on the United States as a whole than an oil import tax . . . . This is because the oil import tax would shift part of the burden back to foreign producers. In addition, the oil import tax would raise the real income of oil producers while exacerbating the losses to consumers. As a result, the gasoline excise tax does not generate economic benefits to any individual States, while the oil import tax does. (p. 25)

In light of this judgment, we might conclude that the U.S. should forgo a gasoline tax and impose only an oil import fee: the higher prices would produce a consumption reduction in the U.S. with less of an impact on the economy. But an import fee is parochial in a way that a gasoline tax is not. Our main aim is the reduction of **global** carbon dioxide emissions and not simply the reduction of U.S. domestic consumption or dependence on foreign oil. As such, a gasoline tax is preferable because, if this policy were generalized to all countries, it would induce even countries self-sufficient in oil to decrease their consumption of gasoline, whereas an import fee would only affect importers. A gasoline tax could be part of a international regime to reduce carbon dioxide emissions worldwide, and the U.S. can play an important symbolic role by imposing such a tax for the specific purpose of reducing emissions.

[55]Policy makers should not underestimate the severe difficulties facing any proposal to tax gasoline in the U.S.. Henry Jacoby of MIT's Sloan School and Tom Schelling of Harvard's Kennedy School both emphasized this in conversation. Jacoby asserted that the animosity to taxes runs deep in American culture: "Taxes are generally viewed by the public as unfair." Schelling was far more blunt: "I'm exceedingly pessimistic that we can do anything about this greenhouse problem. A tax of $1.00 per gallon on gasoline would have minuscule political support. Nothing did more to lose support for Carter's original energy program than his proposed gasoline tax, and the tax was never

Fourth and finally, a taxation proposal should also be judged according to its "social benefit." A gasoline tax might not do well by this criterion, because such a tax is widely considered to be regressive by economists. But it should be possible to compensate for many of its negative effects on wealth distribution. For instance, the tax could be introduced in increments over a number of years, and appropriate rebate and credit schemes could be implemented to compensate poorer households.

Some have recently contended that a gasoline tax would **not** be regressive. For instance, Mathews (1988) writes:

> It is widely but erroneously believed that the poor drive more than the rich, and that a gasoline tax would be highly regressive. The opposite is true. All three measures -- the average number of vehicles per household, the number of miles driven per household and motor fuel expenditures per household -- show that car use rises steeply with income.

Mathews addresses the common claim that because "gasoline represents a disproportionately large share of a poorer family's budget" a gasoline tax would affect the poor more. But, citing a recent government study, she argues "the gasoline tax is not the unfair tax it is thought to be."

Unfortunately policy makers supporting such a tax, the balance of economic opinion seems to weigh against Mathews' view. In conversation, Henry Jacoby of MIT and Henry Lee of Harvard's Kennedy School were quite adamant in asserting that a gasoline tax would be regressive. Lee specifically noted that the poor tend to drive older, larger, badly maintained cars, because they try to minimize the short-term costs of purchase and maintenance; for poor families with such vehicles, high

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implemented. People in Los Angeles don't want to pay a gas tax to reduce their smog, so how are you going to convince farmers, truckers, and ordinary people to pay a tax to keep Bangladesh from being flooded 100 years from now? The Bush Administration probably honestly doesn't know where to go on this issue."

gasoline prices could mean a severe drain on income. In general, for Jacoby, Lee, and other economists the crucial factor seems to be -- not that automobile usage rates are higher for richer households -- but that poorer households spend a larger fraction of their resources on gasoline. A good summary of this position is provided by Gelb (1987, p.5). Although he is writing about the effect of an oil import tax, his comments are equally germane to a gasoline tax:

> An oil import tax would . . . affect the way in which income is distributed over the U.S. population by income bracket, tending to shift relative shares of real income from low-income families to high-income families. Data show (a) the ratio of fuel oil and gasoline spending to income declines as income increases, (b) the ratio of expenditures for all of energy (including electricity and natural gas used in the home) to income is higher at lower incomes than the ratio of expenditures for fuel and gasoline only; and (c) between 1973 and 1981 -- a period of rapidly rising energy prices -- the ratio of total energy expenditures to income rose faster among lower-income families than among higher income families. While the decline in oil prices since 1981, and particularly since December 1985, probably has affected energy spending, it is unlikely to have changed significantly the basic pattern of energy spending by income level. Thus, to the extent that an oil import tax would keep oil prices higher than otherwise, the additional petroleum outlays as a percentage of income would decline, on average, as income increases. Moreover, because the prices of other forms also will rise eventually, the effect on income distribution will be even greater in the long run. These direct and indirect effect of an oil import tax, called "regressive," would tend to offset the otherwise progressive structure of Federal income taxes.[58]

While there may be some room for dispute, it appears there is strong reason to believe that a gasoline tax would be regressive. Policy makers should therefore articulate a clear plan for mitigating the distributional effects of such a tax.

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[58]Similar arguments about the disproportionate impact of energy price increases on poor households, except focusing on residential energy expenditure, are provided by Beebout et al. (1982) and Ruff (1982).

Estimating the Size of the Tax

If policy makers are to argue for a gasoline tax, what size should it be? There appear to be two general ways of arriving at a judgment about the size of the tax. First, we can try to estimate the total value of the external costs we wish to internalize through the tax. But there seems to be no truly satisfactory way of doing this, as indicated in the thorough study by Fisher and Smith (1982). Second, we can decide how much we want to reduce carbon dioxide emissions, and then, using our elasticity figure of -0.8, we can calculate the tax required to bring about this reduction.

While the second method would seem more precise, a judgment derived from either one of these methods must be adjusted in light of the feasibility and social impact of the proposed tax. For example, if we use the second method, we might begin by deciding that we want a 60% reduction in carbon dioxide emissions; and at an elasticity of -0.8, we can then calculate that this reduction would require a 200% increase in the price of gasoline (see Table 1). But this means, given current gasoline prices of around $1.00 a gallon, a tax of at least $2.00 a gallon in the United States.[57] Not only would such a tax probably have grave macroeconomic effects, it is totally outside the bounds of political possibility, and the tax proposal would have to be adjusted accordingly.

Furthermore, when deciding on the size of the tax, we should not take the -0.8 figure **too** seriously, despite the fact that it is the best available of all the

[57]Remember that the producer absorbs some of the cost of a tax. Therefore, if gasoline is $1.00 a gallon, and we want to increase its price to the consumer by $2.00 to $3.00 a gallon, we must impose a tax of **more** than $2.00.

possible long-run fuel-sector elasticities. As mentioned earlier, this figure applies only to a **single** point on the demand curve (or a very small increment), and there is reason to suspect that it does not apply at much higher prices. Some economists have hypothesized that demand is more elastic at higher prices (Bohi and Zimmerman, 1984, p. 148), yet a simple thought experiment might lead us to believe that price elasticity declines. Imagine that a tax is imposed in the U.S. which raises the price of gasoline to, say, $2.25 a gallon. This is roughly a 100% increase; and according to Table 1, this should produce a long-run drop in consumption of 43%. But it seems hard to imagine such a dramatic effect from a gasoline tax of this magnitude, even in the long-run.

Two economists consulted about this imagined world had mixed reactions. Henry Lee concluded, after a moment's reflection, that "43% doesn't seem that unreasonable over a period of fifteen years." But he emphasized that, to have this effect, the price differential between gasoline and other goods (achieved through the tax) would have to be maintained for the long-run duration: "We must increase the price, and **hold** it there in real terms."[58] Douglas Bohi said that there is genuine reason to question the assumption that the price elasticity of demand for gasoline is the same at prices significantly higher than the current price; and he acknowledged that the demand curve for gasoline could be steeper (than the -0.8 curve) at higher prices, which implies a lower elasticity. But he also commented that we have seen dramatic changes in the road-transport fleet since 1973, and that we should not

[58]This means that the government should not compensate for any recessionary impact of a gasoline tax through monetary expansion, because the resulting inflation would undermine the effectiveness of the tax in reducing demand.

underestimate the possibility of continued efficiency improvements if fuel prices provide enough incentive.[59]

Given all this, we should recognize that we will not be able to arrive at a precise judgment about the size of a gasoline tax. The equilibrium results of a given tax are quite uncertain, and this may suggest that we should think about non-tax market methods of reducing gasoline consumption. One concept that is in increasing favor at the moment is the tradeable pollution option or permit. The **Project 88** report comments:

> Tradeable permit systems are generally preferable to pollution taxes. With taxes, it is necessary to guess how much tax will result in how much clean-up. With permits, it is possible to decide how much pollution is the limit, and then issue permits for only that amount. Such systems do not have to begin or stay at the status quo. They can begin by issuing permits for some fraction of current emissions and give permit holders a deadline to get there. They can also be designed to move toward stricter standards. (p. 6)

Due to administrative requirements, this idea is usually thought to be applicable only to large corporations, utilities, or countries as a whole. But perhaps with some imagination it could be used to reduce gasoline consumption: permits could be traded at the level of importer and refiner, distributor, or wholesaler, and much of the cost would be passed on to the consumer. This could produce more fluctuations in the gasoline price, but price would respond as necessary to keep consumption within the prior-identified limit, and policy makers would not have to rely upon uncertain elasticity estimates to decide the appropriate size of a gasoline tax. However, we must remember that very little is known about the consequences

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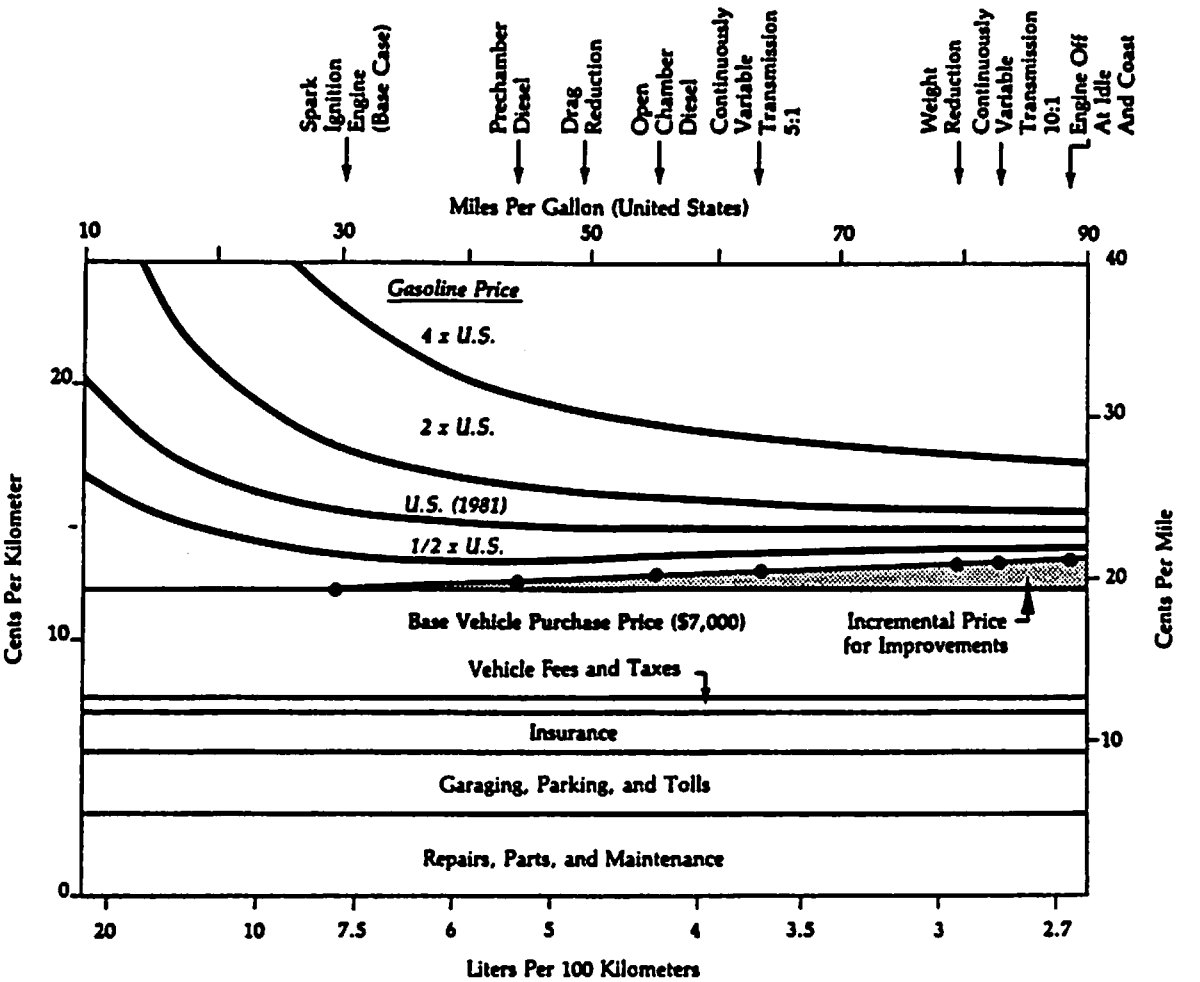
[59]We should wonder, though, whether capital can be indefinitely substituted for energy. Industrialized countries may currently be on the steep part of the efficiency-improvement curve, but sooner or later returns to investments in efficiency are likely to level off, and this means a lower price elasticity for transport energy.

of pollution-permit policies, and a great deal of theoretical and behavioral research is needed before policy makers can make any firm recommendations.

Incentives for Efficiency

The empirical evidence that economists have reviewed suggests that gasoline demand is quite responsive to price over the long-run. But when we calculate the life-cycle costs of high-efficiency automobiles, we find that the average gasoline consumer may not have very much incentive to purchase a car with a fuel efficiency of over 40 miles per gallon. This is dramatically illustrated in Figure 6, which is reproduced from Goldemberg et al. (1987, p. 66) and based on the research of von Hippel and Levi (1983). The graph shows that the cost of operation per mile for an automobile (averaged over 100,000 miles) stops declining at an efficiency of about 40 miles per gallon, even when gasoline is priced at **twice** the 1981 level. Even at **four** times 1981 level, the curve levels off at about 50 miles per gallon. The reason is that the savings achieved through lower operating costs are almost exactly offset by the greater purchase price of higher-efficiency cars.

FIGURE 6. The Costs of Driving Versus Automotive Fuel Economy
(Reproduced from Goldemberg et al., 1987, p. 66)



The indicated energy performance is based on computer simulations of an automobile having various fuel economy improvements added in the sequence shown at the top of the graph. The base car is a 1981 Volkswagen Rabbit (gasoline version).

The figure shows that the reduced operating costs associated with various fuel economy improvements are roughly offset by the increased capital costs of these improvements over a wide range of fuel economy.

Source: F. von Hippel and B.G. Levi, "Automotive Fuel Efficiency: The Opportunity and Weakness of Existing Market Incentives," *Resources and Conservation* (1983): 103-124.

Since the costs of higher efficiency are largely paid when the car is purchased (while the savings from lower operating costs are spread out across the entire life of the car), and since most people do not keep their cars for their entire usable life, it seems that there is little incentive for consumers to invest in efficiency.[60] Once again, it appears, the -0.8 figure may be deceptive, because researchers obtained the data for this elasticity estimate when consumers (in most industrialized countries) were still at the lefthand end of the curve in Figure 6; that is, when they still had a reason to invest in efficiency.

But perhaps such pessimism is unwarranted. Although it is true that consumers must face the costs of efficiency at the time the car is purchased, they are also reminded of the cost of gasoline every time they fill up. Gasoline prices have a visible effect on the day-to-day, month-by-month cash flow of car owners; in the end, it is not clear that the cost of gasoline is less important than the cost of efficiency, if we compare these costs according to their rough psychological salience.[61]

In general, this is a question that needs concerted empirical research. We need to know whether or not the -0.8 figure will continue to hold even when automobile efficiencies surpass the 40 mile per gallon mark. On the assumption that the incentive to purchase energy efficient cars **will** drop off, we should not

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[60]Goldemberg et al. (p. 67) write: "Even if the von Hippel-Levi estimates of the cost of fuel economy improvements prove high, market forces may still provide only a weak incentive to seek high fuel economy, because for highly efficient cars, fuel costs represent a tiny fraction of the total cost of owning and operating a car."

[61]As we found in Section IV, Stern (1984) and Feldman (1987) stress the importance of numerous psychological factors that are not normally incorporated in standard models of economic rationality.

neglect two other policies: an increased gas-guzzler tax and improved vehicle efficiency standards.

A gas-guzzler tax is already in place in the United States: it begins at $500 for automobiles with efficiencies below 22.5 miles per gallon and goes up to $3850 for those under 12.5 miles per gallon. But these standards are currently so low relative to the efficiencies of new American models that they affect luxury imports almost exclusively. This tax needs to be realigned with the fuel efficiencies of the contemporary fleet, and the thresholds should move upwards as efficiencies improve. A heavy tax on those vehicles at the upper end of the fleet's fuel economy range could subsidize a rebate scheme for those at the lower end. Such a program would increase the immediate cost to the gasoline consumer of an inefficient vehicle.

The U.S. first imposed the Corporate Average Fuel Economy (CAFE) standards in 1978. While they have been vociferously opposed by automakers, there is a general consensus that these standards played an important role in the doubling of the efficiency of the average American car between 1978 and 1985. There are, however, real problems with the standards as currently implemented: in particular, they do not effectively cover light trucks (which account for nearly a third of all new car sales), and they do not provide enough lead time for efficiency innovations to move from research and engineering to production. There are many interesting ideas in circulation at the moment as to how the CAFE standards and their implementation might be improved.[82] The most important point to keep in

[82]The Office of Technology Assessment, for example, will soon issue a study of the potential for reducing carbon dioxide emissions in each of the principal economic sectors; and in the transportation sector, they will address the CAFE standards in considerable detail. See in particular

mind, though, is that higher fuel economy standards would be best introduced in combination with higher fuel prices: in this way, the standards will be at least somewhat reinforced by market signals.

VII. CONCLUSIONS

In this report we have surveyed a broad range of theoretical and empirical issues relating to the use of taxes to reduce the consumption of fossil fuels and thereby reduce emissions of carbon dioxide. We have found that, while econometric modeling of energy consumption offers us only limited guidance, there is wide agreement that energy consumption in general, and fuel consumption in particular, is fairly responsive to price over the long-run. Specifically, we found that the own-price long-run elasticity of demand for gasoline in developed economies is about -0.8, which implies that a 100% increase in the gasoline price would eventually induce (perhaps after a period of ten years or longer) a 43% decrease in gasoline consumption. Most of this consumption decrease, it appears, would arise from changes in the pattern and rate of use of the automobile fleet and from improvements in the fuel economy of the fleet. A gasoline tax of this magnitude (somewhat over $1.00 per gallon) seems more politically feasible than other fuel taxes, and its regressive effects can be at least partially mitigated. For these reasons, such a gasoline tax merits the support of policy makers.

But much, much more than this is needed. Even if the tax were as effective as predicted by econometric modelers (and there is reason to think it would not be),

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Ted Parson's (1989) background paper for the OTA's study titled "The Transport Sector and Global Warming."

the 43% decline in U.S. gasoline consumption would reduce global carbon dioxide emissions by only 2 to 3 percent.[63] But in a recent conversation, Michael Oppenheimer of the Environmental Defense Fund suggested that, to prevent a climate catastrophe, humankind needs to reduce its carbon dioxide emissions from current levels by at least **40%** in the next 50 years.

Such a reduction in emissions will require social, institutional, and behavioral changes of a size and speed unprecedented in human history. In the West, we need to move beyond the prevailing ethos of high material consumption that seems so tightly woven into our culture. This means, fundamentally, changing our basic criteria of welfare, our measures of national and individual standard of living, and our understandings of what constitutes the "good life." In the terminology used in this report, we not only need to move **up** the demand curves for the energy services we consume, we need to move and bend the demand curves themselves.

[63]This assumes that U.S. emissions will remain a constant proportion of global carbon dioxide emissions during the period -- which may be a decade or longer -- of adjustment to the tax; but, of course, this proportion will decrease as developing countries increase their emissions.

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THE GLOBAL ENVIRONMENTAL POLICY PROJECT

The Global Environmental Policy Project (GEPP) began in 1989 as a joint effort of the Kennedy School of Government's Energy and Environmental Policy Center (EEPC) and its Science, Technology and Public Policy Program (STPP), and the Harvard Business School Negotiations Project. The Global Environmental Policy Project focuses on four subjects:

- *Options for Negotiations*

  In recent history, regional agreements have emerged bringing together countries who share a common resource. There are lessons to be learned from the formulation and implementation of these environmental negotiations. The Project explores various global negotiations issues, including technology transfer from developed to developing countries, funding mechanisms to cover the cost of reforestation, and CO_2 emissions and reductions.

- *Analytic Tools*

  The analytical tools that we use to evaluate environmental impact and mitigation options were developed to combat problems with local impact and short time frames. These tools are not adequate for the examination of issues, such as global climate change, which are characterized by long-time horizons, tremendous factors of uncertainty, and a broad spectrum of perceptions among nations. The Project is developing a range of analytical techniques for the evaluation of policy options to provide governments with decision rules to assist in their selection among these options.

- *Social Learning*

  GEPP researchers are looking at how nations have responded to issues of global environmental change over the past forty years. What lessons can we draw from these experiences? Are societies improving their responses to issues of environmental change? What impedes more rapid progress? Given that different countries react differently, what can we learn from these different responses and how can we use these lessons in developing future programs and policies?

- *Training*

  Global environmental issues will require nations to look at energy, environment, security and economic policy in a more integrated fashion. Furthermore, they will force countries to absorb more scientific and technical information than they can currently evaluate. Many nations do not have the internal capability independently to assess information being generated on global environmental problems.

  The Project is attempting to develop an executive program to teach senior government officials how to assess and manage global and regional environmental problems.