# ENERGY, THE ENVIRONMENT AND ECONOMIC GROWTH

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CITATION AND REPRODUCTION

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# ENERGY, THE ENVIRONMENT, AND ECONOMIC GROWTH

**by**

**Dale W. Jorgenson and Peter J. Wilcoxen**

## 1. INTRODUCTION

Economic growth is a critical determinant of demands for energy. Utilization of energy, especially combustion of fossil fuels, is an important source of environmental pollution. Growth projections are essential for estimates of future demands and supplies of energy and future requirements for pollution controls to maintain environmental quality. The natural point of departure for modeling economic growth is the neo-classical theory of growth originated by Solow (1956, 1988). This theory has been developed in the form used in modeling the inter-relationships among energy, the environment, and economic growth by Cass (1965) and Koopmans (1967).[1]

Maler (1974, 1975) and Uzawa (1975, 1988) have presented neo-classical theories of economic growth with pollution abatement and Solow (1974a, 1974b) has provided a theory that includes supply and demand for an exhaustible resource. These theories have generated an extensive literature, surveyed by Dasgupta and Heal (1979). In the neo-classical theory of growth, wage rates grow at the same rate as productivity in the long run, while rates of return depend on productivity growth and parameters that describe saving behavior. These long run properties of economic growth are independent of energy and environmental policies.

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1. The Cass-Koopmans theory of economic growth has been discussed by Lucas (1988) and Romer (1989).

The neo-classical theory of economic growth also provides a framework for projecting intermediate run growth trends. These trends depend on the same factors as long run trends, but also depend on energy and environmental policies through their effects on capital accumulation and rates of productivity growth over shorter periods. In this context the intermediate run refers to the time needed for the capital-output ratio to converge to a long run stationary value. This often requires several decades, so that intermediate run trends are critical for policy evaluation.

A striking example of changes in growth trends is the sharp decline in rates of economic growth in the United States and other industrialized countries during the 1970s and 1980s. For example, Jorgenson (1990b) shows that US real output grew at an annual rate of 3.7 percent during the period 1947-1973, while the annual growth rate for the period 1973-1985 was only 2.5 percent. Englander and Mittelstadt (1988) have shown that the slowdown has been even more severe in other industrialized countries. Two events coinciding with the slowdown-the advent of more restrictive environmental controls and the increase in world petroleum prices-have led to a vast outpouring of research directed at a fuller understanding of the interactions among energy supplies and prices, environmental quality and its cost, and the sources of economic growth.[2]

The neo-classical theory of economic growth has provided the framework for a number of important modeling studies of energy and environmental policies. Nordhaus (1992) has presented a Dynamic Integrated Climate-Economy (DICE) model for analyzing the economics of global warming. This is a one-sector neoclassical growth model for the world economy that integrates a production model for world output, a model of intertemporal choice based on utility maximization by a representative consumer, and model of the impact of climate change on

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2. This literature has been surveyed by Christiansen, Gollop, and Havenman (1980) and Christiansen and Tietenberg (1985).

productivity. Nordhaus's model of climate change links climate change to the level of world output through a series of dynamic relationships based on the well-known greenhouse effect.[3]

Nordhaus considers the impact of a policy to control climate change by limiting the emissions of greenhouse gases, such as carbon dioxide. For this purpose he performs two simulations of world economic growth, first, with no controls on greenhouse gas emissions and, second, with optimal controls on these emissions. The optimization criterion is the intertemporal utility function of the representative consumer in the DICE model. The difference between the two simulations is very small for a half century after 1990. The optimal reduction in greenhouse gas emissions begins around nine percent and rises gradually to 14 percent by the year 2100. The optimal policy can be implemented by means of a world carbon tax, which rises from $5 per ton of carbon in the 1990's to $20 per ton by the end of the twenty-first century.[4]

Nordhaus's model of world economic growth provides a dramatic illustration of the power of the neo-classical framework in analyzing the impact of energy and environmental policies. The parameters of this model are calibrated to extensive data on the growth of the world economy. Changes in the global climate are generated by economic activity, especially the combustion of fossil fuels. The physical model of climate change includes the principal features of simulation models for the global climate developed by climatologists. Climate change feeds back to economic activity by reducing productivity levels. These mechanisms provide the basis for the design of an optimal environmental policy by application of a sophisticated version of cost-

3. Overviews of the greenhouse warming problem are presented by Cline (1992), Marine and Richels (1992), Chapter 1, Nordhaus (1991a), and Schelling (1992). We discuss the greenhouse effect and control of global climate change in Section 5 below.
4. A carbon tax was first analyzed by Nordhaus (1979) and has been discussed by the Congressional Budget Office (1990). Alternative policy options for stabilizing the global climate are described in detail by EPA (1989).

benefit analysis.[5]

A carbon tax like that considered by Nordhaus would internalize the externality associated with *carbon* dioxide emissions. However, this externality affects the whole planet, while carbon taxes are the responsibility of individual governments. The design of an appropriate policy must involve international coordination. An important limitation of Nordhaus's approach is that it fails to capture differences among regions of the world economy and gains from international co-operation on policies for emissions control. These limitations have motivated the development of a number of multi-region models of the world economy and global climate change. The GLOBAL 2100 model developed by Manne and Richels (1992) is the one most similar in spirit to Nordhaus's model.

In the GLOBAL 2100 model the world economy is subdivided among five regions-the US, other OECD, the former Soviet Union, China, and the Rest of the World. Each region is represented by a one-sector neo-classical growth model patterned after Manne's (1981) MACRO model. Output of the region is a *function* of capital, labor, and energy inputs with exogenously given growth in productivity. Energy is allocated between electrical and nonelectrical energy. Both forms of energy are supplied by a detailed energy technology assessment (ETA) model of the energy sector. The consumer sector in each region is modeled by means of a representative consumer who maximizes an intertemporal utility function. Environmental policy affects regional output through limitations on carbon dioxide emissions resulting from fossil fuel combustion. The model is employed by Manne and Richels for estimating costs of emissions controls.[6]

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5. Optimal policies for controlling global climate change have also been analyzed by Peck and Teisberg (1990, 1992). Cline (1992) provides a detailed cost-benefit analysis of policies for climate control.

6. Many estimates of costs of emissions controls on carbon dioxide are now available. Detailed surveys are given by Cline (1992), Hoeller, Dean, and Nicolaisen (1991) and Nordhaus (1991b). Dean (1992) presents a survey of estimates of costs of controlling carbon dioxide emissions from six multi-region models of the world economy, including the GLOBAL 2100 model of Manne and

Manne and Richels consider the impact of restrictions on carbon dioxide emissions for each of the five regions individually. For this purpose they perform alternative simulations of regional economic growth, first, with no controls on carbon dioxide emissions to estimate the consequences of 'Business-as-Usual" for energy utilization and emissions levels. The principal alternative simulation involves stabilizing these emissions at 1990 level through the year 2000, reducing them to twenty percent below this level by the year 2020, and stabilizing them at this level thereafter. The costs of this policy for the US mounts to one percent of the gross domestic product (GDP) by the year 2000. These losses rise to two percent of the GDP by the year 2020 and eventually to 2.5 percent. This policy can be implemented by means of a carbon tax, which begins at $135 per ton in 1990 and rises sharply as emissions are reduced. The tax eventually reaches a level of $208 per ton.

Manne and Richels consider the sensitivity of their results to alternative assumptions about the availability of energy supplies and technologies and alternative carbon dioxide limits. They consider the economic impact of reducing US emissions to fifty percent of 1990 levels by the year 2010 and stabilizing at that level thereafter. This produces much more substantial economic losses and requires considerably higher tax levels. Interaction among regions in the GLOBAL 2100 occurs through the world petroleum market and a hypothetical international market for emissions permits. Manne and Richels demonstate that there would be sizable gains from international trade in these permits. For example, the US would find it worthwhile to import permits from China and the Rest of the World regions; in the year 2020 these imports would be valued at around $50 billion. The costs of restrictions on emissions would be reduced substantially by introducing international coordination of global climate policy through tradeable permits.

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Richels (1992). These estimates are based on comparable assumptions about future world economic growth and world petroleum prices.

The GLOBAL 2100 model of Manne and Richels provides another excellent example of the potential of the neo-classical theory of economic growth for modeling the impact of energy and environmental policies. Their model is useful in assessing the costs of restrictions on carbon dioxide emissions and the potential benefits of international coordination. Through application of their energy technology assessment (ETA) model for each region, Manne and Richels also provide much valuable information on the potential payoff from accelerated research and development on new energy sources and alternative energy technologies. However, the detail available for the individual regions is very limited, except for the energy sector. Their approach fails to capture important differences among industries and consumers that are critical to assessments of alternative energy and environmental policies at the national level. To overcome these limitations it is essential to employ an econometric approach for modeling the impacts of these policies. We next consider the application of this approach to the US, the region that has been studied most intensively.[7]

The framework for econometric analysis of the impact of energy and environmental policies is provided by intertemporal general equilibrium modeling.[8] The one-sector neo-classical growth models used by Nordhaus (1992) in modeling the world economy or Manne and Richels (1992) in modeling each region in their fiveregion model of the world economy provide illustrations of intertemporal general equilibrium models. The organizing mechanism of these models is an intertemporal price system balancing demand and supply for products and factors of production. In Nordhaus's DICE model there is only one product, world output, and two factors of production, capital and labor inputs. In the GLOBAL 2100 model of Manne and

7. Beaver (1992) presents a detailed survey of models of the US economy that have been used in modeling the impacts of energy and environmental policies in ENT-12, a project of the Energy Modeling Form at Stanford University.

8. The classic formulation of intertemporal general equilibrium theory is by Lindahl (1939). A detailed survey of intertemporal general equilibrium theory is presented by Stokey and Lucas (1989).

Richels there are three products in each region-regional output, electrical energy, and non-electrical energy-and two factors of production-capital and labor.

In addition, the intertemporal price system links the prices of assets in every time period to the discounted value of future capital services. This forward-looking feature is combined with backward linkages among investment, capital stock, and capital services in modeling the dynamics of economic growth. Neither Nordhaus (1992) nor Manne and Richels (1992) have limited their considerations to characterization of economic growth in the long run. The alternative time paths of economic growth generated in their simulations depend on energy and environmental policies through their impact on capital accumulation. In Nordhaus's model productivity growth depends on these policies through the impact of greenhouse gas emissions on climate change and the effects of climate change on productivity. Productivity growth in the Manne-Richels model depends on the introduction of new sources of energy supplies and energy technologies in the ETA submodel of the energy sector.

In disaggregating the economic impacts of energy and environmental policies for the US, we preserve the key features of more highly aggregated intertemporal general equilibrium models. One important dimension for disaggregation is to introduce a distinction among industries and commodities in order to measure policy impacts for narrower segments of the economy. This also makes it possible to model differences among industries in responses to changes in energy prices and the imposition of pollution controls. A second dimension for disaggregation is to distinguish among households by level of wealth and demographic characteristics. This makes it possible to model differences in responses to price changes and environmental controls. It is also useful in examining the distributional effects of energy and environmental policies.[9] We begin our discussion of intertemporal general equilibrium modeling by

9. We describe possible approaches to calculation of distributional effects in Section 6 below.

focusing on the econometric methodology that is required.

At the outset of our discussion it is essential to recognize that the predominant tradition in general equilibrium modeling does not employ econometric methods. This tradition originated with the seminal work of Leontief (1951), beginning with implementations of the static input-output model over half a century ago. Leontief (1953) gave a further impetus to the development of general equilibrium modeling by introducing a dynamic input-output model. This model can be regarded as an important progenitor of the intertemporal general equilibrium models described below. Empirical work associated with input-output analysis is based on parametrizing technology and preferences from a single inter-industry *transactions* table.

The usefulness of the "fixed coefficients" assumption that underlies input-output analysis is hardly subject to dispute. By linearizing technology and preferences Leontief solved at one stroke the two fundamental problems that arise in practical implementation of general equilibrium models. First, the resulting general equilibrium model can be solved as a system of linear equations with constant coefficients. Second, the unknown parameters describing technology and preferences can be estimated from a single data point. The data required are now available for all countries that have implemented the United Nations (1968) System of National Accounts.

The input-output approach was applied to modeling of environmental policy by Ayres and Kneese (1969) and Kneese, Ayres, and d'Arge (1970). Their work was especially notable for introducing a "materials balance" approach based on conservation of mass for all economic activities. Materials balances are useful in bringing out the fact that material not embodied in final products must be embodied in emissions of pollutants. These emissions accumulate as solid waste or enter the atmosphere or the hydrosphere and reduce air or water quality. In implementing the materials balance approach, the assumption that pollutants are generated in fixed proportions to output is a natural complement to the fixed coefficients assumption of Leontief’s

input-output model.[10]

The most detailed implementation of the input-output approach to modeling energy and environmental policy is the United Nations Study presented by Leontief, Carter, and Petri (1977). In this study the world economy is divided among fifteen regions, including four regions representing industrialized countries-North America, Western Europe, Japan, and Oceania-and eleven regions representing countries at various stages of development. A fixed coefficients input-output model with 45 industrial sectors and including resource requirements and pollution control activities is constructed for each region. The growth rate of GDP for each region is taken to be exogenously given. The regions are treated separately and also linked through international trade. One of the principal conclusions is that the availability of resources and requirements for pollution control do not pose insurmountable obstacles to growth of the developing countries.

One perspective on the United Nations Study is that it provides a response to the Meadows (1972) Report, *Limits to Growth,* for the Club of Rome. This Report employs simulations based on systems dynamics to demonstrate the possibility of exhaustion of resources and inability to control pollution as barriers to growth of industrialized and developing countries. The viewpoint of the United Nations Study is reflected in the World Commission on Environment and Development Report (1987), *Our Common Future,* also known as the Brundtland Report. This Report argues that economic development and maintenance of environmental quality are compatible through "sustainable development". [11]

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10. Detailed surveys of fixed coefficient input-output models applied to environmental policy, including those of Leontief (1970) and Leontief and Ford (1973), are presented by Forsund (1985) and James, Jansen, and Opschoor (1978). The "materials balance" approach is considered in the context of the Arrow-Debreu theory of general equilibrium by Maler (1974, 1985).

11. The concept of sustainable development is discussed by the World Bank (1992). Meadows (1992) provides an update of the earlier Club of Rome Report.

The obvious objection to the fixed coefficients approach to modeling energy and environmental policies is that these policies induce changes in the input-output coefficients. In fact, the objective of pollution control regulations is to induce producers and consumers to substitute less polluting inputs for more polluting ones. A prime example is the substitution of low sulfur coal for high sulfur coal by electric utilities and manufacturing firms to comply with regulations on sulfur dioxide emissions. Another important example is the shift from leaded to unleaded motor fuels in order to dean up motor vehicle emissions.

The first successful implementation of an applied general equilibrium model without the fixed coefficients assumption of input-output analysis is due to Johansen (1960). Johansen retained the fixed coefficients assumption in modeling demands for intermediate goods, but employed linear logarithmic or Cobb-Douglas production functions in modeling the substitution between capital and labor services and technical change. He replaced the fixed coefficients assumption for household behavior by a system of demand functions originated by Frisch (1959). Finally, he developed a method for solving the resulting nonlinear general equilibrium model for growth rates of sectoral output levels and prices and implemented this model for Norway. Johansen's multi-sectoral growth (MSG) model is another important progenitor for the models of intertemporal general equilibrium we describe below.

Linear logarithmic production functions have the obvious advantage that the capital and labor input coefficients respond to price changes. Furthermore, the relative shares of these inputs in the value of output are fixed, so that the unknown parameters characterizing substitution between capital and labor inputs can_ be estimated from a single data point. In describing producer behavior Johansen employed econometric methods only in estimating constant rates of technical change. Similarly, the unknown parameters of the demand system proposed by Frisch can be determined from a single data point, except for one parameter that must be

determined econometrically.

The essential features of Johansen's approach have been preserved in the applied general equilibrium models surveyed by Bergman (1985) and Fullerton, Henderson, and Shoven (1984). The unknown parameters describing technology and preferences in these models are determined by "calibration" to a single data point. Data from a single inter-industry transactions table are supplemented by a small number of parameters estimated econometrically. The obvious disadvantage of this approach is that highly restrictive assumptions on technology and preferences are required to make calibration feasible.[12]

Almost all general equilibrium models retain the fixed coefficients assumption of Leontief and Johansen for modeling demand for intermediate goods. However, this assumption is directly contradicted by massive evidence of price-induced energy conservation in response to higher world energy prices beginning in 1973.[13] Reductions in energy utilization induced by the successive energy crises of the 1970's and the higher level of energy prices prevailing in the 1980's has been documented in great detail by Schipper and Meyers (1992). This extensive survey covers nine OECD economies, including the US, for the period 1970-1989 and describes energy conservation in residential, manufacturing, other industry, services, passenger transport, and freight transport sectors. Reductions in energy-output ratios for these activities average 15-20 percent.[14]

Fixed coefficients for intermediate goods also rule out a very important response to environmental regulations by assumption. This is the introduction of special

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12. Johansen's approach has been used in modeling environmental policies for Norway by Forsund and Strom (1976). We discuss the calibration method for parametrization in more detail below.
13. We describe reductions in energy utilization after 1973 for US industries in Section 4 below. Long run trends in US energy utilization have been analyzed by Schurr and Netschert (1962) and Schurr, Burwell, Devine, and Sonenblum (1990).
14. Price-induced energy conservation in the US has been analyzed in greater detail by Hogan and Jorgenson (1991), Jorgenson (1981, 1984b), Jorgenson and Fraumeni (1981), and Jorgenson and Stoker (1984).

devices to treat wastes after they have been generated, substituting capital in the form of pollution control devices for other inputs such as energy or materials. This is commonly known as end-of-pipe abatement and is frequently the method of choice for retrofitting existing facilities to meet environmental standards. A typical example is the use of electrostatic precipitators to reduce the emissions of particulates from combustion. Regulations promulgated in the US by the Environmental Protection Agency effectively encourage the use of this approach by setting standards for emissions on the basis of the "best available technology."

Another important limitation of the Johansen approach is that changes in technology are taken to be exogenous. This rules out another important method for pollution abatement by assumption. This is the introduction of changes in technology by redesigning production methods to reduce emissions. An important example is the introduction of fluidized bed technology for combustion, which results in reduced emissions. Gollop and Roberts (1983, 1985) have constructed a detailed econometric model of electric utility firms based on a cost function that incorporates the impact of environmental regulations on the cost of producing electricity and the rate of productivity growth. They conclude that the annual productivity growth of electric utilities impacted by more restrictive emissions controls declined by .59 percentage points over the period 1974-1979. This resulted from switching technologies to meet new standards for air quality.

To represent technologies and preferences that overcome the limitations of the Johansen approach, it is essential to employ econometric methods. A possible extension of Johansen's approach would be to estimate elasticities of substitution between capital and labor inputs along the lines suggested by Arrow, Chenery, Minhas, and Solow (1961). Unfortunately, constant elasticity of substitution (CES) production functions cannot easily encompass substitution among capital, labor, energy, and materials inputs. As Uzawa (1962) and McFadden (1963) have shown, constant

elasticities of substitution among more than two inputs imply, essentially, that elasticities of substitution among all inputs must be the same. An alternative approach to the implementation of econometric models of producer behavior is to generate complete systems of demand functions for inputs of capital, labor, energy, and materials inputs in each industrial sector. Each system gives quantities of inputs demanded as functions of prices and output. This approach to modeling producer behavior was originated by Berndt and Jorgenson (1973) and employed in modeling energy policy and US economic growth by Hudson and Jorgenson (1974). The approach was extended to incorporate endogenous technical change by Jorgenson and Fraumeni (1981).[15] A model combining substitution among capital, labor, energy and materials inputs and endogenous technical change is utilized in modeling environmental policy and U.S. economic growth by Jorgenson and Wilcoxen (1990b).

The econometric approach for modeling producer behavior has been implemented for Norway by Longva and Olsen (1983). The results are utilized in modeling energy policy and Norwegian economic growth by Longva, Lorentsen, and Olsen (1983). An updated and revised version of this model has been employed in assessing the impact of restrictions on carbon dioxide emissions on Norwegian economic growth by Glomsrod, Vennemo, and Johnsen (1992). Hazilla and Kopp (1986) have constructed an econometric model of producer behavior for the same thirty-five sectors of the US economy analyzed by Jorgenson and Fraumeni (1981). Hazilla and Kopp (1990) use this model in measuring the costs of US environmental regulations.[16]

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15. Alternative models of endogenous productivity growth are surveyed by Jorgenson (1984a, 1990b). A comprehensive survey of models of producer behavior constructed along the lines of Berndt and Jorgenson (1973) is presented by Jorgenson (1986).
16. The same sectoral disaggregation has been used by the Congressional Budget Office (1990) in analyzing the effects of a carbon tax on US economic growth. Surveys of the literature on the econometric approach to general equilibrium modeling are given by Bergman (1990), Hazilla and Kopp (1990), and Jorgenson (1982). Bergman provides detailed comparisons with alternative

As in the descriptions of technology by Leontief and Johansen, production in the econometric approach is characterized by constant returns to scale in each sector. As a consequence, commodity prices can be expressed as a function of factor prices, using the nonsubstitution theorem of Samuelson (1951). This greatly facilitates the solution of the econometric general equilibrium models constructed by Hudson and Jorgenson (1974) and Jorgenson and Wilcoxen (1990b), since the nonsubstitution theorem permits a substantial reduction in dimensionality of the space of prices to be determined by the model. The corresponding feature of the Johansen approach has been exploited in applications of the "fixed point" methods for solving nonlinear general equilibrium models pioneered by Scarf (1973, 1984).

Similarly, econometric models of consumer behavior can be used to overcome the limitations of the Frisch (1959) model employed by Johansen. Models stemming from the pathbreaking contributions of Schultz (1938), Stone (1954), and Wold (1953) consist of complete systems of demand functions, giving quantities demanded as functions of prices and total expenditure. These models incorporate the restrictions implied by the theory of consumer behavior by introducing the notion of a representative consumer. Aggregate demand functions are treated as if they could be generated by a single utilizing maximizing individual. Per capita quantities demanded can be expressed as functions of prices and per capita expenditure.

The obvious difficulty with the representative consumer approach is that aggregate demand functions can be expressed as the sum of individual demand functions. Aggregate demand functions depend on prices and total expenditures, as in the theory of individual consumer behavior. However, these demand functions depend on individual total expenditures rather than aggregate expenditure. If individual total expenditures are allowed to vary independently, models based on a representative

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approaches to general equilibrium modeling.

consumer imply restrictions that severely limit the dependence of individual demand functions on individual expenditure.

The simplest form of restrictions required for the representative consumer approach is to require that preferences are identical and homothetic for all consumers. This set of restrictions is implicit in the linear logarithmic demand systems employed by Stone (1954) and Wold (1953). Homothetic preferences are inconsistent with well-established empirical regularities in the behavior of individual consumers, such as Engel's Law, which states that the proportion of expenditure devoted to food is a declining proportion of total expenditure. Identical preferences for individual households are inconsistent with empirical findings that expenditure patterns depend on demographic characteristics of individual consumers.[17]

A weaker set of restrictions for the existence of a representative consumer has been presented by Gorman (1953), requiring that quantities consumed are linear in total expenditure with slopes that are identical for all consumers. Muellbauer (1975) and Lewbel (1989) have presented generalizations of these conditions, requiring that preferences are identical for all consumers, but that quantities consumed are not necessarily linear functions of expenditure.[18] Econometric models of aggregate consumer behavior based on the theory of a representative consumer have been constructed by Berndt, Darrough, and Diewert (1977) and Deaton and Muellbauer (1980a, 1980b). The econometric general equilibrium models of Glomsrud, Vennemo, and Johnsen (1992) and Hazilla and Kopp (1990) employ the representative consumer approach in modeling consumer behavior.

An alternative approach to econometric modeling of aggregate consumer behavior is provided by Lau's (1982) theory of exact aggregation. This approach

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17. Reviews of the literature are presented by Deaton and Muellbauer (1980b) and Jorgenson (1990a).
18. The implications of these restrictions have been discussed by Jorgenson (1984a, 1990a) and Kirman (1992).

makes it possible to dispense with the notion of a representative consumer. Systems of aggregate demand functions depend on statistics of the joint distribution of individual total expenditures and attributes of individuals associated with differences in preferences. One of the most remarkable features of models based on exact aggregation is that systems of demand functions for individuals can be recovered uniquely from the system of aggregate demand functions. This makes it possible to exploit all the implications of the economic theory of the individual consumer in constructing an econometric model of aggregate consumer behavior.

The implementation of an econometric model of aggregate consumer behavior based on the theory of exact aggregation has been carried out by Jorgenson, Lau, and Stoker (1982). Their approach requires time series data on prices and aggregate quantities consumed. This approach also requires cross section data on individual quantities consumed, individual total expenditures, and attributes of individual households, such as demographic characteristics.[19] By contrast the non-econometric approaches of Leontief and Johansen require only a single data point for prices, aggregate quantities consumed, and aggregate expenditure.

We continue our presentation of econometric modeling of the impact of energy and environmental policies by considering the intertemporal general equilibrium model of the US economy constructed by Jorgenson and Wilcoxen (1990b). The general equilibrium model of production employed by Jorgenson and Wilcoxen is based on the model originated by Jorgenson and Fraumeni (1981). This model includes systems of demand functions for capital, labor, energy, and materials inputs and a model of endogenous productivity growth for each of thirty-five sectors of the US economy. The Jorgenson-Wilcoxen model incorporates a model of aggregate

19. The theory of exact aggregation is discussed by Jorgenson, Lau, and Stoker (1982) and Lau (1982). Econometric models based on the theory of exact aggregation are surveyed by Jorgenson (1990a) and Stoker (1993).

consumer behavior based on the exact aggregation approach of Jorgenson, Lau, and Stoker (1982). This model dispenses with the notion of a representative consumer employed in previous econometric models of aggregate consumer behavior. The model includes a system of demand functions for five commodity groups-energy, food, non-durable goods, capital services, and other services. We outline the Jorgenson-Wilcoxen model in more detail in Section 2 below.

Jorgenson and Wilcoxen (1990a) have presented a highly disaggregated model of the impact of environmental regulations on US economic growth. Detailed data on costs of compliance imposed on individual industries by these regulations are utilized in modeling the impact of environmental policy. Alternative regulatory policies generate different costs of production for these industries and different time paths of economic growth for the US economy. The industries most affected by environmental regulations are the motor vehicles and coal mining industries. These regulations have led to a substantial decline in the national product, amounting to a reduction of almost 2.6 percent in the long run. This reduction is produced by an even more severe decline in capital accumulation, illustrating the importance of the dynamics of adjustment of economic growth to its long run trend. We outline the results of this study in Section 3.

We have already summarized the studies of environmental policies for control of global warming by Nordhaus (1992) and Manne and Richels (1992). A very significant issue in modeling the impact of these policies is the price responsiveness of greenhouse gas emissions to changes in energy prices. In Section 4 we present an analysis of a "natural experiment" provided by variations in energy prices during the 1970's and 1980's. Over the period 1972-1987 US emissions of carbon dioxide were stabilized by price-induced energy conservation. A major portion of the corresponding reduction in the growth rate of national output almost two-thirds-can be attributed to oil price surges that took place in 1973-1975 and 1978-1980. The change in

the oil price levels between 1972 and 1987 accounted for about one-third of the slowdown in the growth of output. A more detailed analysis of the stabilization of carbon dioxide emissions is given by Jorgenson and Wilcoxen (1992b).

Finally, we turn our attention to the cost of controlling US carbon dioxide emissions. For this purpose we summarize the results of a study of these costs by Jorgen, son and Wilcoxen (1992a) in Section 5. Jorgenson and Wilcoxen have considered three alternative sets of restrictions on carbon dioxide emissions-stabilizing these emissions at 1990 levels, curtailing emissions by twenty percent of 1990 levels of the period 1990-2005 and stabilizing thereafter, and allowing emissions to increase through the year 2000 and stabilizing at that level. The costs of stabilization at 1990 levels amount to a loss in the national product of half a percentage point. However, these costs rise at an increasing rate as emissions targets are made more restrictive. In Section 6 we provide an overall evaluation of the econometric approach for modeling the impact of energy and environmental policies.

## 2. AN OVERVIEW OF THE MODEL

Our analysis of the impact of energy and environmental policies is based on simulations of US economic growth, using an intertemporal general equilibrium model of the US economy. This model has been implemented econometrically by Jorgenson and Wilcoxen (1990b). In this section we outline the model, emphasizing features that are critical in assessing policy impacts. The starting point is a system of national accounts for the US developed by Jorgenson (1980) and implemented by Fraumeni and Jorgenson (1980). This accounting system provides the time series data needed for econometric modeling of producer and consumer behavior.[20]

The critical innovation in the accounting system implemented by Fraumeni and Jorgenson is the development of accounts for investment, capital stock, and capital services and the corresponding prices. These accounts incorporate a backwardlooking accumulation equation for capital, linking the current flow of capital services to all past investments. They also include a forward-looking equation for the price of capital services, linking the price of investment goods to all future prices of capital services. Equations of this type are essential for modeling the dynamics of economic growth. The capital accounts employed by Jorgenson and Wilcoxen are described in detail by Jorgenson (1990b).

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20. Conventional systems of national accounts, such as the United Nations (1968) System of National Accounts and the US National Income and Product Accounts are unsatisfactory for modeling purposes, since they do not successfully integrate capital accounts with income and production accounts. The system of US national accounts presented by Fraumeni and Jorgenson (1980) disaggregates the accounts constructed by Christensen and Jorgenson (1973) to the industry level. The Christensen-Jorgenson system is used in modeling the US economy by Jorgenson and Yun (1990).

## 2.1. Producer Behavior

We have constructed submodels for each of four sectors of the US economy-business, household, government, and the rest of the world. Since many of the most important features of our model are contained in our submodel of the business sector, we begin our presentation with this sector. Energy and environmental policies affect different industries in very different ways. For example, fossil fuel combustion results in emissions of pollutants, so that modeling the response to pollution control policies requires distinguishing among industries with different energy intensities. Accordingly, we have subdivided the business sector into the thirty-five industries shown in Table 2.1. Each of these corresponds, roughly, to a two-digit industry in the Standard Industrial Classification. This level of industrial disaggregation makes it possible to measure the impact of alternative policies on relatively narrow segments of the US economy.

We have also divided the output of the business sector into thirty-five commodities, each one the primary product of one of the industries. Many industries produce secondary products as well, for example, the textile industry produces both textiles and apparel, so that we have allowed for joint production. Each commodity is allocated between deliveries to intermediate demands by other industries and deliveries to final demands by households, governments, and the rest of the world. We represent the technology of each industry by means of an econometric model of producer behavior. In order to estimate the unknown parameters of these production models we have constructed an annual time series of inter-industry transactions tables for the US economy for the period 1947 through 1985.[21] The data for

21. Inter-industry transactions tables for the US are derived from those of the Bureau of Economic Analysis (1984). Income data are from the US national income and product accounts, also developed by the Bureau of Economic Analysis (1986). The data on capital and labor services are based on those of Jorgenson, Gollop, and Fraumeni (1987). Our data integrate the capital accounts described by Jorgenson (1990b) with an accounting system based on the United Nations

each year are divided between a use table and *a make* table. The use table shows the quantities of each commodity-intermediate inputs, primary factors of production, and noncompeting imports-used by each industry and final demand category.[22] The make table gives the amount of each commodity produced by each industry. In the absence of joint production this would be a diagonal array. The organization of the use and make tables is illustrated in Figures 2.1 and 2.2; Table 2.2 provides definitions of the variables appearing in these figures.

The econometric method for parametrizing our model stands in sharp contrast to the calibration method used in previous general equilibrium modeling. Calibration involves choosing parameters to replicate the data for a particular year.[23] Almost all general equilibrium models employ the assumption of fixed "input-output" coefficients for intermediate goods, following Johansen (1960). This allows the ratio of the input of each commodity to the output of an industry to be calculated from a single use table like the one presented in Figure 2.1; however, it rules out substitution among intermediate goods, such as energy and materials, by assumption. It also ignores the distinction between industries and commodities and rules out joint production.

The econometric approach to parametrization has several advantages over the calibration approach. First, by using an extensive time series of data rather than a single data point, we can derive the response of production patterns to changes in prices from historical experience. This is particularly important for the analysis of energy and environmental policies, since energy prices have varied widely and

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(1968) System of National Accounts. Details are given by Wilcoxen (1988), Appendix C.

22. Noncompeting imports are imported commodities that are not produced domestically.

23. See Mansur and Whalley (1984) for more detail on the calibration approach. An example of this approach is Borges and Goulder (1984), who present a model of energy policy calibrated to data for the year 1973. A more recent example is given by Whalley and Wigle (1991), who present a multi-region model of the world economy and analyze the consequences of imposing an international carbon tax.

Figure 2.1: Organization of the Use Table

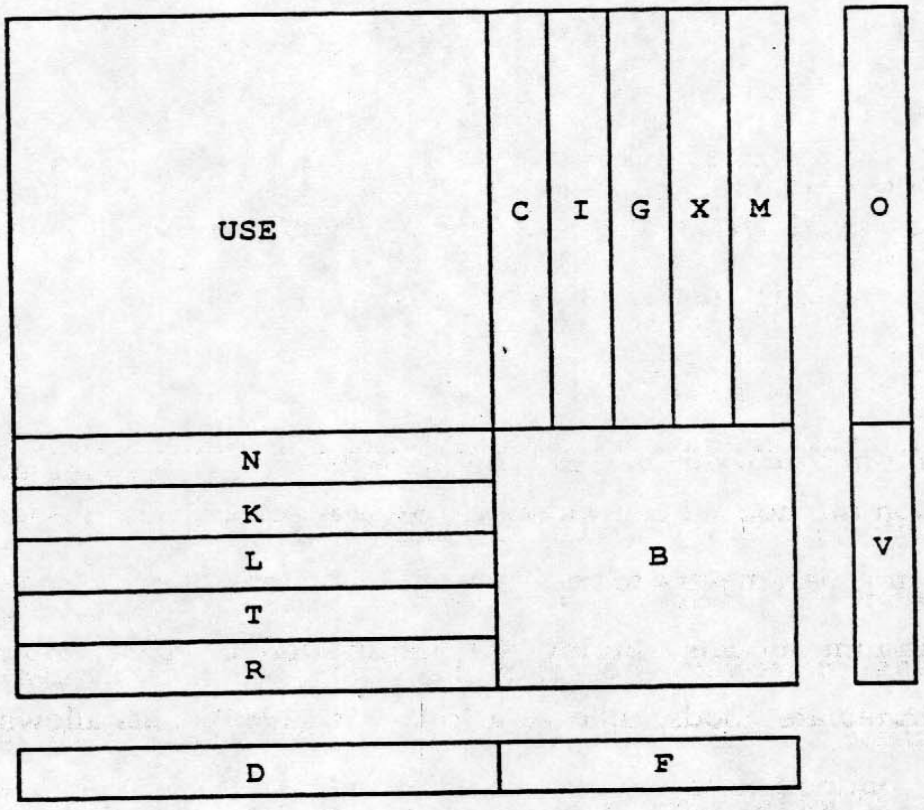
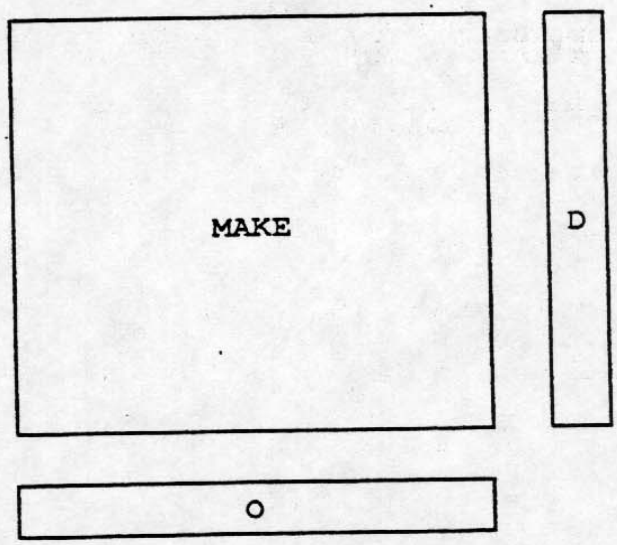



Figure 2.2: Organization of the Make Table



## Table 2.2: Make and Use Table Variables

| Category | Variable | Description |
|---|---|---|
| Industry-Commodity Flows: | | |
| | USE | Commodities *Used* by Industries (use table) |
| | MAKE | Commodities *Made* by Industries (make table) |
| Final Demand Columns: | | |
| | C | Personal Consumption |
| | I | Gross Private Domestic Investment |
| | G | Government Spending |
| | X | Exports |
| | M | Imports |
| Value Added Rows: | | |
| | N | Noncompeting Imports |
| | K | Capital |
| | L | Labor |
| | T | Net Taxes |
| | R | Rest of the World |
| Commodity and Industry Output: | | |
| | O | Commodity Output |
| | D | Industry Output |
| Other Variables: | | |
| | B | Value Added Sold Directly To Final Demand |
| | V | Total Value Added |
| | F | Total Final Demand |

environmental policies have changed substantially during our sample period. The calibration approach imposes responses to these changes through the choice of functional forms. For example, elasticities of substitution are set equal to zero by imposing the Leontief functional form used in input-output analysis or unity by imposing the Cobb-Douglas functional form employed by Johansen (1960). More generally, all elasticities of substitution are set equal to each other by imposing the constant elasticity of substitution functional form.[24]

A second advantage of the econometric approach is that parameters estimated from time series are much less likely to be affected by the peculiarities of the data for a particular time period. By construction, parameters obtained by calibration are forced to absorb all the random errors present in the data for a single benchmark year. This poses a severe problem when the benchmark year is unusual in some respect. For example, parameters calibrated to the year 1973 would incorporate into the model all the distortions in energy markets that resulted from price controls and the rationing of energy during the first oil crisis. Econometric parametrization greatly mitigates this problem by reducing the influence of disturbances for a particular time period.

Empirical evidence on substitutability among inputs is essential in analyzing the impact of environmental and energy policies. If it is easy for industries to substitute among inputs, the effects of these policies will be very different than if substitution were limited. Although calibration avoids the burden of data collection required by econometric estimation, it also specifies the substitutability among inputs by assumption rather than relying on empirical evidence. This can easily lead to substantial distortions in estimating the effects of energy and environmental policies.

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24. Surveys of functional forms employed in modeling producer behavior have been presented by Fuss, McFadden, and Mundlak (1978), Jorgenson (1986), and Lau (1986).

An important feature of our production submodel is that an industry's productivity growth can be biased toward some inputs and away from others. Biased productivity growth is a common feature of historical data but is often excluded from models of production. By allowing for biased productivity growth, our model provides a separation between price-induced reductions in energy utilization and those resulting from changes in technology.[25] In addition, the rate of productivity growth

for each industry in our model is determined endogenously as a function of input prices. Other econometric models for analyzing energy and environmental policies, for example, Hazilla and Kopp (1990), Hudson and Jorgenson (1974), and Longva, Lorentsen, and Olsen (1983) exclude biases in productivity growth and take the rate of productivity growth to be exogenous.

Another important feature of our production submodel is that we allow for joint production. Accordingly, the price of an industry's output may differ from the price of its primary product. Recall our example that the textile industry produces both textiles and apparel, so that the price of the industry's output is a function of the prices of both the textile and apparel commodities. To capture this, we include a price function for each commodity, giving the price of that commodity as a function of the prices of the outputs of all industries that produce it. We parametrize these commodity price functions econometrically, using data from the make table shown in Figure 2.2.

Our models of producer behavior are based on two-stage allocation. At the first stage the value of each industry's output is allocated among four commodity groups-capital, labor, energy, and materials. We take the price of output to be a homothetically separable function of the prices of commodities within each of these

25. Dean (1992) has drawn attention to the fact that this separation is the key to differences in estimates of the costs of reducing carbon dioxide emissions among alternative models of the world economy.

groups. This price function must be homogeneous of degree one, nondecreasing, and concave in the input prices. These restrictions are incorporated into the system of input demand functions that we construct for each industry.[26]

At the second stage of our production models the value of the energy and materials aggregates is allocated among individual commodities. The price of energy is a function of the prices of coal, crude petroleum, refined petroleum, electricity, and natural gas. In order to limit the number of estimated parameters in the materials aggregate, we employ a hierarchical tier structure of ten subaggregates.[27] Wederive demands for inputs of capital and labor services and the thirty-five intermediate goods into each industry from the price function for that industry.

To present our production model more formally, we first require some notation. Let the thirty-five industries be indexed by *i*. We denote the quantity of output from industry *i* by $Z_i$ , and the quantities of inputs of capital, labor, energy and materials by $K_i$ , $L_i$ , $E_i$ and $M_i$ . Similarly, we denote the price of output from industry *i* by *qi,* and the prices of the four inputs *by* $p_K^i$, $p_L^i$, $p_E^i$ and $p_M^i$. Further, we define the shares of inputs in the value of output by:

$$v_K^i = \frac{p_K^i K_i}{q_i Z_i}, \quad v_L^i = \frac{p_L^i L_i}{q_i Z_i}, \quad v_E^i = \frac{p_E^i E_i}{q_i Z_i}, \quad v_M^i = \frac{p_M^i M_i}{q_i Z_i} .$$

We find it convenient to define the vector of input value shares for industry i as follows:

26. A more detailed discussion of our econometric methodology is presented by Jorgenson (1984a, 1986).
27. Two-stage allocation in the context of producer behavior is discussed in more detail by Jorgenson (1986) and Blackorby, Primont, and Russell (1978). The tier structure for our models of producer behavior is described by Wilcoxen (1988), Appendix A.

$$v_i = (v_K^i, v_L^i, v_E^i, v_M^i) .$$

Similarly, we define the vector of logarithms of input prices faced by the industry as:

$$\ln p_i = ( \ln p_K^i, \ln p_L^i, \ln p_E^i, \ln p_M^i )' .$$

We assume that industry *i* allocates the value of its output among the four inputs in accord with the translog price function:

$$\ln q_i = \alpha_0^i + \ln p_i{}'\alpha_p^i + \alpha_t^i g_i(t)$$
$$+ \frac{1}{2}\ln p_i{}'B_{pp}^i \ln p_i + \ln p_i{}'\beta_{pt}^i g_i(t) + \frac{1}{2}\beta_{tt}^i g_i^2(t) . \qquad (2.1)$$

The scalars $\alpha_0^i, \alpha_t^i, \beta_{tt}^i,$ the vectors $\alpha_p^i, \beta_{pt}^i,$ and the matrix $B_{pp}^i$ are unknown parameters that differ among industries, reflecting differences in technology. The function $g_i(t)$ contains additional unknown parameters and will be discussed in more detail below.

We can derive the value shares of inputs to industry *i* by differentiating the price function with respect to logarithms of the input prices to obtain:

$$v_i = \alpha_p^i + \beta_{pp}^i \ln p_i + \beta_{pt}^i g_i(t) .$$

The elements of $B_{pp}^i$ can be interpreted as *share elasticities* and represent the degree of substitutability among inputs. These parameters capture the price responsiveness of demands for energy and other inputs. The elements of $\beta_{pt}^i$ are *biases of productivity*

*growth* and represent the impact of changes in productivity on the value shares of the inputs.[28] These parameters incorporate "autonomous" improvements in the efficiency of utilization of energy and other inputs. By fitting both sets of parameters to historical data we are able to separate price-induced changes in input coefficients from those that result from changes in technology.

The limiting behavior of the function $g_i(t)$ presents a potential problem for long run simulations. In order for the price function to be homogeneous of degree one, the elements of $\beta_{pt}^{i}$ must sum to zero. If any of the elements is nonzero, there will be at least one negative element. Unless $g_i(t)$ remains bounded as *t* becomes large, the value share of the corresponding input will eventually become negative.[29] Accordingly, we take $g_i(t)$ to be logistic in form:

$$g_i(t) = \frac{1}{1 + e^{-\mu_i(t-\tau_i)}}, \qquad (2.2)$$

where the scalars $\mu_i$ and $\tau_i$ are unknown parameters which differ among industries. In the limit each of these functions goes to unity. Although this specification does not guarantee that the input value shares remain positive since extremely large elements of $\beta_{pt}^{i}$ could still cause problems, we have found that it does so in practice.

Equation (2.2) also solves a second potential problem in long run simulations. If productivity grows indefinitely, the existence of a balanced growth equilibrium requires that the rates of growth must eventually become the same for all industries.

Otherwise, the industry with the highest rate of productivity growth would eventually come to dominate the economy. In our model, productivity growth is limited.

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28. The translog price function was introduced by Christensen, Jorgenson, and Lau (1971, 1973). For further discussion of share elasticities and biases of productivity growth, see Jorgenson (1986).

29. This is often overlooked in modeling producer behavior, where it is customary to take these *functions* to be linear in time: g; (t)=t . See, for example, Jorgenson (1984a)

To show this we differentiate (2.1) with respect to time to obtain the endogenous rate of productivity growth in industry *i*, say $v_t^i$ *:*

$$-v_t^i = (\alpha_t^i + \beta_{pt}^{i\prime} \ln p_i + \beta_{tt}^i g_i(t))\, \dot{g}_i(t) \cdot$$

From the logistic formulation (2.2) it is dear that $g_i(t)$ goes to zero in the limit, so that the level of productivity in each industry approaches a constant. This formulation has the advantages of representing productivity growth during the sample period in a flexible way, while producing long run behavior of the economy consistent with balanced growth equilibrium.

The demand side of our model can be divided between intermediate and final demands for the thirty-five commodity groups, capital and labor services, and noncompeting imports presented in the use table, Figure 2.1. Our models of producer behavior determine value shares for inputs of commodities, primary factors of production, and noncompeting imports into each industry. These value shares incorporate an income-expenditure identity for the industry, since the value of output must be equal to the value of all inputs. The value shares determine inputs per unit of output as functions of the input and output prices. The input-output coefficients are multiplied by the output of the industry to obtain the input quantities. These quantities are added over the thirty-five industries to obtain total intermediate demands for each commodity group, capital and labor services, and noncompeting imports.

In summary, our model of producer behavior consists of two parts. The first is a set of thirty-five industry price functions and the second is a set of thirty-five commodity price functions. We have described how the industry price functions determine input demands and output prices in detail. The commodity price functions link output prices to commodity prices and determine the allocation of the output of each

commodity among industries. The industry price functions account for the industry columns in the use table, Figure 2.1, and the commodity price functions for the commodity columns in the make table, Figure 2.2. We turn next to modeling the final demand categories.

### 2.2. Consumer Behavior

Energy and environmental policies have different impacts on different households. For example, the imposition of a tax on energy would affect the relative prices faced by consumers. An increase in the price of energy resulting from the tax would adversely affect those consumers who devote a larger share of total expenditure to energy. To capture these differences among households, we have subdivided the household sector into demographic groups that differ by characteristics such as family size, age of head, region of residence, race, and urban versus rural location. We treat each household as a consuming unit, so that the household behaves like an individual maximizing a utility function.

We represent the preferences of each household by means of an econometric model of consumer behavior. Our models of consumer behavior incorporate time series data on personal consumption expenditures from the annual inter-industry transactions tables for the U.S. economy represented in Figure 2.1. The econometric approach for parametrization enables us to derive the response of household expenditure patterns to changes in prices from historical experience. Empirical evidence on substitutability among goods and services by households is essential in analyzing the impact of energy and environmental policies. If it is easy for households to substitute among commodities, the effects of these policies will be very different than if substitution were limited.

The econometric approach to modeling consumer behavior has the same advantages over the calibration approach as those we have described for modeling producer behavior. An additional feature of our models of consumer behavior is that they incorporate detailed cross section data on the impact of demographic differences among households and levels of total expenditure on household expenditure patterns. We do not require that consumer demands are homothetic, so that patterns of individual expenditure change as total expenditure varies, even in the absence of price changes. This captures an important characteristic of cross section observations on household expenditure patterns that is usually ignored in general equilibrium modeling. Finally, we aggregate over individual demand functions to obtain a system of aggregate demand functions. This makes it possible to dispense with the notion of a representative consumer.

Our econometric model of consumer behavior is based on two-stage allocation. We can summarize the representation of consumer behavior in terms of an indirect utility function for each household. At the first stage the household allocates total expenditure among five commodity groups- energy, food, nondurable goods, capital services, and other services. The indirect utility function must be homothetically separable in the prices of the commodities within each of these groups. This function must also be homogeneous of degree zero in prices faced by the household and total expenditure on all commodities. Finally, the function must be nonincreasing in the prices, nondecreasing in total expenditure, and quasi-convex in prices and expenditure. These restrictions are incorporated into the system of demand functions that we construct for each household.[30]

At the second stage of our model of consumer behavior, expenditure on each of the five commodity groups is allocated among labor and capital services and the

30. The particular form of our model follows Jorgenson and Slesnick (1987). For further discussion of our econometric methodology, see Jorgenson (1984a, 1990a).

individual commodities included in our model according to a hierarchical tier structure of demands. In order to keep the number of estimated parameters small we break up these commodity groups into a total of fifteen subaggregates.[31] As an example, the price of energy is a function of the prices of coal, refined petroleum, electricity, and natural gas. This results in a submodel of household energy consumption that is analogous to those employed in our econometric models of producer behavior.

To present the consumption model more formally, we require some additional notation. First, let the number of households be *J*, and the individual households be indexed *by j*.[32] Next, let the five commodity group *n* be indexed *by* $p_n$. We denote the price of commodity group n by $p_n$. Prices are assumed to be the same for all households. Similarly, we denote the quantity of commodity group *n* demanded by the household *j by* $x_{nj}$. In addition, if the total expenditure of consumer *j* is $Y_j$, the following budget constaint must hold:

$$Y_j = \sum_{n=1}^{5} p_n x_{nj} \cdot$$

To allow for differences in preferences among households, we allow the indirect utility function to depend on a vector of attributes denoted $A_j$. Further, we define the expenditure share of consumer *j* on commodity *n* by:

$$w_{nj} = p_n x_{nj} / Y_j \cdot$$

.

31. Two-stage allocation in the context of consumer behavior is discussed in more detail by Jorgenson, Slesnick, and Stoker (1987, 1988) and Blackorby, Primont, and Russell (1978). The tier structure for our model of consumer behavior is described by Wilcoxen (1988), Appendix A.
32. The number of households varies over the sample period 1947 through 1985, but is approximately one hundred million at the end of the period.

We find it convenient to define the vector of expenditure shares for consumer *j* as follows:

$$w_j = (w_{1j}, w_{2j} \cdots w_{5j})' .$$

Similarly, we define the vector of logarithms of prices faced by all consumers as:

$$\ln p = (\ln p_1, \ln p_2 \cdots \ln p_5)' .$$

Finally, we define the ratios of these prices to total expenditures for consumer *j* as:

$$\ln \frac{p}{Y_j} = ( \ln \frac{p_1}{Y_j}, \ln \frac{p_2}{Y_j} \cdots \ln \frac{p_5}{Y_j} )' .$$

We assume that household *j* allocates its total expenditure among the five commodity groups in accord with the translog indirect utility function:

$$\ln U_j = \ln(\frac{p}{Y_j})'\alpha_p + \frac{1}{2}\ln(\frac{p}{Y_j})'B_{pp} \ln(\frac{p}{Y_j}) + \ln(\frac{p}{Y_j})'B_{pA} A_j . \qquad (2.3)$$

The vector $\alpha_p$ and the matrices $B_{pp}$ and $B_{pA}$ re unknown parameters that are the same for all households. The vector of attributes $A_j$ incorporates differences in preferences among households. The elements of this vector are one-zero dummy variables that classify households by the demographic characteristics-family size, age of head, region of residence, race, and urban versus rural location. Cross-classifying households by these characteristics, we distinguish among a total of 672 different

household types-[33]

From the indirect utility function (2.3), we can derive the expenditure shares of household *j* using the logarithmic form of Roy's identity. This produces the following:

$$w_j = \frac{1}{B_j}( \alpha_p + B_{pp} \ln\frac{p}{Y_j} + B_{pA} A_j ) ,$$

where the denominator $B_j$ takes the form:

$$B_j = \iota'\alpha_p + \iota'B_{pp} \ln\frac{p}{Y_j} + \iota'B_{pA} A_j ,$$

and $\iota'$ is a vector of ones.

To derive a model of aggregate consumer behavior we assume that aggregate demand functions can be constructed from individual demand functions by exact aggregation. This requires that individual expenditure shares are linear in functions of the attributes $A_j$ and total expenditure $Y_j$ that vary among households. These conditions will be satisfied if and only if the terms involving the attributes and expenditures do not appear in the denominators of the individual expenditure shares. Thus, we require that:

$$\iota'B_{pp}\iota = 0 ,$$

---

33. There are seven categories for family size, *six* categories for age of head, four categories for region of residence, two categories for race, and two categories for urban versus rural location. For further details, see Jorgenson and Slesnick (1987). The translog indirect utility function was introduced by Christensen, Jorgenson, and Lau (1975). Surveys of functional forms employed in modeling consumer behavior have been presented by Blundell (1988), Deaton (1986), and Lau (1986).

$$\iota' B_{pA} = 0 .$$

In addition, we find it convenient to employ the normalization:

$$\iota' \alpha_p = -1.$$

The exact aggregation restrictions and the normalization given above imply that the denominators for individual households $B_j$, each reduce to:

$$B = -1 + \iota' B_{pp} \ln p ,$$

where the subscript *j* is no longer needed, since the denominator is the same for all households. Under these restrictions the individual expenditure shares can be written:

$$w_j = \frac{1}{B}( \alpha_p + B_{pp} \ln p - B_{pp} \iota \ln Y_j + B_{pA} A_j ) .$$

The individual expenditure shares are linear in the logarithm of expenditure $\ln Y_j$ and the attributes $A_j$ so we have satisfied the conditions for exact aggregation.

Aggregate expenditure shares, which we denote by *w*, are obtained by multiplying the individual expenditure shares by total expenditure for each household $Y_j$, adding over all households, and dividing by aggregate expenditure $\sum Y_j$ to give:

$$w = \frac{1}{B}( \alpha_p + B_{pp} \ln p - B_{pp} \iota \frac{\sum Y_j \ln Y_j}{\sum Y_j} + B_{pA} \frac{\sum Y_j A_j}{\sum Y_j} ) . \qquad (2.4)$$

The parameters of this system are precisely the same as those of the household demand equations. The parameters $B_{Pp}$ $B_{pp}$ esent the degree of substitutability among commodity groups within the household sector, while the parameters $B_{pA}$ reflect the $B_{pA}$ :t of changes in the demographic composition of the population and variations in relative expenditure levels for different demographic groups. Under homogeneity of degree zero, the vector $B_{pp}\iota$ captures the impact of changes in the level of aggregate expenditure and its distribution among households.

Unless preferences are homothetic, so that the elements of the vector $B_{pp}\iota$ are all zero, the composition of personal consumption expenditures varies with the level of aggregate expenditure and its distribution. Potentially, this could lead to a problem for long run simulations similar to the one we encountered in modeling production. If aggregate expenditure were to increase indefinitely, eventually one of the expenditure shares would become negative. In practice, however, two other features of the model limit the growth of total expenditure. First, industry productivity levels eventually become constant, so that per capita total expenditure converges to a stationary limit. Second, our projection of the future US population also converges to a stationary limit. This implies that aggregate expenditure eventually approaches a steady state value.[34]

The system of expenditure shares shown in (2.4) allocates total expenditure to five broad groups of consumer goods. Expenditure on each of these groups is then broken down to the level of individual commodities, using a nested tier structure similar to that we have used for production. Given prices and total expenditure, this system allows us to calculate the elements of personal consumption column in the make table of Figure 2.1. We employ the model to represent aggregate consumer behavior in simulations of the U.S. economy under alternative energy and

34. Projections of population and the long run behavior of the economy are discussed in greater detail below.

environmental policies.

To determine the level of total expenditure we embed our model of personal consumption expenditures in a higher-level system that represents consumer preferences between goods and leisure and between saving and consumption. At the highest level each household allocates *full wealth,* defined as the sum of human and nonhuman wealth, across time periods. We formalize this decision by introducing a representative agent who maximizes an additive intertemporal utility function, subject to an intertemporal budget constraint. The allocation of full wealth is determined by the rate of time preference and the intertemporal elasticity of substitution.

The allocation of full wealth to the current time period is *full consumption,* defined as an aggregate of goods and leisure. Given this allocation, each household proceeds to a second stage of the optimization process-choosing the mix of leisure and goods. We represent household preferences at this stage by means of a representative agent with an indirect utility function that depends on the prices of leisure and goods. We derive demands for leisure and goods as functions of these prices and the wealth allocated to the current period. This implies an allocation of the household's exogenously given time endowment between leisure time and the labor market, so that this stage of the optimization process determines labor supply.

Our higher level model of consumer behavior consists of two parts. At the highest level, we assume each household maximizes an additively separable intertemporal utility function:

$$U = \sum_{t=0}^{\infty} N_0 \prod_{s=1}^{t} \left( \frac{1+n_s}{1+\rho} \right) \ln F_t \ . \qquad (2.5)$$

where $F_t$ is a per capita full consumption in period $t$, $p$ *is* the rate of time preference, $N_o$ is the initial population, and $n_s$ is the population growth rate in period $s$ .

The household chooses the future path of full consumption *F* to maximize the intertemporal utility function $U$, subject to an intertemporal budget constraint. This requires that the present value of full consumption is no greater than household wealth. Wealth, in turn, is the present value of future earnings from the supply of capital and labor services, transfers from the government and the imputed value of leisure time. The conditions for optimality can be expressed in the form of an Euler equation. This equation gives the value of full consumption in one period in terms of the value of full consumption in the next period, the discount rate, and the rate of population growth.[35]

The Euler equation is forward-looking, so that the current level of full consumption incorporates expectations about all future prices and discount rates. The solution of our model includes this forward-looking relationship in every time period. The future prices and discount rates determined by the model enter full consumption for earlier periods through the assumption of perfect foresight or rational expectations. Under this assumption full consumption in every period is based on expectations about future prices and discount rates that are fulfilled by the solution of the model.

Once each period's full consumption has been found, we proceed to the second part of the representative agent household model. In this stage, the household divides the value of full consumption between personal consumption expenditures and leisure time. This has three effects. First, by determining the value of personal consumption expenditures it completes our model for household sector final demand. Second, the difference between the quantity of leisure consumed and the household's total time endowment determines the quantity of labor supplied.[36]

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35. The Euler equation approach to modeling intertemporal consumer behavior was originated by Hall (1978). Our application of this approach to full consumption follows Jorgenson and Yun (1990).

36. We assume the household has a single exogenous endowment of time which can be used for either labor or leisure. During the sample period, 1947 through 1985, we calculate the endowment by adjusting the population for educational attainment; for later periods, we employ the population projections of the Bureau of the Census and our own projections of future educational attainment.

Third, saving is determined by the difference between current income from the supply of capital and labor services and personal consumption expenditures. Labor market time is allocated among the thirty-five industries represented in the model by equating labor supply with the sum of labor inputs demanded by these industries. In addition, labor services are included in demands for personal consumption expenditures and public consumption. We assume that labor is perfectly mobile among sectors, so that the price of labor services is proportional to a single wage rate for the economy as a whole. The supply price of labor is the numeraire for our price system.

We model the household allocation decision by assuming that full consumption is an aggregate of goods and leisure. The share of each in full consumption depends on the price of consumption goods, the price of leisure, and the household's share elasticity between the two. We take the price of consumption goods to be the cost of living index generated from the first stage of our model of consumer behavior by Jorgenson and Slesnick (1990). We take the price of leisure time to be the wage rate less the marginal tax rate on labor income.

Our model of consumer behavior allocates the value of full consumption between personal consumption expenditures and leisure time. Given aggregate expenditure on goods and services and its distribution among households, this model then allocates personal consumption expenditures among commodity groups, including capital and labor services and noncompeting imports. Finally, the income of the household sector is the sum of incomes from the supply of capital and labor services, interest payments from governments and the rest of the world, all net of taxes, and transfers from the government. Savings are equal to the difference between income and consumption, less personal transfers to foreigners and nontax payments to governments. This is the income-expenditure identity of the household sector.

In summary, our model of household behavior consists of three stages. First, it includes a system of expenditure share equations derived from maximization of a household utility function and satisfying conditions for exact aggregation. Second, it includes a higher level representative agent model that determines the intertemporal allocation of consumption through an Euler equation derived from maximization of an intertemporal utility function. Third, the representative agent model also allocates full consumption between goods and leisure, determining personal consumption expenditures, labor supply, and saving.

### 2.3. Investment and Capital Formation

Our investment model, like our model of saving, is based on perfect foresight or rational expectations. Under this assumption the price of investment goods in every time period is based on expectations of future capital service prices and discount rates that are fulfilled by the solution of the model. In particular, we require that the price of new investment goods is always equal to the present value of future capital services.[37] The price of investment goods and the discounted value of future rental prices are brought into equilibrium by adjustments in future prices and rates of return. This incorporates the forward-looking dynamics of asset pricing into our model of intertemporal equilibrium.

For tractability we assume there is a single capital stock in the economy which is perfectly malleable and mobile among sectors, so that it can be reallocated among industries and final demand categories at zero cost. Under this assumption changes in energy and environmental policy can affect the distribution of capital and labor supplies among sectors, even in the short run. However, the total supply of capital

37. The relationship between the price of investment goods and the rental price of capital services is discussed in greater detail by Jorgenson (1989).

in our model in each time period is perfectly inelastic, since the available stock of capital is determined by past investments. An accumulation equation relates capital stock to investments in all past time periods and incorporates the backward-looking dynamics of capital formation into our model of intertemporal equilibrium.

Since capital is perfectly malleable, the price of capital services in each sector is proportional to a single price of capital services for the economy as a whole. This rental price balances each period's supply with the sum of demands by all thirty-five industrial sectors together with the demand for personal consumption. Our model gives the price of capital services in terms of the price of investment goods at the beginning and end of each period, the rate of return to capital for the economy as a whole, the rate of depreciation, and variables describing the tax structure for income from capital. The income from capital in each period is equal to the value of capital services.

New capital goods are produced from the individual commodities included in our model. Each new unit of capital is an aggregate of commodities purchased for investment in producers' and consumers' durables, residential and nonresidential structures, and inventories. We have represented the technology for production of new capital goods by means of a price function for investment goods. We have estimated the unknown parameters of this investment submodel from time series data on gross private domestic investment from the annual inter-industry tables for the US economy represented in the use table, Figure 2.1. As with our model of producer behavior, we use a nested tier structure of submodels to capture substitution among different inputs in the construction of new capital.M

The behavioral equations for our model include a system of demand functions for investment goods by business and household sectors. The business sector

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38. The tier structure for our model of production for new capital goods is presented by Wilcoxen (1988), Appendix A.

purchases goods for investments in producers' durables, residential and nonresidential structures, and inventories. The household sector purchases goods for investments in consumers' durables and residential structures. We generate value shares for all types of investment goods from the price function for new capital goods. We use these value shares to allocate the value of investment goods among commodity groups, resulting in the final demands for gross private domestic investment given in the use table, Figure 2.1. Finally, we determine the quantity of each commodity by dividing the value of investment in that commodity by the corresponding price.

Our investment submodel allocates gross private domestic investment among commodity groups. The value of this investment must be equal to savings. The balance sheet identity of the household sector sets private wealth equal to the sum of the value of capital stock in the private sector, claims on governments, and claims on the rest of the world. The change in the value private wealth from period to period is the sum of private savings and the revaluation of wealth as the result of inflation.

In summary, capital formation in our model is the outcome of intertemporal optimization by producers. Optimization by producers is forward-looking and incorporates expectations about future prices and rates of return. Optimization by consumers is also forward-looking and depends on these same expectations. Both types of optimization are very important for modeling the impact of future energy and environmental policies. The effects of these policies will be anticipated by producers and consumers, so that future policies will have important consequences for current decisions.

### 2.4. Government and Foreign Trade

The two remaining final demand categories in our model are the government and rest of the world sectors. We determine final demands for government

consumption from the income-expenditure identity for the government sector.[39] The first step is to compute total tax revenue by applying exogenous tax rates to all taxable transactions in the economy. We then add the capital income of government enterprises, which is determined endogenously, and nontax receipts, determined exogenously, to tax receipts to obtain total government revenue.

The key assumption of our submodel of the government sector is that the government budget deficit can be specified exogenously. We add the deficit to total revenue to obtain total government spending. To arrive at government purchases of goods and services, we subtract interest paid to domestic and foreign holders of government bonds together with government transfer payments to domestic and foreign recipients. We allocate the remainder among commodity groups according to fixed shares constructed from historical data. Finally, we determine the quantity of each commodity by dividing the value of government spending on that commodity by its price.

Foreign trade has two quite different components-imports and exports. We assume that imports are imperfect substitutes for similar domestic commodities.[40] The goods actually purchased by households and firms reflect substitutions between domestic and imported products. The price responsiveness of these purchases is estimated from historical data taken from the import and export columns of the use table, Figure 2.1, in our annual inter-industry transactions tables. In addition, the allocations of domestic supplies between domestic and imported commodities incorporate logistic time trends that capture determinants other than relative prices. The logistic functions approach unity in the limit, so that these trends eventually

39. Our treatment of government spending differs from the US national accounts in that we have assigned government enterprises to the corresponding industry wherever possible. We include the remaining purchases by the government sector in final demands by governments.
40. This approach was originated by Armington (1969). See Wilcoxen (1988) and Ho (1989) for further details on our implementation of this approach.

disappear. Since the prices of imports are given exogenously, the sum of intermediate and final demands implicitly determines quantities of imports of each commodity.

Exports, on the other hand, are modeled by a set of explicit foreign demand equations, one for each commodity, that depend on exogenously given foreign income and the foreign price of US exports. Foreign prices are computed from domestic prices by adjusting for subsidies and the exchange rate. The demand elasticities in these equations are estimated from historical data. Our model incorporates the income-expenditure identity of the rest of the world sector. The current account surplus is equal to. the value of exports less the value of imports, plus interest received on domestic holdings of foreign bonds, less private and government transfers abroad, and less interest on government bonds paid to foreigners. The key assumption of our submodel of the rest of the world sector is that the current account is exogenous and the exchange rate is endogenous.

In summary, final demands by governments are determined by first generating government revenues. Total expenditure is then determined from the incomeexpenditure identity of the government sector. The allocation of this expenditure among commodity groups is given exogenously. Final demands by the rest of the world are determined by modeling import demands and export supplies separately. The current account balance from the income-expenditure identity for the rest of the world sector is taken to be exogenous, so that the exchange rate is determined by the equilibrium of the model.

### 2.5. Constructing the Base Case

In order to analyze the impact of changes in energy and environmental policies, we simulate the growth of the US economy with and without changes in these policies.[41] Our first step is to generate a simulation with no changes in policy that we

41. Our solution method is described in Wilcoxen (1988), Appendix E. Methods for solving intertemporal general equilibrium models are surveyed in detail by Wilcoxen (1992).

call the *base case.* The second step is to change the exogenous variables of the model to reflect a proposed policy change. We then produce a simulation that we refer to as the *alternative case.* Finally, we compare the two simulations to assess the effects of the change in policy. Obviously, the assumptions underlying the base case are of considerable importance in interpreting the results of our simulations.

We conclude this overview by outlining the solution of our model. An intertemporal submodel incorporates backward-looking and forward-looking equations that determine the time paths of capital stock, full consumption, and the price of assets. Given the values of these variables in any time period, an intratemporal submodel determines prices that balance demands and supplies for the thirty-five commodity groups included in the model, capital and labor services, and noncompeting imports. These two submodels must be solved simultaneously to obtain a complete intertemporal equilibrium.

To construct a simulation of US economic growth we first require the values of all exogenous variables in every time period. These variables are set equal to their historical values for the sample period, 1947 through 1985. We project the values for all exogenous variables for the post-sample period 1986 through 2050. After 2050 we assume that these variables remain constant at their values in 2050, which allows the model to converge to a steady state by the year 2100. The most important exogenous variables are those associated with US population growth and the corresponding change in the time endowment of the US economy. We project population by age, sex and educational attainment through the year 2050, using demographic assumptions consistent with Bureau of the Census projections.[42]

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42. Our breakdown of the US population by age, educational attainment, and sex is based on the system of demographic accounts compiled by Jorgenson and Fraumeni (1989). The population projections are discussed in detail by Wilcoxen (1988), Appendix B.

After 2050 we hold population constant, which is roughly consistent with Census Bureau projections. We project educational attainment by assuming that future demographic cohorts will have the same level of attainment as the cohort reaching age 35 in the year 1985. We then transform our population projection into a projection of the time endowment used in our model of the labor market by assuming that relative wages across all categories of workers are constant at 1985 levels. Since capital accumulation is endogenous, these population projections effectively determine the size of the economy in the more distant future.

Next, we consider exogenous components of our submodels of the government and rest of the world sectors. We set all tax rates to their values in 1985, the last year in our sample period. We project a gradual decline in the government deficit through the year 2025, after which the deficit is held at four percent of the nominal value of the government debt. This has the effect of maintaining a constant ratio of the value of the government debt to the value of the national product when the inflation rate is four percent, as it is in our steady state. We assume that prices of imports in foreign currency and before tariffs remain constant in real terms at 1985 levels. Our projections of the current account deficit fall gradually to zero by the year 2000. After that we project a small current account surplus sufficient to produce a stock of net claims on foreigners by the year 2050 equal to the same proportion of national wealth as in 1982.

Given projections of the exogenous variables of our model of the US economy, we can divide the simulation of US economic growth into two steps. The first step is to construct a stationary solution corresponding to constant values of all exogenous variables. In the stationary solution both full consumption and capital stock are constant. We determine the stationary rate of return from the Euler equation from our model of consumer behavior. Similarly, we determine the stationary level of investment from our accumulation equation for capital stock. We take this stationary

solution to be our projection of the US economy for all years after 2100.

Our second step in the generation of a simulation is to construct a transition path to the steady state of our model, beginning with the initial level of capital stock. For this purpose we combine the solutions of our intertemporal and intratemporal models. Our intertemporal model determines time paths of full consumption, capital stock, and the price of new capital goods. These time paths are consistent with the forward-looking Euler equation from our model of consumer behavior and the asset pricing equation from our model of investment behavior. The model also determines the time path of capital stock consistent with the backward-looking accumulation equation for capital stock.

The solution of our intratemporal model determines prices for outputs of the thirty-five industries as functions of the prices of capital and labor services and noncompeting imports. These output prices are determined from the industry price functions included in our submodel of the business sector. Given these prices, the domestic supply prices for the thirty-five commodities included in this submodel are determined from the commodity price functions. Finally, the domestic supply price for each commodity is combined with the price of imports to determine the total supply price for each commodity. These prices enter the determination of intermediate demands by all industries and final demands by business, household, government, and rest of the world sectors.

The prices of competing and noncompeting imports are given exogenously in every time period. The prices of capital and labor services are determined by balancing demands and supplies for these services. The supply of capital services is determined by previous investments and is taken as given in each period. The supply of labor services is determined endogenously within our model of consumer behavior. This model allocates full consumption in each period between personal consumption expenditures and leisure time. The model also allocates the exogenously given time

endowment between the labor market and leisure time.

Our intratemporal model also guarantees that income-expenditure identities for all thirty-five industries and the household, government, and the rest of the world sectors are satisfied. These identities imply that gross private domestic investment is equal to private savings plus the current account deficit less the government budget deficit. Since we take the government and current account deficits to be exogenous, changes in gross private domestic investment are driven by changes in private savings. Thus, changes in the rate of capital accumulation depend on changes in private savings and the price of investment goods.

It is interesting to contrast the behavior of our model with that of a one-sector neo-classical growth model. In the short run the supply of capital in our model is perfectly inelastic since it is completely determined by past investment. In the long run, however, the supply of capital is perfectly elastic, since the rate of return depends only on productivity growth and parameters that describe the intertemporal preferences of the household sector. Thus, in the long run the rate of return in our model is independent of energy and environmental policy, just as in a one-sector neo-classical growth model. Since our model has many sectors, however, different policies result in different levels of capital intensity, all corresponding to the same rate of return. This is impossible in a one-sector model.

In summary, we construct a simulation of US economic growth by solving our model for given values of all exogenous variables in all time periods. First, we solve an intertemporal submodel that contains forward-looking equations determining the time paths of asset prices and full consumption. This submodel also includes a backward-looking equation determining the time path of capital stock from past investments. Given the values of these variables, our intratemporal or one-period submodel determines prices that balance demand and supply for the thirty-five commodity groups included in the model, capital and labor services, and noncompeting

imports. We solve the two submodels simultaneously to obtain the full intertemporal equilibrium.

## 3. THE IMPACT OF ENVIRONMENTAL REGULATION

Our next objective is to assess the impact of environmental regulations introduced in the 1970's and early 1980's. Our approach will be to use the model of Section 2 to simulate the growth of the US economy with and without regulation. We begin by observing that our base case implicitly includes environmental regulation since it is based on historical data. Thus, to determine the effect of regulation we conduct counterfactual simulations in which regulation is removed from the economy. In addition, we decompose the overall effect of regulation into components associated with both pollution control in industry and controls on motor vehicle emissions. We conclude by estimating the overall impact of environmental regulation by eliminating both types of pollution control.

Removing environmental regulation produces simulations which differ from the base case at the steady state, at the initial (first year) equilibrium, and along the transition path between the two. The difference between the new steady state and the base case shows the long run impact of environmental regulation after the capital stock has adjusted. The difference between the new initial equilibrium and the base case gives the short run impact of a change in policy before the capital stock can adjust at all. However, since agents in the model have perfect foresight, this initial equilibrium reflects changes along the entire time path of future regulatory policy. Finally, the transition path between the initial equilibrium and the steady state traces out the economy's adjustment to the new environmental policy.

In presenting the results of our simulations we begin by quantifying the impact of pollution controls on production costs. We then incorporate these cost changes into the model and run counterfactual simulations. In interpreting the simulation results, we first consider the impact of environmental regulation on the steady state of the economy, concentrating our analysis on a few key variables. Next, we analyze

the transition path of economy from the initial equilibrium to the new steady state. We focus particular attention on the path of capital stock, since it is the most important overall measure of the effect of the change in policy. We also discuss a number of other important variables including the price of investment goods, the rental price of capital services and the level of the gross national product (GNP).

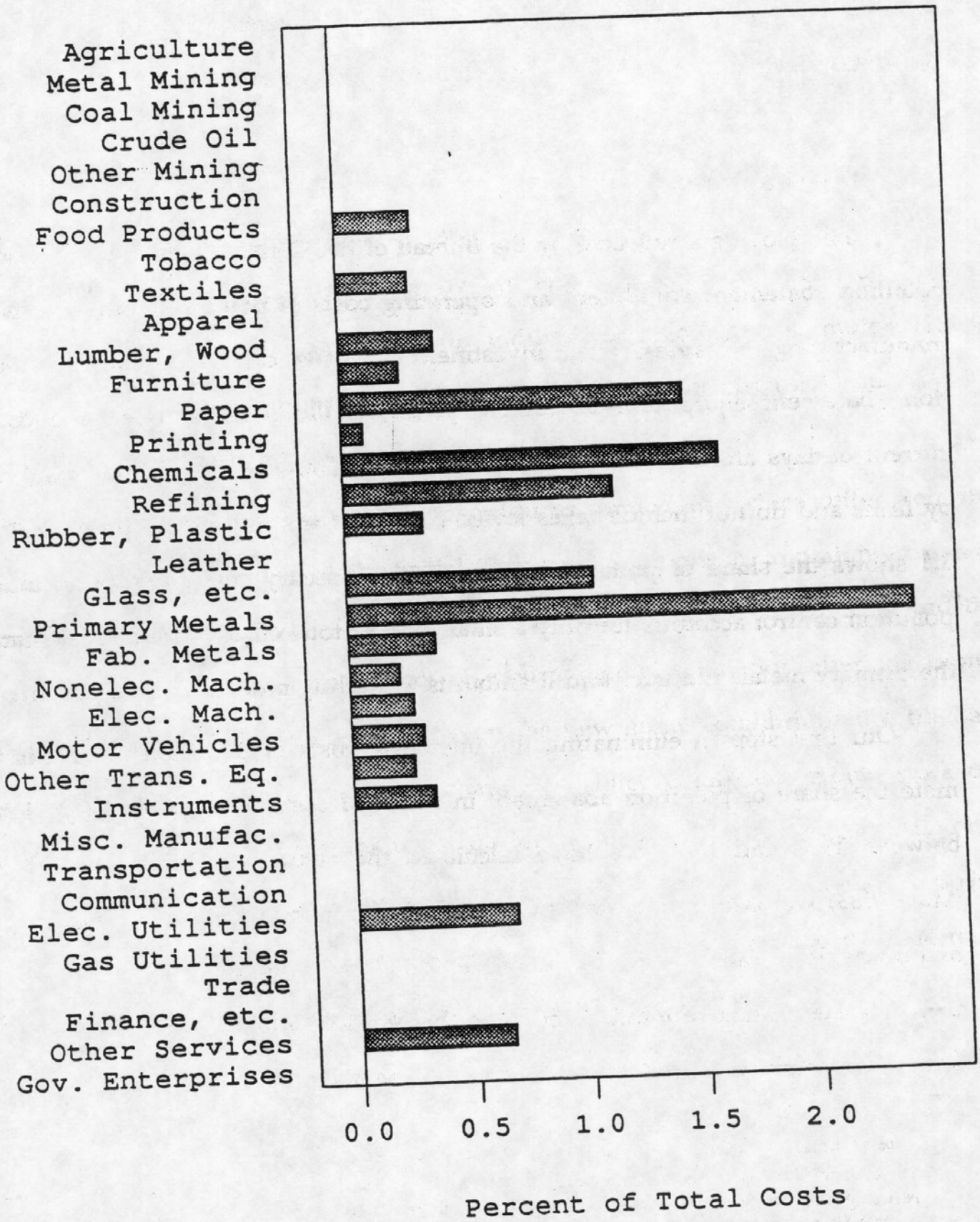
### 3.1. Operating Costs

We employ data collected by the Bureau of the Census to estimate investment in pollution abatement equipment and operating costs of pollution control activities for manufacturing industries.[43] The investment data give capital expenditures on pollution abatement equipment in current prices, while data on operating costs give current outlays attributable to pollution control. These are the actual costs reported by firms and do not include taxes levied as part of the Superfund program.` [4] Figure 3.1 shows the share of pollution abatement in industry costs. For most industries, pollution control accounts for only a small part of total costs. The largest share is for the primary metals industry and it amounts to slightly more than two percent.

Our first step in eliminating the operating costs of pollution control is to estimate the share of pollution abatement in the total costs of each industry. For years between 1973 and 1985, we have calculated the actual share from historical data. After 1983, we assume that the share remained constant at its 1983 value. Outside manufacturing, data were only available for electric utilities and wastewater treatment (wastewater treatment is part of the services industry). For both of these industries, data on operating costs and investment expenditures for pollution

43. The Census data come from various issues of the annual publication, *Pollution Abatement Costs and Expenditures.* A detailed description of our data is given by Wilcoxen (1988), Appendix D.
44. Superfund taxes amounting to more than a billion dollars a year were placed on the petroleum refining and chemicals industries in 1981 and on the primary metals industry in 1986. These may have had a substantial impact on US economic growth, but we do not examine their consequences in this chapter.

Figure 3.1: Abatement Costs by Industry



abatement are available from the Bureau of Economic Analysis-[45]

For electric utilities, the Bureau of Economic Analysis also estimates the extra cost of burning low-sulfur fuels to comply with sulfur dioxide regulations. The principal low-sulfur fuel used by utilities is low-sulfur coal. In terms of our model, switching from high-sulfur to low-sulfur coal changes the relative proportions of the two products in the output of the coal industry. Since low-sulfur coal is more expensive when transportation costs are included, this increases the price of coal. Eliminating regulations on sulfur emissions would lower the price of coal by permitting substitution toward high-sulfur grades. We model the impact of lifting these restrictions by subtracting the differential between high cost and low cost coal from the cost of coal production.[46]

Twenty of the thirty-five industries in our model are subject to pollution abatement regulations. We use the share of abatement costs in total costs for each industry to compute the share of total costs excluding pollution abatement. Let the share for industry *i* be denoted $\lambda_i$. Since our data set on pollution abatement ends in 1983, we assume the shares for later years are constant at their 1983 values. To simulate the effect of eliminating the operating costs associated with pollution abatement we insert the cost shares $\lambda_i$ into the cost function for each industry. More precisely, we modify the translog price functions as follows:

$$\ln q_i = \ln \lambda_i + \alpha_0^i + \ln p_i{}' \alpha_p^i + \alpha_t^i g_i(t)$$
$$+ \frac{1}{2} \ln p_i{}' B_{pp}^i \ln p_i + \ln p_i{}' \beta_{pt}^i g_i(t) + \frac{1}{2} \beta_{tt}^i g_i^2(t) .$$

45. Further details are given by Wilcoxen (1988), Appendix D.
46. Details of our methodology for estimating cost differentials between high-sulfur and low-sulfur coal are given by Wilcoxen (1988), Appendix D.

This has the effect of excluding operating costs associated with pollution control from total costs in each industry.

The long run impact of eliminating the operating costs of pollution abatement is summarized in the column labeled ENV in Table 3.1. The output of the economy, as measured by the gross national product, rises by .728 percent. Much of this comes from an increase-in. the capital stock which rises by savings in the long run, the rate of return is unaffected by regulation. However, the price of new investment goods falls by the price of capital services. Cheaper capital services lead to a fall in the prices of goods and services and a rise in full consumption by .278 percent. This increase is less than that of gross national product, since full consumption includes leisure time as well as personal consumption expenditures. Finally, the exchange rate, which gives the domestic cost of foreign goods, falls slightly, indicating an increase in the international competitiveness of the US economy.[47]

The long run effects of eliminating operating costs associated with pollution abatement on the prices and outputs of individual industries are shown in Figure 3.2. Figure 3.2(a) shows the percentage change in the steady state purchaser's price of each commodity while Figure 3.2(b) gives percentage changes in industry output levels. Not surprisingly, the principal beneficiaries of eliminating operating costs are the most heavily regulated industries. The greatest expansion of output occurs in coal production, since the fuel cost differential between low-sulfur and high-sulfur coal is large relative to the total costs of the coal industry. Turning to manufacturing industries, primary metals, paper, and chemicals have the largest gains in output from the elimination of operating costs for pollution abatement. Several other sectors benefit from the removal of operating costs of pollution abatement, but the impact is fairly modest.

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47. An alternative analysis of the impact of environmental regulation on US international competitiveness is given by Kalt (1988).

Table 3.1: The Effects of Removing Environmental Regulation

| Variable | Percentage Change in Steady State | | | |
|---|---|---|---|---|
| | ENV | INV | MV | ALL |
| Capital Stock | .544 | 2.266 | 1.118 | 3.792 |
| Price of Investment Goods | -.897 | -2.652 | -1.323 | -4.520 |
| Full Consumption | .278 | .489 | .282 | .975 |
| Real GNP | .728 | 1.290 | .752 | 2.592 |
| Rental Price of Capital | -.907 | -2.730 | -1.358 | -4.635 |
| Exchange Rate | -.703 | -.462 | -.392 | -1.298 |

Figure 3.2(a): Effect of ENV on Prices

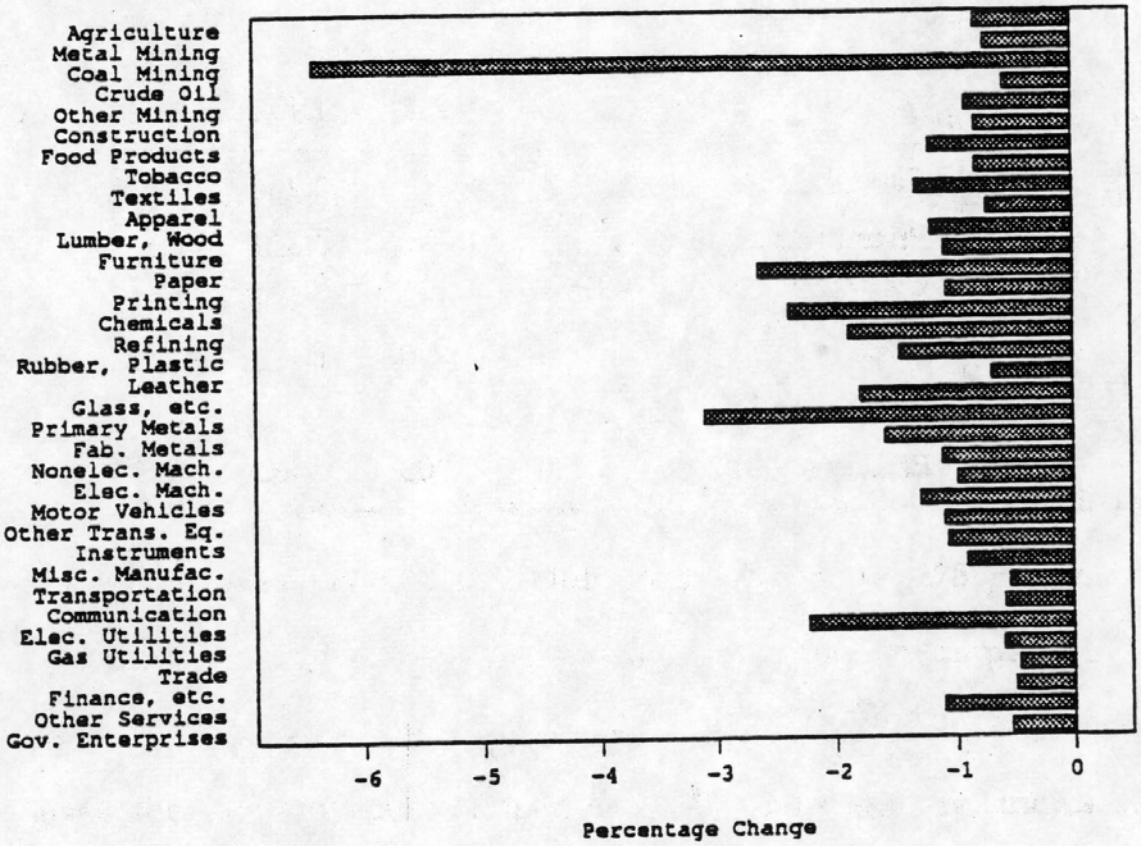
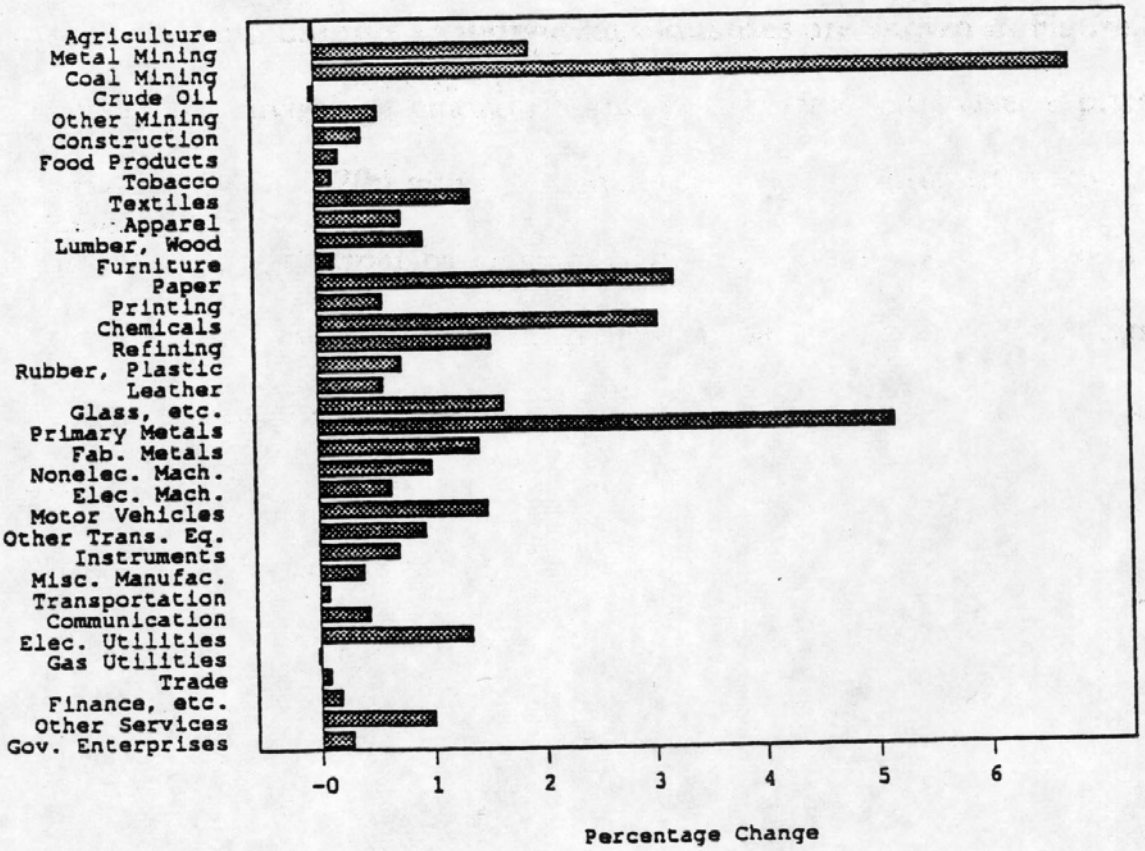



Figure 3.2(b): Effect of ENV on Output



We now turn from the long run impact of eliminating operating costs to its dynamic effects. Figure 3.3 shows the effects of removing operating costs on the time paths of full consumption, the price of new capital goods, the capital stock and the level of gross national product. After 1973, the price of investment goods falls slowly, reflecting the gradual price decline brought about by the elimination of operating costs associated with increasingly stringent re tions. Lower costs of investment goods tend to increase the rate of return, stimulate savings, and produce more rapid capital accumulation. Additional capital eventually brings down the rental price of capital, lowering costs still further. This, in turn, raises the level of GNP.

The transition from the short run to the steady state is relatively slow, requiring almost three decades for the capital stock to adjust to the change in environmental policy. Figure 3.3(c) shows that the adjustment process is not complete until the year 2000. In part this reflects the nature of the experiment: the actual regulations were imposed gradually, so their removal is also gradual. On the other hand, full consumption attains its final value fairly quickly as a consequence of intertemporal optimization by households. Since income is permanently higher in the future, consumption rises in anticipation. However, the rise of consumption is dampened by an increase in the rate of return that produces greater investment.

### 3.2. Investment in Pollution Control Equipment

For some industries the most important impact of environmental regulation is through mandatory investment in costly pollution abatement equipment. Investment in pollution control devices crowds out investment for ordinary capital accumulation, reducing the rate of economic growth. Our second simulation is designed to assess the impact of this investment.

Figure 3.3(a): Full Consumption

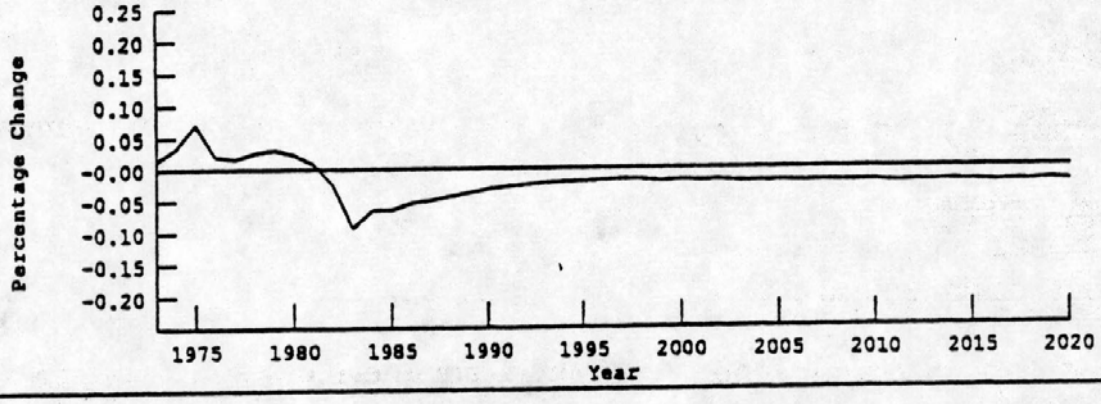



Figure 3.3(b): Price of Investment Goods

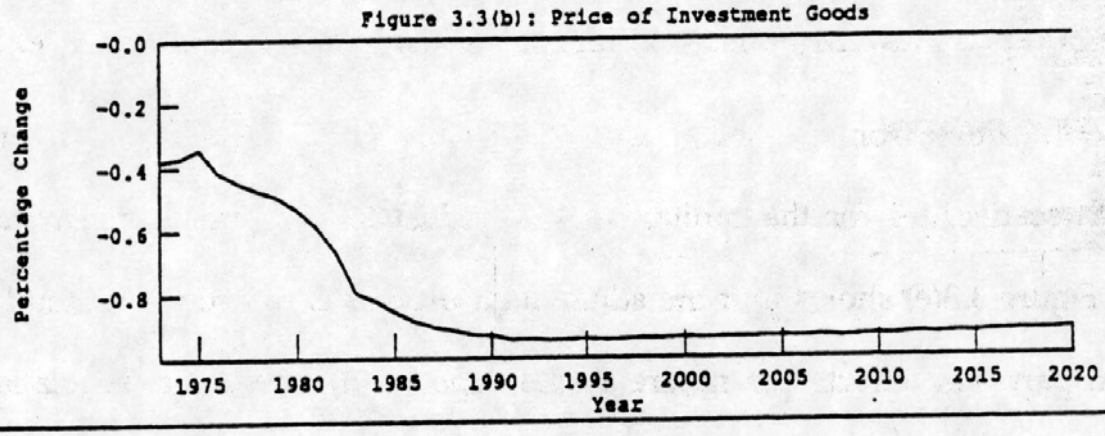



Figure 3.3(c): Capital Stock

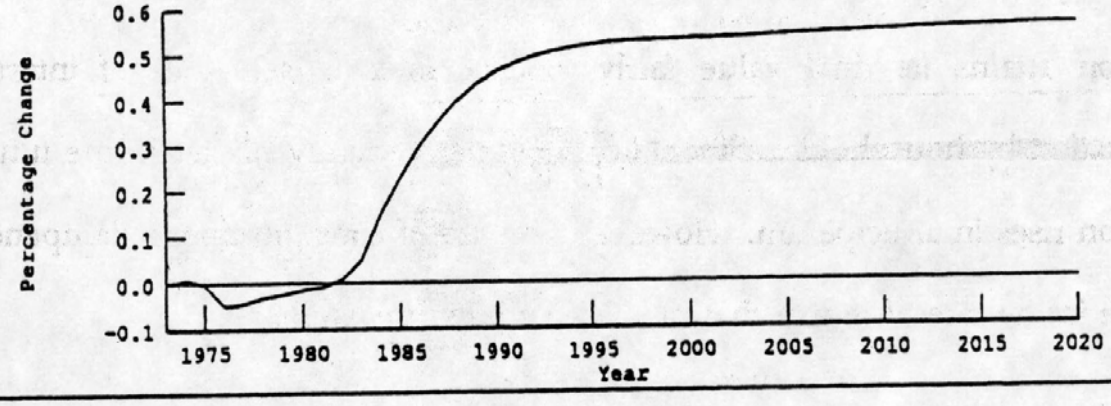
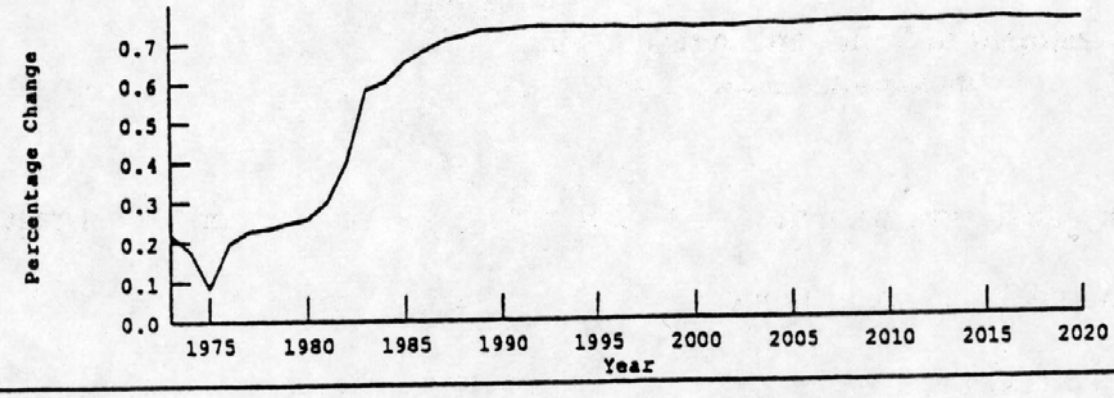



Figure 3.3(d): Real GNP



The share of pollution control in total investment rose to a peak in the early 1970's and then declined substantially. This can be attributed to the fact that much of the early effort in pollution control was directed at reducing emissions from existing sources by retrofitting equipment already in place. Later, restrictions on emissions from new sources became more important. New source regulations increase the cost of new investments because producers are required to purchase pollution abatement equipment whenever they acquire new investment goods. The economic effects of retrofitting are quite different from investment in new source control, so we distinguish between the two in constructing our counterfactual simulation.

We begin by assuming that investment in pollution control equipment provides no benefits to producers other than satisfying environmental regulations. Accordingly, we simulate mandated investment as an increase in the price of investment goods. Unfortunately, our dataset does not distinguish between investments required for new and existing facilities. To separate the two, we assume the backlog of investment for retrofitting old sources was eliminated by 1983. This allows us to infer that the 1983 share of pollution abatement devices in total investment was due entirely to new investment. Thus, we can simulate the impact of removing environmental regulations on new investment by reducing the price of investment goods by that proportion. This captures the effect of requirements for pollution abatement on investment in new capital goods, but does not include the effect of windfall losses to owners of the capital associated with old sources of emissions.

This approach has certain limitations that should be pointed out. First, it relies on the assumption that capital is completely malleable and mobile between sectors. An alternative technique would be to incorporate costs of adjustment into our models of producer behavior. However, this approach would lead to considerable additional complexity in modeling and simulating producer behavior. Moreover, the long run impact of environmental regulations would be unaffected by costs of adjustment,

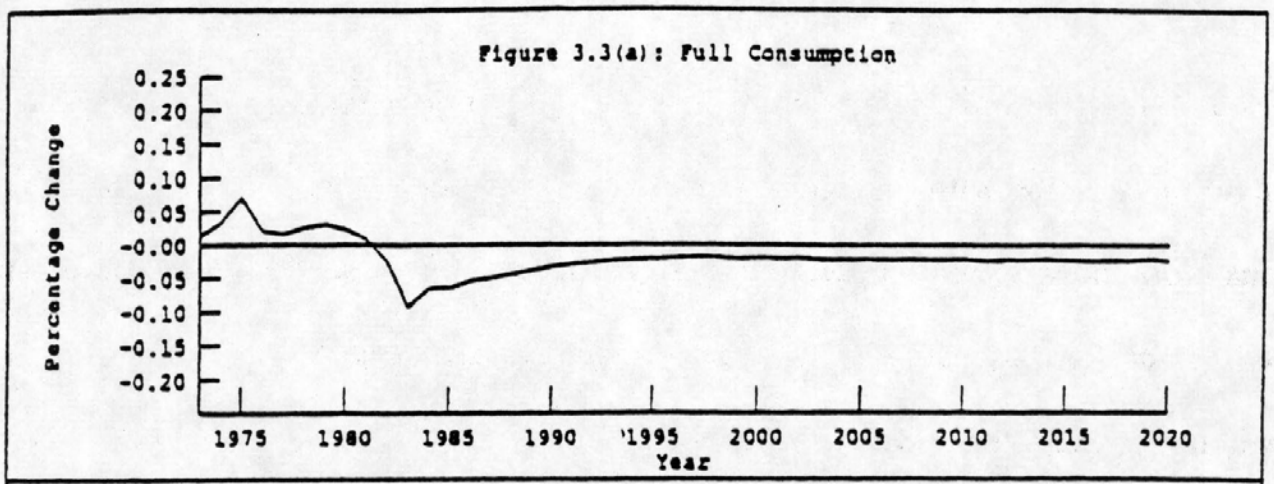


Figure 3.3(a): Full Consumption
Percentage Change
0.25
0.20
0.15
0.10
0.05
-0.00
-0.05
-0.10
-0.15
-0.20
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

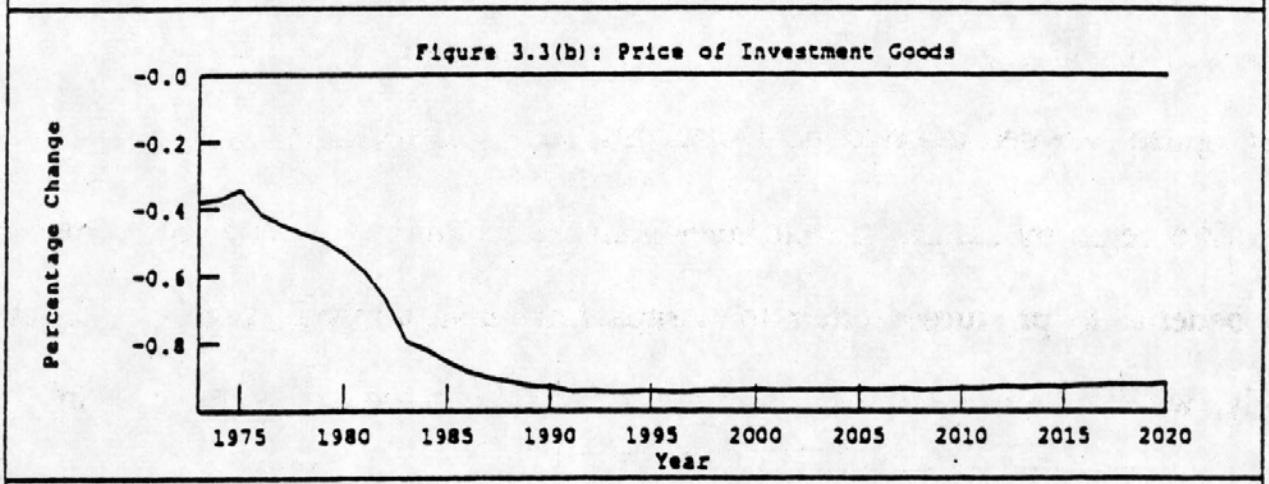


Figure 3.3(b): Price of Investment Goods
Percentage Change
-0.0
-0.2
-0.4
-0.6
-0.8
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

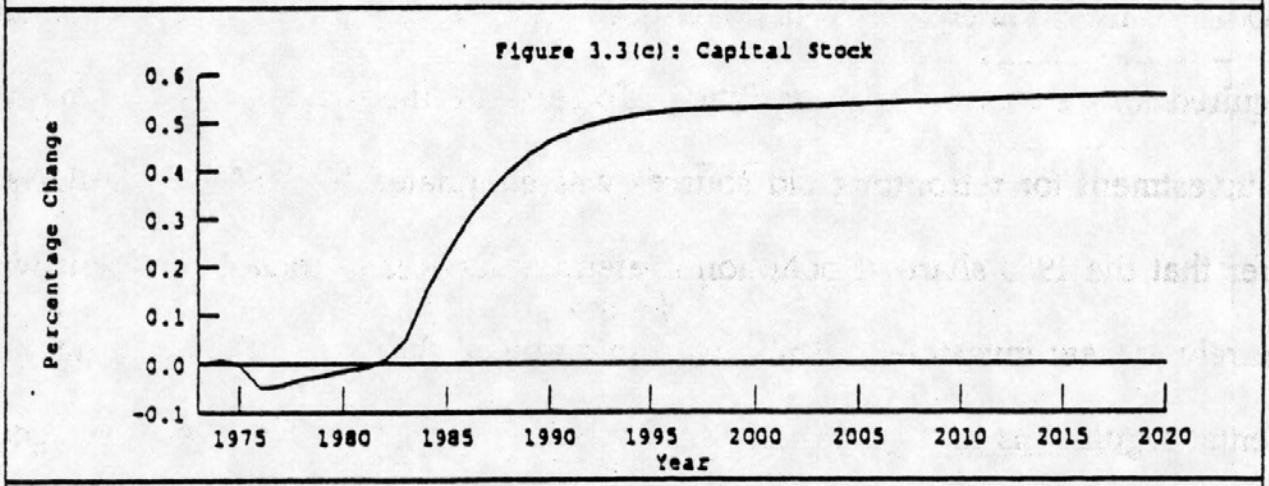


Figure 3.3(c): Capital Stock
Percentage Change
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

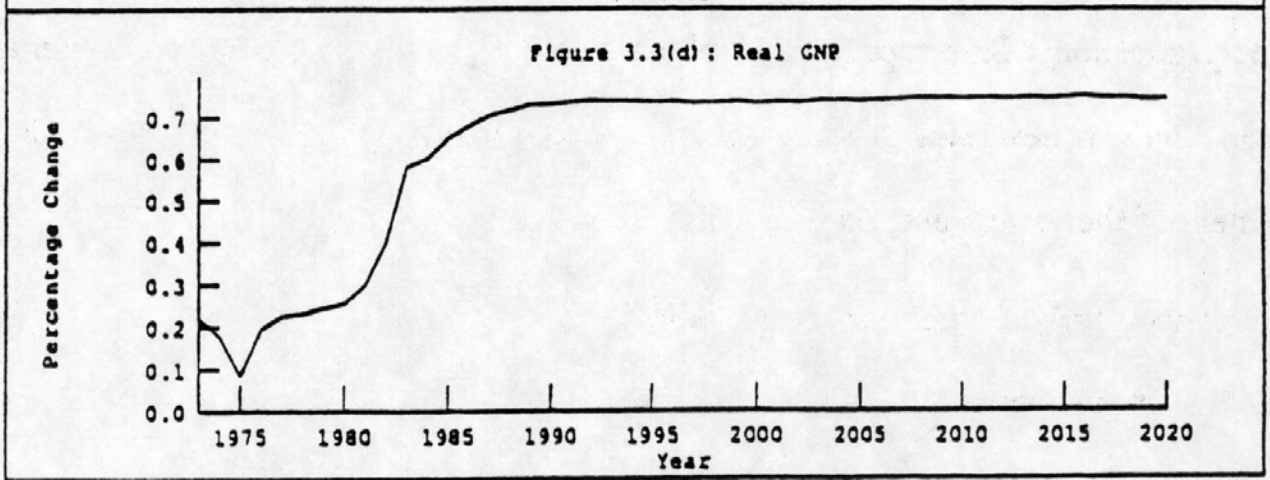


Figure 3.3(d): Real GNP
Percentage Change
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

Figure 3.4(a): Effect of INV on Prices

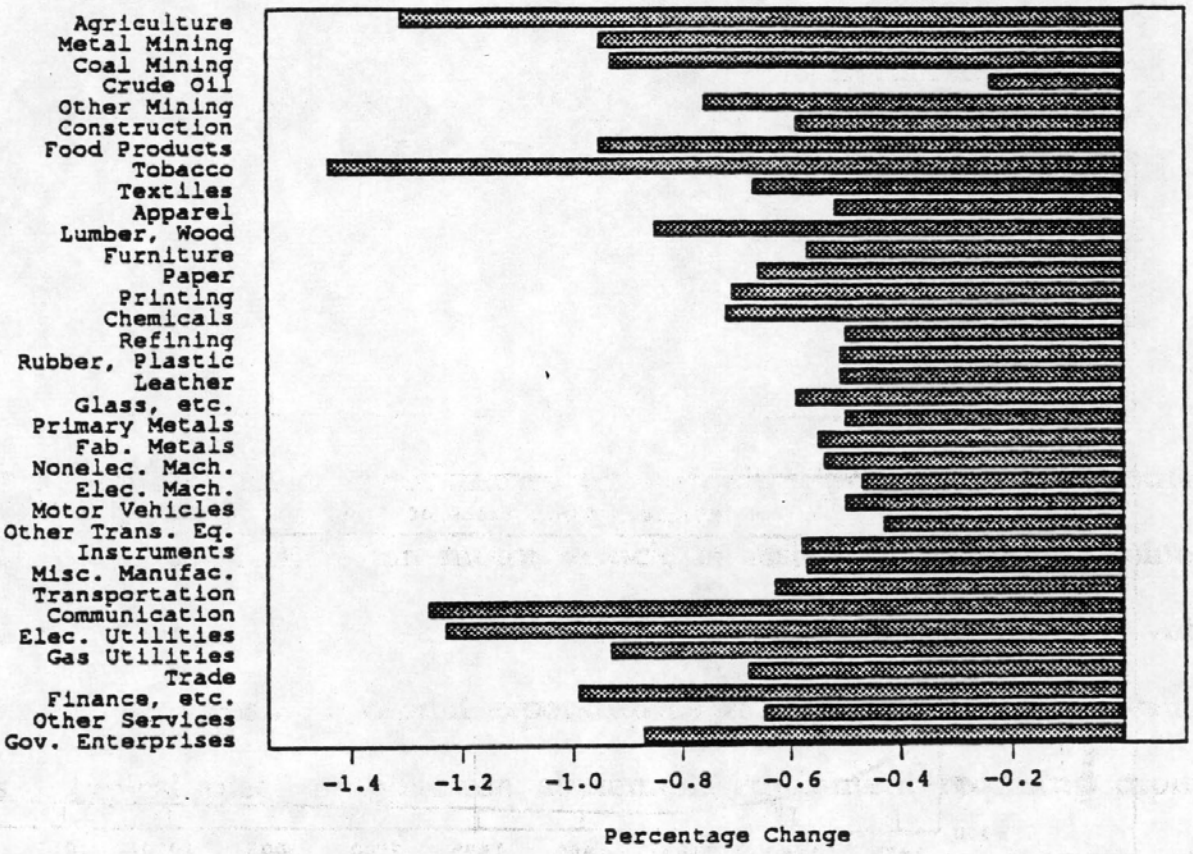



Figure 3.4(b): Effect of INV on Output

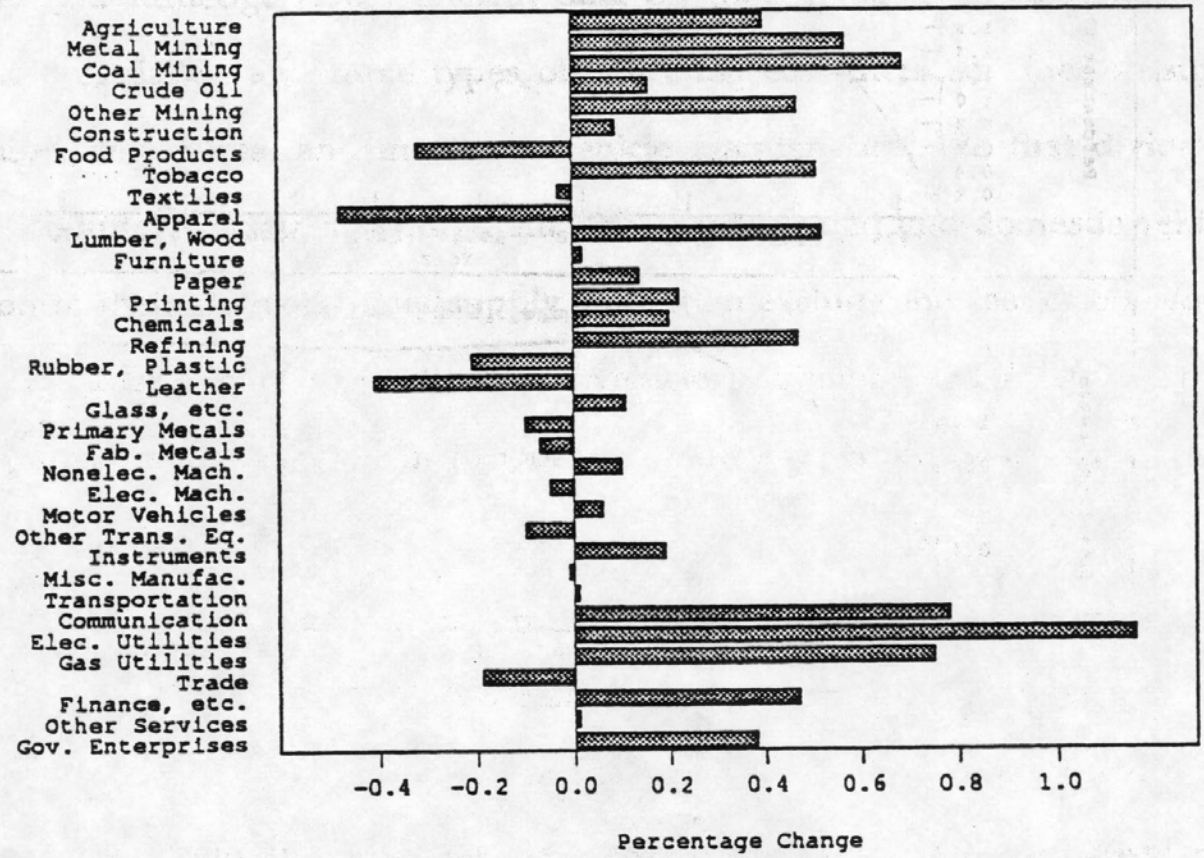


Figure 3.5(a): Full Consumption

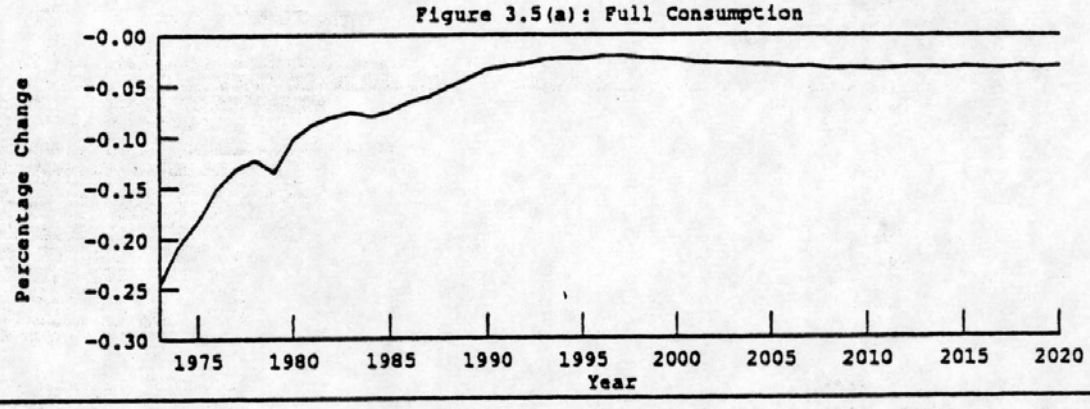



Figure 3.5(b): Price of Investment Goods

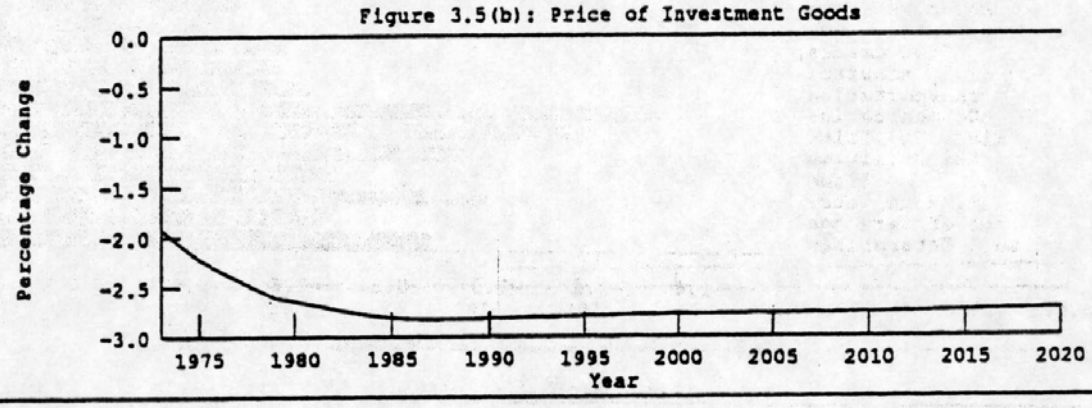



Figure 3.5(c): Capital Stock

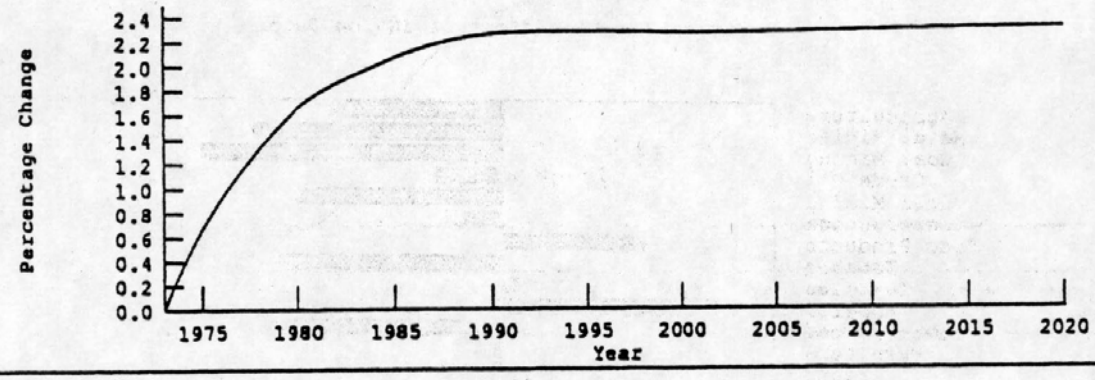
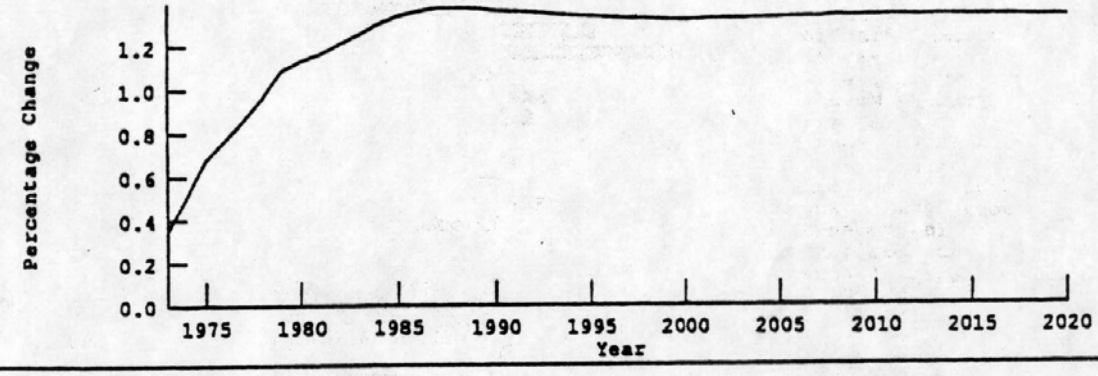



Figure 3.5(d): Real GNP



become cheaper, beginning in 1973, the rate of return rises, driving up investment and producing a sharp increase in the capital stock. The initial surge in investment is financed by an increase in savings brought about by a temporary drop in consumption. Later, consumption rises as the capital stock grows.

### 3.3. Motor Vehicle Emissions Control

Environmental regulation is not limited to controlling pollution by industries in the business sector. Restrictions on motor vehicle emissions affect both businesses and households. Like pollution control in industry, the reduction of motor vehicle exhaust emissions requires both capital expenditures and operating costs. A catalytic converter is a typical piece of pollution abatement equipment requiring capital a expenditure and the premium paid for unleaded gasoline is an example of an increase in operating costs.

Kappler and Rutledge (1985) present data on the capital costs associated with motor vehicle regulation and three types of operating cost-increased fuel consumption, increased fuel prices, and increased vehicle maintenance. We first divide the total cost of pollution abatement equipment between imported and domestic vehicles in proportion to their shares in total supply. We then exclude the cost of this equipment from the total cost of domestic motor vehicle production, while reducing the price of imported motor vehicles in proportion to the cost of pollution control devices.

Given the industries in our model, the price premium for unleaded motor fuels can best be modeled as a change in the cost of output of the petroleum refining sector. This is similar to the treatment of the fuel cost differential between high-sulfur and low-sulfur coal. Only the operating costs associated with higher fuel prices were removed in this simulation; fuel consumption and vehicle maintenance were held

constant. Consequently, our results understate the overall impact of emission controls.

As shown in column MV of Table 3.1, the long run economic impact of imposing emissions controls on motor vehicles is similar in magnitude to the impact of pollution controls in industry (column ENV). The capital stock rises by 1.118 percent, full consumption increases by 0.282 percent, real GNP increases by 0.752 percent and the exchange rate appreciates by 0.392 percent. Almost all of the impact is due to the drop in motor vehicle prices resulting from the elimination of required pollution control equipment. Motor vehicles are one of the principal inputs into the production of investment goods, so that changes in their price have a significant effect on the overall price of investment goods. As with our investment simulation, a drop in the price of investment goods raises the rate of return and leads to large changes in the capital stock.

The long run effects of eliminating motor vehicle emissions controls on commodity prices and industry outputs are shown in Figure 3.6. The principal beneficiary of the elimination of these regulations is the motor vehicles industry itself. This is due in part to the fact that the demand for motor vehicles is price elastic: a price change of seven percent produces an output change of fourteen percent. Thus, a small drop in price produces a large change in output. Two other industries also benefit significantly from the change in policy-petroleum refining and electric utilities. Both gain from the reduction in fuel prices associated with elimination of the fuel price premium.

The dynamic response of the economy to an elimination of vehicle regulations is so similar to the response for the investment simulation that we omit the graphs. The differences can be attributed to the fact that vehicle regulation began in earnest somewhat later and the imposed significantly smaller changes on the price of investment goods.

Figure 3.6(a): Effect of MV on Prices

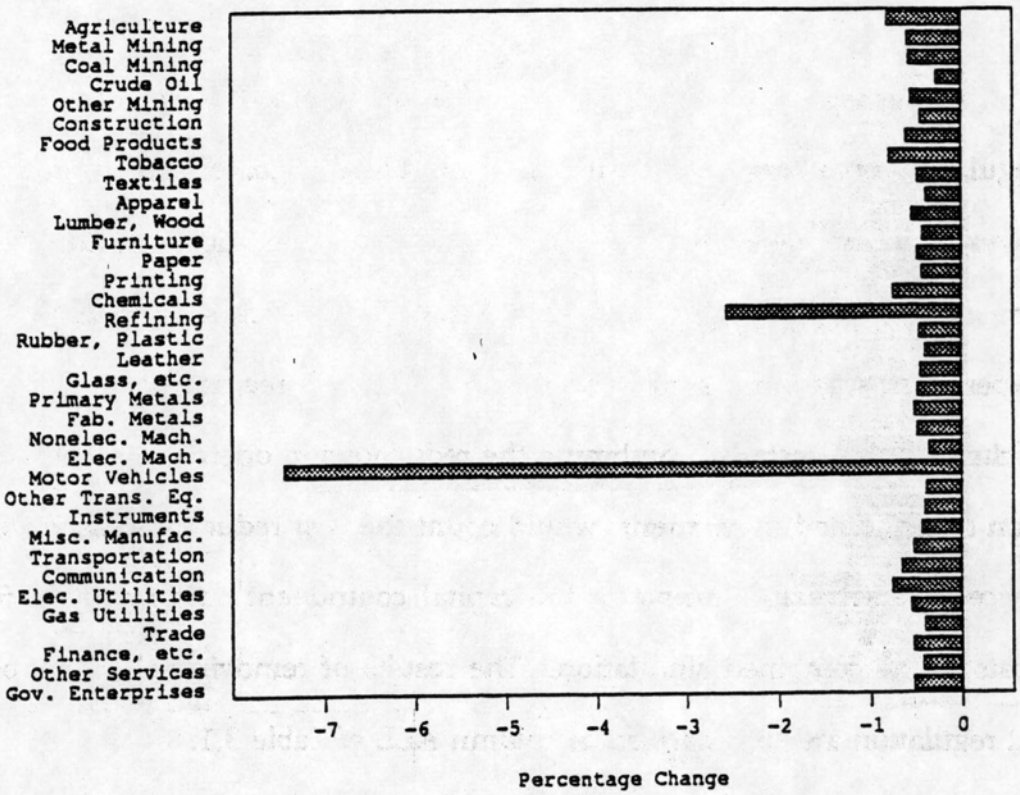
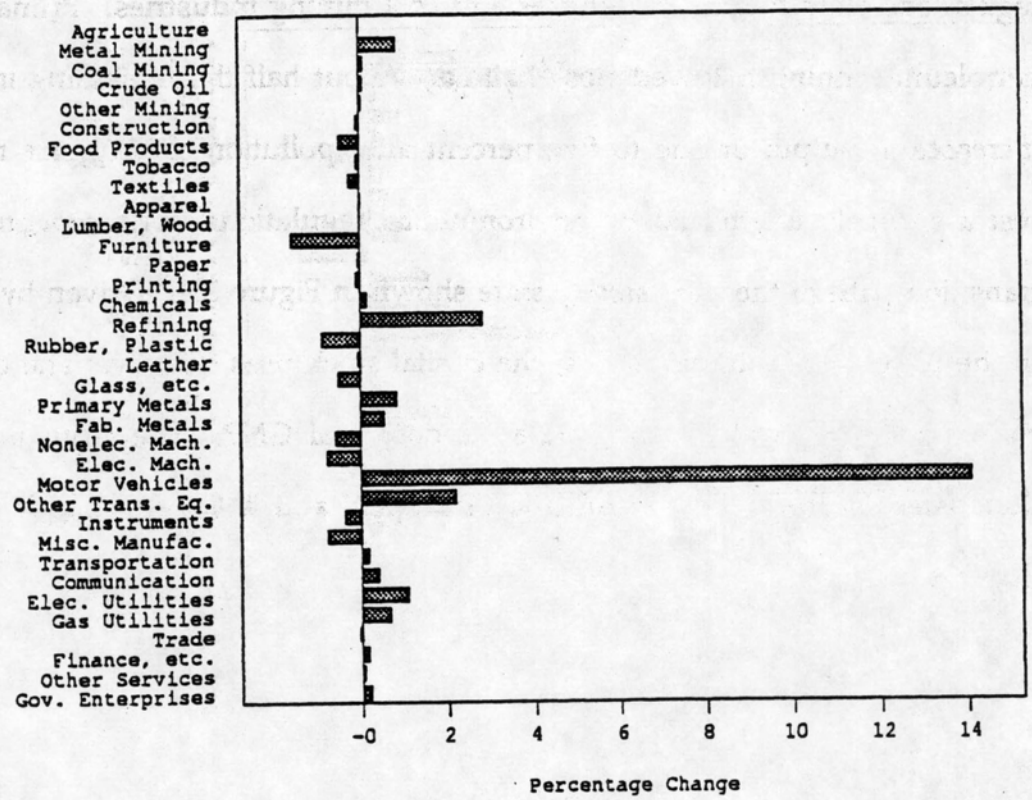



Figure 3.6(b): Effect of MV on Output



### 3.4. The Overall Impact of Environmental Regulation

To measure the total impact of eliminating all three costs of environmental regulation-operating costs resulting from pollution abatement in industry, mandated investments to meet environmental standards in particular industries and cost of emission controls on motor vehicles-we performed a final simulation. However, this experiment was not a simple combination of the three components. Operating costs include capital costs, so combining the reductions in operating costs with the elimination of mandated investment would count the cost reductions associated with capital twice. To solve this problem, the capital component was removed from operating costs in the combined simulation. The results of removing all forms of environmental regulation are summarized in column ALL of Table 3.1.

The long run consequences of pollution control for different commodities and industries are presented in Figure 3.7. The sectors hit hardest by environmental regulations were the motor vehicles and coal mining industries. Primary metals and petroleum refining followed dose behind. About half the remaining industries have increases in output of one to five percent after pollution controls are removed. The rest are largely unaffected by environmental regulations. The economy follows the transition path to the new steady state shown in Figure 3.8. Driven by large changes in the price of investment goods, the capital stock rises sharply. The quantity of full consumption rises at a similar rate, as does real GNP. The adjustment process is dominated by the rapid accumulation of capital and is largely completed within two decades.

Figure 3.7(a): Effect of ALL on Prices

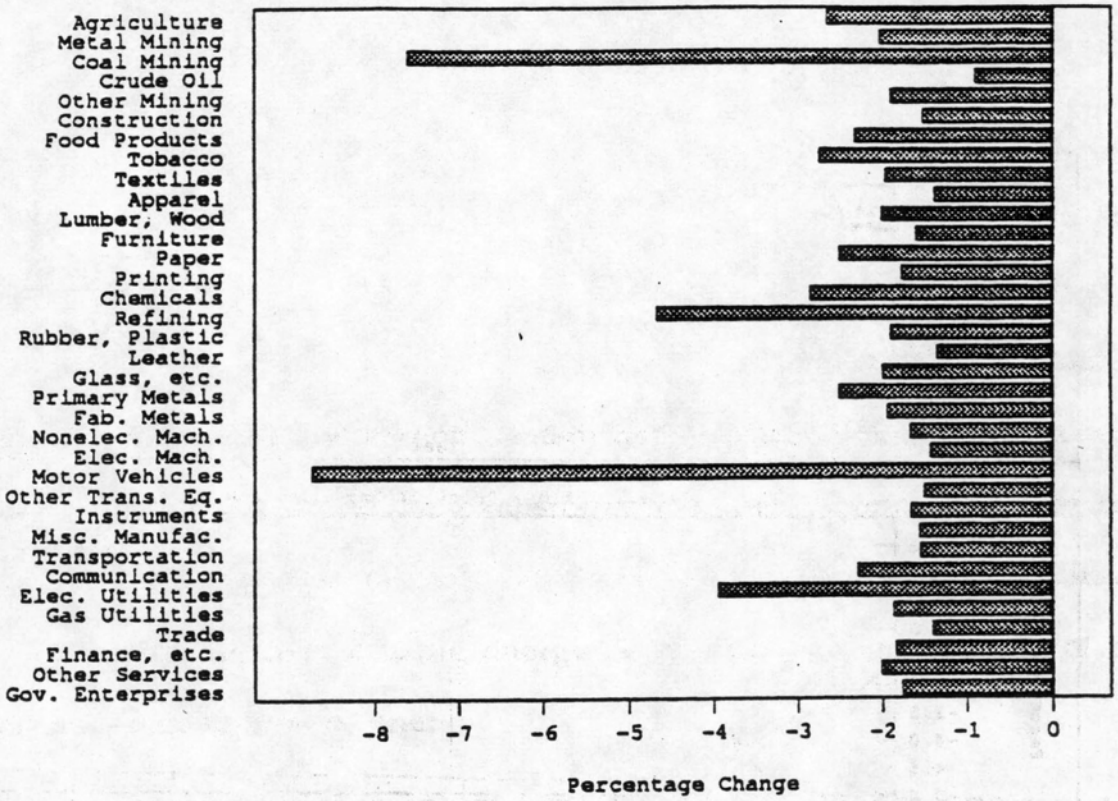
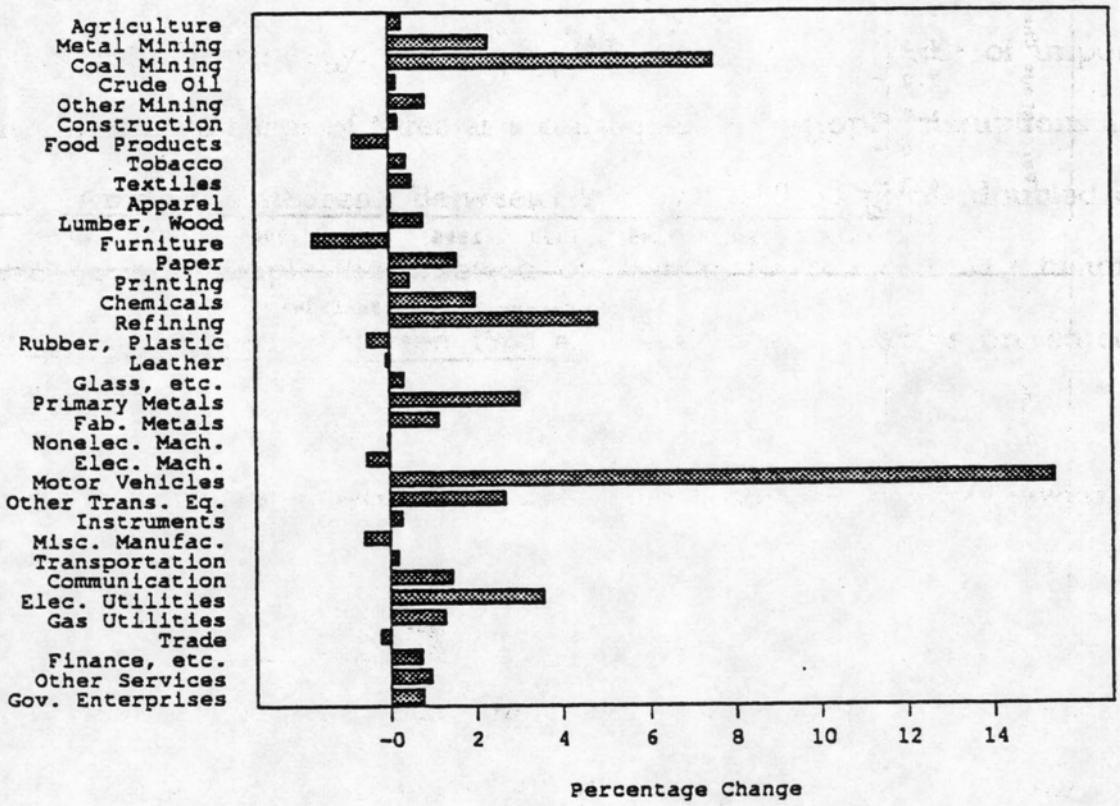



Figure 3.7(b): Effect of ALL on Output



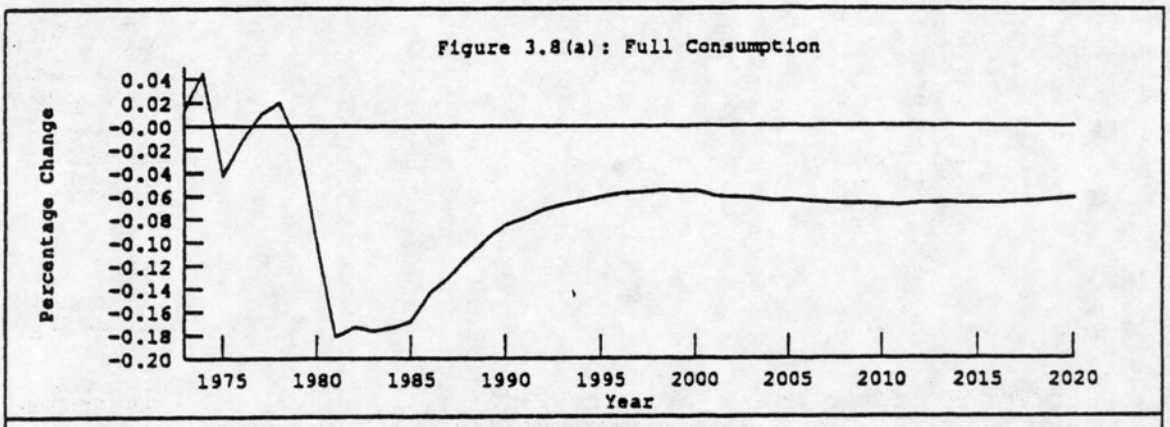


Figure 3.8(a): Full Consumption
Percentage Change
0.04
0.02
-0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

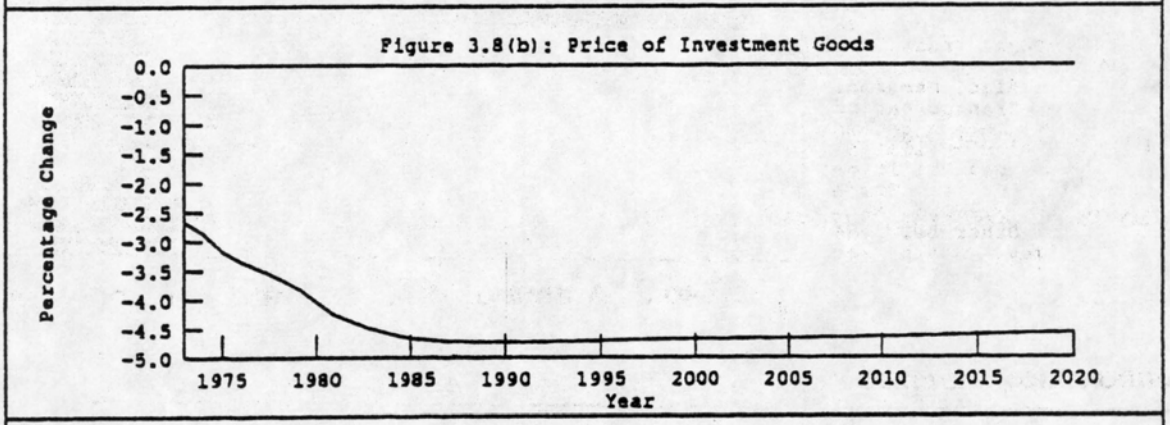


Figure 3.8(b): Price of Investment Goods
Percentage Change
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

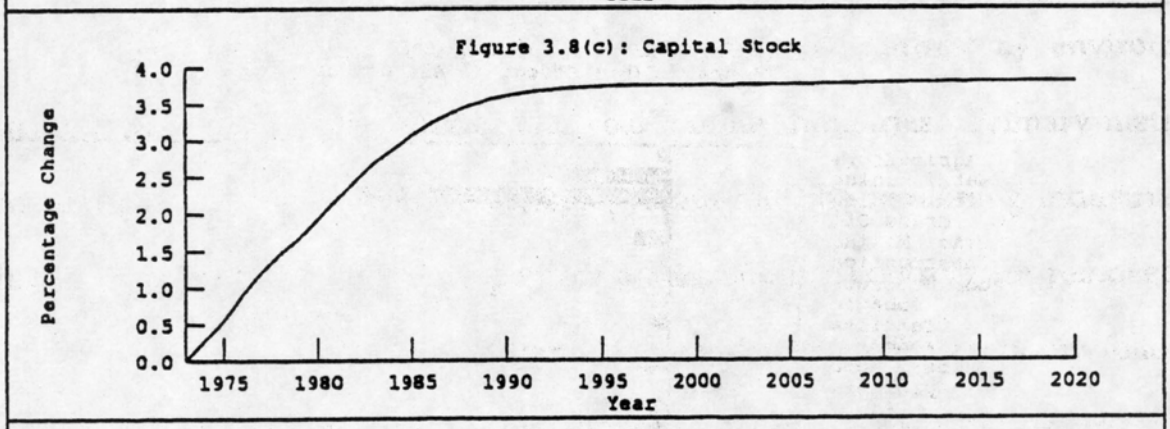


Figure 3.8(c): Capital Stock
Percentage Change
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year

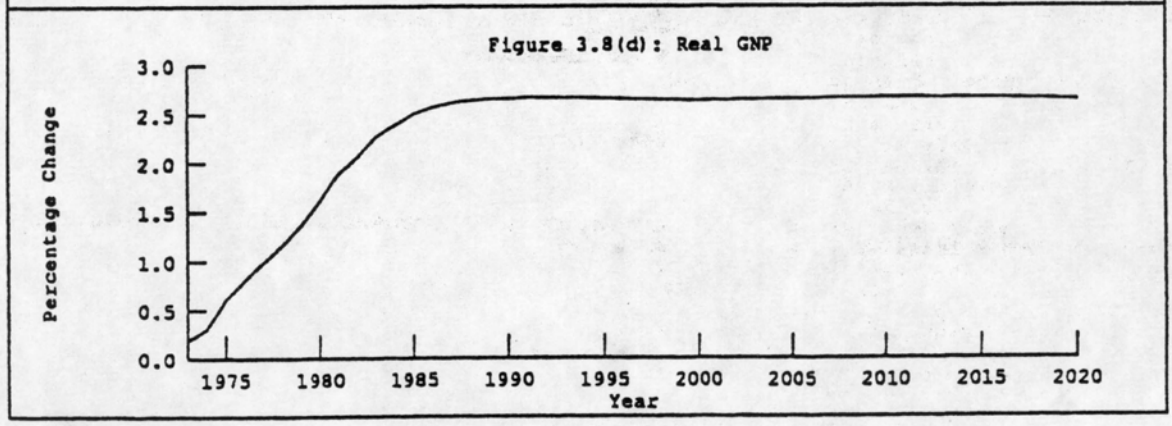


Figure 3.8(d): Real GNP
Percentage Change
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Year