CONTRIBUTION OF HIGHWAY CAPITAL TO INDUSTRY AND NATIONAL PRODUCTIVITY GROWTH

by

M. Ishaq Nadiri[*]
and
Theofanis P. Mamuneas[**]

September, 1996

[*] New York University and NBER
[**] University of Cyprus

This report was prepared for Apogee Research, Inc., for the Federal Highway Administration Office of Policy Development, Work Order Number BAT-94-008.

TABLE OF CONTENTS

I. INTRODUCTION

The United States and many other advanced industrial countries are concerned about the slowdown in productivity growth since the early 1970s. Major factors considered in the literature as potential causes of the decline in productivity growth include one or more of the following developments: inadequate rates of investment in the stock of private capital, misallocation of capital services and underutilization of its capacity; rising energy prices; changes in labor force composition, including the entrance of women and minorities with lower skill levels; declining rates of investment in R&D capital and a slowdown in the rate of technical change; a shift away from manufacturing toward a service-oriented economy; mismeasurement of output, particularly in the service industries; and inadequate measurement of quality improvements in labor and capital inputs. This list can easily be extended to include many other explanations.

The literature analyzing the productivity slowdown in the U.S. and other advanced economies is voluminous making it beyond the scope of this report to discuss all the very complex and controversial issues discussed therein. One thing that does stand out, however, is that until recently, most of the empirical literature on production functions and productivity treated production in the private sector independently from the quality and availability of public sector services. Early work by Arrow and Kurz (1970) and Grossman and Lucas (1974) has shown that public capital may enter the private sector production function. Several types of public capital services are particularly important for enhancing output and productivity growth of the private sector, the most important being the quality and capacity of the network of various types of physical public and private infrastructure in an economy, the quality of education and training provided or financed by the public sector, and the extent of technological innovation and R&D supported by the public sector. These types of "social overhead capital" are clearly important in reducing production costs and improving the quality of private sector production. The provision of public capital often requires a sizable initial investment and is generally considered a "public goods" in that their services are jointly consumed by multiple users. The financing of infrastructure facilities through the tax system, and the incidence of such taxes, is generally not addressed in production and cost function studies.

Recent discussions in the literature have emphasized inadequate growth of infrastructure capital as a cause of the slowdown in productivity at the aggregate and industry levels. Numerous studies have been undertaken to clarify the relationship between productivity growth and public infrastructure capital. These studies can broadly be classified as those which estimate a neoclassical production function augmented to include the publicly financed infrastructure capital stock as a factor of production, and those which utilize the dual approach to production function analysis by estimating cost or profit functions. The latter approach utilizes market data about the prices of private inputs and output, and offers several statistical and methodological advantages over production function analysis that are discussed later in this report.

The level of aggregation used in estimating production and cost functions varies considerably among the different studies. Some studies use highly aggregate national or international data and others use regional or state level data. Some studies use cross-section-time series data covering metropolitan SMSAs, while others employ industry-level data. Studies often differ in their coverage of industries, geographic regions, modeling methodology and use of econometric estimation techniques. Therefore, it is not surprising that the statistical results reported in the literature measuring the effects of infrastructure capital on the economy are often quite diverse and sometimes contradictory.

Clearly, no consensus has yet emerged on the precise causes of the productivity growth slowdown and the controversy is frequently fueled by proponents of specific causes who argue as though there were a single explanation for the slowdown rather than a combination of factors. To meet the challenge posed by the diversity of the sources of productivity growth and to better understand the role played in the process by infrastructure capital (which in this study refers to highway capital) we formulate a structural model that incorporates most of the important forces likely to explain productivity growth. It is logical that the framework for such a model include the effects of a variety of demand and supply factors as well as highway infrastructure capital on the acceleration or deceleration in productivity growth. The relative contribution of highway capital, as well as other factors, can best be evaluated within such a general framework.

A significant feature of this study is its comprehensive coverage of the US economy. Most studies, as discussed in the following section, focus on the aggregate economy or consider only a subset of industries. This study estimates a model using industry data covering the entire U.S. economy and also derives "aggregate" estimates of the effects of both demand and supply factors as well as highway capital on the movements of aggregate productivity growth at the national level. In the process, we obtain the marginal benefits of highway capital stock in each industry and its contribution to industry productivity growth and also the aggregate marginal benefit of highway capital to output and productivity growth for the economy as a whole.

In this study we concentrate on the contribution of a specific component of total public infrastructure capital i.e., highway capital. We explore the role it plays in enhancing private sector productivity both at the aggregate economy and disaggregated industry levels. Two measures of highway capital are used: total highway capital including roads under federal, state, and local government jurisdiction; and the stock of upper level roads excluding local government investments in roads and streets. The latter includes the federal-aid highway system, with the exception of expenditures on secondary rural roads, and represents approximately 70 percent of total highway capital stock. As such, it is referred to in this report as the non-local highway system, or NLS. The purpose of incorporating the NLS stock in the analysis is to advance analysis of a highway network consistent with the underlying definition of the National Highway System (NHS). This is required because the NHS has only recently been approved and a series of investment data sufficient to estimate a capital stock for this component of the total highway system is not available.

The relevant policy questions addressed in this report are:

- What is the productivity of highway capital and what is the overall social rate of return to this type of capital?
- Is there any evidence of over- or under-supply of this capital in the post-war period?
- If a shortage of highway capital is evident, can it explain some of the decline in the aggregate productivity growth? If so, by how much?
- What is the optimal level of highway capital from the perspective of the private production sector and how does it compare to its actual level?
- What is the effect of this type of highway capital on the private sector cost of, and demand for, labor, capital, and intermediate inputs?, and
- What are the marginal benefits to the private sector of an increase in highway capital and how do they differ across industries?

To begin to answer these questions we develop an analytical framework possessing several advantages over existing models reported in the literature:

- The role of aggregate demand on the productive behavior of individual industries is explicitly taken into account. That is, the effects of changes in aggregate income and population on industry demand and, consequently, on its productivity growth are estimated.
- Account is taken of the contribution changes in real factor prices, including wages and capital rental prices, may have on productivity growth;

- The direct and indirect effects of an increase in highway capital on total and industry output and productivity growth are estimated;
- The impact of highway capital, both total stock and the NLS subset, on demand for inputs such as demand for employment and private sector physical capital are estimated (i.e., whether an increase in highway capital stock is biased in favor of labor or capital).

The remainder of the report is organized as follows. Section II briefly summarizes the main results reported in the literature on the contribution of public infrastructure capital to productivity growth using production, cost, and profit, function approaches.[1] The section concludes with a summary of the overall results that may be obtained from the available literature.

Section III specifies a general analytical model consisting of demand and cost functions for individual industries. The analytical structure allows estimation of the structural parameters for each industry and provides a framework for decomposing total factor productivity growth into several components including the contribution of highway infrastructure capital. This methodology allows us to trace the effects of aggregate demand, population growth, real factor prices, technical change, and highway capital on total factor productivity (TFP) growth and production of each industry.

Section IV specifies the econometric model and describes the sources of data used to estimate it. The primary data are a cross-section, time series of prices and quantities of output and inputs for 35 industry sectors for the period 1950-1989. These industries collectively cover the entire US economy and provide a basis to estimate the contributions of various factors to the growth of output and productivity for the overall economy.

---

[1] More comprehensive surveys of the production function approach may be found in Aschauer (1993) and Federal Highway Administration (1992).

Section V presents summary statistics for several model specifications. Results of sensitivity tests that examine the stability of the econometric model are reported. Criticisms aimed at previous time-series econometric models designed to quantify the contribution of public infrastructure to economic growth and productivity are specifically addressed:

- **Spurious correlation**. The relationship between private sector productivity and infrastructure capital may be spurious, or false, because of a common trend among measures of output, private sector capital and labor, and public capital;
- **Simultaneity**. The potential simultaneous, or jointly determined, relationship between (aggregate) output and public capital is considered in the modeling framework; and
- **Omitted variables**. The omission of variables from the analysis, such as the rapid rise in energy and material input prices, that may affect productivity and possibly be attributed to public capital, are accounted for in this framework.

This section addresses these criticisms by econometrically testing alternative specifications of the model, focusing specifically on highway capital.

Section VI presents empirical estimates of the effect of total highway and NLS capital on industry production costs. The results of two versions of the model, Model A and B, are provided. In Model A the stock of highway capital is measured by total highway capital while in Model B total highway capital is split into two components, total highway capital and NLS highway capital. Estimates of the effect of an increase in total highway and NLS capital on the derived demand for inputs such as labor, capital and materials are presented.

Section VI also presents the results of a decomposition of total factor productivity growth into its various components, including highway capital, by industry. Estimates of the marginal benefits of a change in the level of total highway capital and NLS capital to each industry are provided with an analysis of the implied taxes and subsidies if each industry were to make optimal use of the available highway capital.

Section VI provides measures of the contribution of total highway capital and NLS to the national economy's output and productivity growth based on “aggregated” industry-specific estimates. As an alternative approach, we also “aggregate” industry data and re-estimate the model. Findings from the "aggregated" and "aggregate" estimation approaches are compared with each other and with those reported in the literature as an indication of where the results of this study are positioned relative to both national level and less aggregate studies. Next, the social net rate of return to both total highway capital and NLS are calculated. Optimal levels of both types of highway capital are derived from the model and compared with their actual levels to assess the extent of an over- or under-investment in highway stocks. The rates of return to highway capital are compared with those to private sector capital stock and with the interest rate. Section VII provides a brief summary and conclusion followed by an Appendix and References.

II. LITERATURE REVIEW: RESULTS FROM PRODUCTION AND COST (PROFIT) FUNCTION METHODS

A. Production Function Methods

The basic framework for incorporating public infrastructure in an aggregate production function is straightforward: expand a production function to include not only the private factors of production, labor and capital, but public capital as well. Specifically, redefine the production function $Y = A * F(K, L)$ as $Y = \tilde{A} * F(K, L, S)$ where Y is the level of output, A is the level of productivity, K is the stock of private capital, L is employment, S is the government financed infrastructure capital stock and $\tilde{A}$ is total factor productivity purged of the influence of the government capital stock. A commonly used specification is the Cobb-Douglas production function, estimated by Aschauer (1989b) and others:

$$Y = \tilde{A} K^{\alpha} L^{\beta} S^{\gamma} .$$

Taking natural logarithms of this equation yields the typical estimation equation:

$$\ln Y = \ln \tilde{A} + \alpha \ln K + \beta \ln L + \gamma \ln S.$$

Aschauer found γ, the elasticity of output (Y) with respect to public capital (S), to be positive, ranging from 0.39 to 0.56.[2] The marginal product of public capital (MP_S), defined as $MP_s = \gamma \cdot \frac{Y}{S}$, implied by this result is 100 percent or more. The implication is that an increase in government capital pays for itself in terms of higher output within one year. Much of the subsequent research is a reaction to this high rate of return to public capital.[3]

---

[2] Specifically, the elasticity is defined as $\gamma = \varepsilon_{YS} = \frac{\partial Y}{\partial S} \frac{S}{Y}$.

[3] For a cogent discussion, see Gramlich (1994).

The literature examining the effect of public infrastructure capital on output growth and productivity using the production function framework is extensive. Production function studies can be combined into two broad categories: (a) national level studies, and (b) regional or state level studies. Table 1 summarizes the characteristic features of a selected number of production function studies. Aschauer (1989) stimulated an extensive discussion of the nature and magnitude of the impact of infrastructure capital on output and productivity growth.[4] He estimated an aggregate production function and argued that infrastructure capital financed by the public sector increases the productive capacity of the private sector, and that public infrastructure investment stimulates private sector investment by enhancing the rate of return to private sector investment. Munnell (1990a) extended this line of argument, and her results generally support the proposition that there is a strong and significant effect of public infrastructure capital on productivity growth.

Both Aschauer and Munnell employ aggregate time-series data of the United States to estimate the relationship between private output and the stock of nonmilitary public capital. The latter includes highways and streets, educational buildings, hospital buildings, sewer and water facilities, conservation and development facilities, gas, electric, and transit facilities, and other miscellaneous nonmilitary structures and equipment. As previously noted, Aschauer estimates the elasticity of output with respect to public capital from 0.39 to 0.56.

---

[4] For a review of the literature, see Aschauer (1993).

Table 1: Selected Production Function Studies

AUTHOR	EQUATION	DATA	ELASTICITY *	COMMENTS
ASCHAUER (1989)	Cobb-Douglas production function and TFP regressions	time series 1949-85 Private Business Economy	0.39- 0.36 0.37-0.41 Significant	Constant returns to scale (CRS) in all inputs, including public capital input
MUNNELL (1990a)	Cobb-Douglas production function reproduces Aschauer	time series 1948-1987 private non- farm sector	0.34-0.41 Significant	CRS in all inputs; also priv. and publ. cap. coef. equal
MUNNELL (1990b)	Cobb-Douglas production function	cross-sect. time series 48 states 1970-1986	0.15	see Munnell 1991 and other references
MUNNELL (1991)	Cobb-Douglas production function	cross-sect. Average 1970-1986 states values 12 high endowm. 26 mid. endowm. 10 low endowm.	0.14 0.11 0.22 Significant	Returns to Scale 1.01 1.03 1.04
GARCIA-MILA AND McGUIRE (1988)	Cobb-Douglas production function	cross-sect. time series 14 annual obs. of 48 states gross state prod. labor, capital expenditures on education and highways	Highways: 0.045-0.044 Education: 0.16-0.072 Significant	Returns to Scale 1.04 Cannot reject increasing returns to scale
EBERTS (1988)	Translog production function	cross-sect. manufacturing 1958-1978 38 Metropolitan Areas	0.04 Significant	CRS; public and private capital substitutes public and labor complements
HULTEN AND SCHWAB (1991a)	Cobb-Douglas production function with first differences.	time series 1949-1985 same as Aschauer	0.42 Significant 0.028 Insignificant	(-) coeff. for labor
TATOM (1991)	Cobb-Douglas production function including energy price, with first differences.	time series 1974-1987 Business Sect.	0.146 Insignificant	CRS
MERA (1972)	Cobb-Douglas production function	Japan pooled data of regions and time 3 sectors 4 classifications of social overhead capital	0.22 0.20 (.50) 0.12-0.18 Significant	
FORD AND PORET (1991)	TFP regressions	USA and 11 OECD countries time series and country cross-section	Half of countries significant effect after 1960 Mixed support of Aschauer results	
HULTEN AND SCHWAB (1991b)	TFP regressions	cross section time series regional study of Snow-Sun Belt 1970-1986 Gross output value added	public capital insignif. in all regressions private capital insignif. in gross output regres. signif. in value added implying scale .88	

*Coefficient of infrastructure capital in logarithmic equation.

In a related study, Munnell finds an elasticity of 0.33 for output per man-hour with respect to public capital. She uses the estimated coefficients from the aggregate production function to calculate annual percentage changes in multifactor productivity and concludes: “The drop in labor productivity has not been due to a decline in the growth of some mystical concept of multifactor productivity or technical progress. Rather, it has been due to a decline in the growth of public infrastructure." (Munnell, 1990a, p.20)

These results generated a variety of criticisms:

- The belief that the estimated elasticities and their implied marginal productivity of public capital are extremely high. For example, the marginal productivity of public infrastructure capital based on Aschauer's estimates exceeds that of private capital by several times, a result that Aaron(1990) viewed as highly implausible.
- The aggregate time series correlation may not reflect a causal relation, but, rather, a spurious, or false, correlation between production and public capital. That is, both labor productivity and public infrastructure spending have declined over the same period due to other forces (Aaron (1990) and Tatom (1991)).
- Reverse causation may be present between public infrastructure capital and productivity growth. The argument is that the positive coefficient for public capital obtained in various studies may reflect the effect of productivity growth on infrastructure capital rather than the reverse. Also there is some evidence of a lack of robustness when more recent data are used to estimate the aggregate production function of Aschauer and Munnell.

Several production function studies address infrastructure and productivity relationships at the state level using time-series cross-section data for the 48 contiguous states. The cross-sectional aspect of these data have certain advantages which mitigate the possibility of spurious correlation over time. As a whole, studies based on state-level data support a relatively lower but still positive relationship between public infrastructure and productivity. Munnell's (1990b) elasticity estimates show that, while public capital has a positive effect on output productivity, it is only half the size of the effect of private capital. For example, a one percent increase in public capital results in a 0.15 percent increase in output, whereas a one percent increase in private capital results in a 0.31 percent increase in output. The estimated output elasticity of labor is 0.59. Calculating the marginal product shows that an additional unit of public capital increases output by the same amount as an additional unit of private capital. The results remain plausible when public capital is split into three components -- highways, water and sewer systems, and other. The first two, constituting the largest part of core infrastructure, have larger effects than the "other" category.

Using Munnell's data, Eisner (1991) suggests that for all functions considered, the significance of public capital holds up when the data are arranged to reflect cross-sectional variation, but disappears when the data are arranged to allow for time-series variation. This suggests that states with more public capital per capita have more output per capita, but that a state that increases its public capital in some year does not get more output in that year as a result. Therefore, Eisner regards the direction of causation between output and public capital as undecided and postulates that a lag structure is required to obtain a true time-series relationship between output and public capital.

Calculating manufacturing productivity growth rates for the years 1951 to 1978 for major regions of the United States, Hulten and Schwab (1984) test whether different rates of public capital growth correspond to different rates of productivity growth. They find that differences in output growth are not due to differences in the growth of public infrastructure, but rather to variation in the rates of growth of capital and labor. When they expand this analysis to include the years 1978 to 1986 (Hulten and Schwab (1991)) their conclusion remains the same: public infrastructure has had little impact on regional economic growth.

These disparate results are likely due to whether the unobserved state-specific characteristics are controlled in the estimation process or not. Holtz-Eakin (1992) tested the hypothesis that the positive and strong effect of infrastructure will diminish or disappear if state-specific effects are accounted for. McGuire (1992) estimates four different specifications of a state-level production function with public capital as an input: Cobb-Douglas without state effects; Cobb-Douglas with state effects (fixed or random effects); and translog without state effects. The four specifications of the model yield broadly similar results, with public capital having a positive and statistically significant effect on gross state product (GSP). When public capital is split into its three component parts (highways, water and sewers, and other), highways has the strongest impact. Water and sewers has a much smaller but usually significant effect, and other public capital is not statistically significant or has a negative effect on private output. Indeed, some economists hypothesize that state-level data may systematically underestimate the productivity value of public capital, because such data cannot capture the aggregate effects of public capital as a system.

Similar findings have been reported in a number of production function studies which utilize even more disaggregate data. Studies by Eberts (1988), Eberts and Fogarty (1987), and Duffy-Deno and Eberts (1989) use data at the metropolitan level. They test the direction of causation between infrastructure capital and output and estimate the magnitude of the elasticity of output with respect to infrastructure capital. Their findings suggest that causation runs mostly from infrastructure capital to output growth and there is a positive but considerably smaller elasticity of output with respect to public capital than those based on the aggregate production function relationship between infrastructure and growth of output and productivity.

From a reading of the evidence based on these production function studies it is possible to draw the following conclusions:

(1) Early estimates based on aggregate production function analyses are likely to have overstated the magnitude of the effects of public infrastructure capital on output and productivity growth;

(2) Estimates based on state level data indicate a relatively smaller contribution of infrastructure and that the composition of infrastructure capital matters; some types of infrastructure may have a greater effect on productivity than others;

(3) There are serious estimation problems in both aggregate national level time series studies and state and regional level studies that lead to highly disparate results; and

(4) Overall, it seems that the recent studies report relatively smaller elasticity estimates for infrastructure than Aschauer's original study. The evidence points to a positive but lower elasticity of output with respect to public infrastructure capital of about 0.20 to 0.30 at the national level and possibly a lower range at the regional level.

One reason for the wide range of estimates of the elasticity of output with respect to infrastructure capital based on production function estimates may be due to minimal structure imposed on the data. If sufficient structure is not imposed on the data, provided the underlying data are not subject to serious measurement problems, the parameter estimates of the underlying production structure are likely to be biased and the estimates are not likely to be robust. In estimating production functions, whether using national or state level data, the production function is treated as a purely technological relationship between output and inputs, and firms optimization decisions with respect to how much output to produce and what mix of inputs to use in the production process is not considered specifically. In reality, inputs and output are simultaneously determined when firms optimize (minimize) their profit (costs). When firms' optimization is explicitly considered, the marginal productivity conditions for the inputs should be estimated jointly with the production function. If these conditions are not explicitly considered, the estimated production function parameters are likely to be seriously mismeasured.

B. Cost (Profit) Function Methods

Although production function analyses provide a useful first look at linkages between infrastructure investment and productivity growth, they do not provide detailed consideration of the effects of public investment on the economic decisions and performance of the firm. Production function analyses invariably omit factor input prices that affect factor utilization, and can thereby lead to biased estimates of production function coefficients. The cost function approach offers detailed information on cost elasticity of output as well as specific effects of infrastructure capital on demand for private sector inputs. Using cost function methodologies, it is possible to trace, in considerable detail, the effect of infrastructure investment on firm's production structure and performance including technical change, scale economies, and demand for employment, materials and private capital stock.

The cost- or profit-function approach takes explicit account of the firm's optimization behavior by considering both inputs and outputs as endogenous variables, while prices, which are market determined and thus considered beyond the immediate control of the firm, are the only exogenous variables. In addition, most production function studies of infrastructure employ a Cobb-Douglas specification, which, *a priori,* imposes the restrictive condition of a unitary elasticity of substitution among inputs, including infrastructure capital. Rather than impose such restrictions at the outset, they should be tested within the framework of a more flexible cost function specification. To avoid shortcomings inherent in the Cobb-Douglas specification, most cost and profit function studies incorporate more flexible functional forms such as the translog or generalized Leontief functions. A further advantage of cost functions is that they yield direct estimates of the various Allen-Uzawa elasticities of substitution. These parameters are the key to describing the pattern and degree of substitutability and complementarity among the factors of production.[5] Furthermore, in cost models, the effect of public capital on the demand for inputs can be directly estimated. If the effect is positive, public capital and the private inputs are complements; if it is negative, public capital and private inputs are substitutes.

There are relatively few studies using the cost (profit) function approach to analyze the effect of infrastructure capital or other types of publicly financed capital on output and productivity growth. Several of these studies and their more important features are summarized in Table 2.

Cost functions are also estimated using diverse sets of data at the national and international level, state and metropolitan level, and industry level. Differences also occur with respect to assumptions about the optimizing behavior of firms, and the specification of the cost function, with special preference shown for the translog or generalized Leontief functional forms. In addition, different authors use different notions of public infrastructure. Some focus on core infrastructure, while others use the total stock of public capital. Even though a single estimate cannot be provided for the effect of public infrastructure on total cost or on its contribution to productivity, all available cost (profit) function studies reach the general conclusion that publicly financed capital contributes positively to productivity by generating cost savings.

---

[5] In the production function context, estimation of the elasticities of substitution requires that the matrix of production coefficients be inverted. This exaggerates the estimation errors and reduces the statistical precision of the computed elasticities of substitution (Nadiri and Schankerman (1981)).

Table 2: Cost or Profit Function Estimates

DESCRIPTION				DIRECT EFFECT	INDIRECT EFFECT		
Author	**Unit of Analysis**	**Specification**	**Public Capital**	**Cost**	**Labor**	**Capital**	**Intermediate**
BERNDT AND HANSSON (1991)	Sweden Private Sector 1960-1988	Variable Cost Labor Requirement Function	Core Public Capital	Cost Savings Unclear	Short-run complements	----	----
DENO (1988)	USA 36 SMSA Manufacturing Industries 1970-78 Pooled	Profit Truncated Translog	Highway, Water and Sewer Adjusted with the proportion of population employed by the sector	Profit increase Elasticity = .08 to .5	Gross complements Elasticity = 0.1 to .4	Gross complements Elasticity = 0.11 to .4	----
CONRAD AND SEITZ (1992)	West Germany Manufacturing Construction, Trade and Transport 1960-1988 Time-Series	Cost Translog and MR=MC	Total Adjusted with capacity utilization rate	Cost Savings	Substitutes	Complements	Substitutes
KEELER AND YING (1988)	USA Trucking Industry 1960-1988 Regional Pooled	Cost Translog	Highway Stock	Cost Savings	----	----	----
LYNDE AND RICHMOND (1992)	USA Nonfinancial Corporate Business Sector 1958-1989 Time-Series	Cost Translog P = MC and CRS	Total Federal and State	Cost Savings	Substitutes Elasticity = -.45 to -.49	Complements Elasticity = .71 to .90	----
LYNDE AND RICHMOND (1993)	U.K. Manufacturing sector 1966:1 to 1992:2 value added	Cost translog	Total	Cost Savings	----	Substitutes	----
MORRISON AND SCHWARTZ (1991)	USA Manufacturing by State 1971-1987 Pooled by Region State specific Effects	Variable Cost Generalized Leontief P=MC	Core	Cost Savings Elasticity = -.10 to -.27	----	----	----

Table 2: Cost or Profit Function Estimates (Cont'd)

DESCRIPTION				**DIRECT EFFECT**	**INDIRECT EFFECT**		
Author	**Unit of Analysis**	**Specification**	**Public Capital**	**Cost**	**Labor**	**Capital**	**Intermediate**
NADIRI AND MAMUNEAS (1991)	USA Manufacturing 12 2-digit industries 1955-1986 Pooled Industry Specific Effects	Cost Translog CRS for Private Inputs	Total Stock Adjusted with Capacity Utilization Rate	Cost Savings Elasticity = 0 to -.21	Substitutes Elasticity = 0 to -1.4	Substitutes Elasticity = -.02 to -1.4	Complements Elasticity =.12 to .76
SEITZ (1992a)	West Germany 31 2-digit Industries 1970-1989 Pooled Industry Specific Effects	Cost Generalized Leontief	Public Roads Length of Motorway System	Cost Savings	Substitutes Elasticity = -.0004	Complements Elasticity = .03 to .04	----
SEITZ (1992b)	West Germany 31 2-digit Industries 1970-1989 Pooled Industry Specific Effects	Cost Generalized Leontief	Total Core	Cost Savings	Substitutes Elasticity = -.15 to -.13	Complements Elasticity = .34 to .86	----
SHAH (1992)	Mexican Manufacturing Sector 26 3-digit Industries Pooled	Variable Cost Translog	Total Adjusted with industries' output proportion	Cost Savings	Complements Elasticity = -.006	Complements Elasticity = -.002	Substitutes Elasticity = .005

NOTE: CRS = Constant Returns to Scale

Lynde and Richmond (1992) estimate a translog cost function using aggregate US nonfinancial corporate business sector data for the period 1958 to 1989. They impose constant returns to scale on all inputs, public capital included, and assume firms behave competitively. Their findings suggest that publicly financed infrastructure reduces costs of production in the nonfinancial corporate business sector.

Nadiri and Mamuneas (1993) estimate a translog cost function for 12 industries of the manufacturing sector for the period 1955 to 1986. Their findings indicate that an increase in public infrastructure as well as publicly financed R&D reduces the cost to the industries in their sample. The magnitudes of the cost elasticities of infrastructure capital vary across the 12 industries ranging from -0.05 to -0.21. For the US road freight transport industry, Keeler and Ying (1988) estimate a translog cost function for regional trucking firms for the period 1950 to 1973. They find that highway infrastructure has a significant effect on the productivity growth of the trucking industry, generating benefits that would justify about half of the cost of the Federal-aid Highway System.

Morrison and Schwartz (1991) estimate a variable cost function using state level data for the total manufacturing sector over the period 1971 to 1987. They specify a generalized Leontief cost function, treating private and public capital as exogenous variables. They estimate a system of input-output equations for production labor, non-production labor and energy, and a short-run output price equation (p = mc) to incorporate profit maximization. The estimation is carried out for four regions-- Northeast, North-Central, South and West. Their results suggest that an increase of one percent of public capital reduces manufacturing costs from 0.15 percent in the Northeast to 0.25 percent in the West. In addition, the authors calculate the contribution of infrastructure to productivity growth for each region and the various states. Deno (1988) estimates a translog profit function for the manufacturing industries from 1970 to 1978 using data from 36 SMSAs. The effects of highway, sewer and water capital on output supply and demands for capital and labor are estimated. In order to take into account the collective nature of public capital, he multiplies the public capital stocks by the percentage of the metropolitan population employed in the manufacturing sector. His findings suggest that all types of public capital contribute positively to output growth, but that highway and sewer capital contribute the most to output growth, capital formation and employment. He finds that output supply responds strongly to total public capital with an elasticity of 0.69. The corresponding elasticities for specific types of capital are 0.31 for highway capital, 0.30 for sewer capital, and 0.07 for water capital.

Berndt and Hansson (1991) estimate a short-run (variable) cost function using aggregate data from the Swedish private sector, by specifying a labor requirement function and assuming that private and public capital are fixed in the short run. They find that public infrastructure and labor inputs are complements during the 1960's and 1980's, but were substitutes in the 1970's. The authors conclude that an increase in public infrastructure reduces private costs. In addition, the authors estimate the ratio of the optimal amount of infrastructure capital to the existing capital stock and conclude that for the period 1970 to 1988 there was excess infrastructure for Swedish private production needs.

Lynde and Richmond (1993) estimate a translog cost function for U.K. manufacturing using quarterly data for the period 1966-1990. In their study, the elasticity of output with respect to public capital averages 0.20, and they attribute approximately 40 percent of the productivity slowdown to the decline in the public capital to manufacturing labor ratio. Their estimates indicate a significant role for public capital in the production of value-added output of the manufacturing sector. Shah (1992) estimates a translog variable cost function using data on twenty-six Mexican three-digit level manufacturing industries. He treats labor and materials as variable inputs and private and public capital as fixed inputs. The short run effect of public capital is found to reduce variable costs. He argues that there is underinvestment in public capital.

Conrad and Seitz (1992) estimate a translog cost function and impose a marginal revenue equal to marginal cost condition for the manufacturing, construction and trade, and transport sectors of the West German economy for the period 1960 to 1988. They find substantial cost reductions in these sectors due to infrastructure investment. Similar results are reported by Seitz (1992a,b) for the effect of core and total public capital stock on the production cost of 31 two-digit industries of the West German manufacturing sector from 1970 to 1987.

In general, evidence gathered from cost (profit) function studies suggests that the contribution of infrastructure on output growth is positive, but its magnitude is relatively smaller than those suggested by production function efforts. Also, there is evidence of an important influence of infrastructure capital on the demand for private sector inputs such labor, materials and capital. Most of the studies suggest, as noted later, a substitutional relationship between infrastructure capital and private inputs, holding the level of output constant.

From this brief review of literature on the linkage and magnitude of the contribution of infrastructure capital to growth in output and productivity, several tentative statements are in order.

1. There is a preponderance of evidence that suggests that infrastructure capital contributes significantly to growth in output, reductions in cost and increases in profitability. The magnitude of these contributions, however, vary considerably from one study to another because of differences in econometric methodology and level of data aggregation.
2. There appears to be a convergence toward a much lower estimate of the magnitude of the contribution of infrastructure capital to output and

productivity growth than suggested in the original Aschauer work. Output elasticity estimates of infrastructure capital at the national level in the range of 0.16 to 0.25 appear to be in order. Estimates based on state and metropolitan level data suggest elasticities of approximately 0.06 to 0.20.

3. Most studies indicate an underinvestment in public infrastructure capital, the degree of which varies among different studies. Most of the cost function studies suggest a substitutional relationship between private capital and infrastructure capital, although some studies report a complementary relationship.

4. The available studies are either too aggregate or partial in their coverage of the economy. Most of these studies, particularly those at the national level, use real GDP, a value added measure, as the dependent variable. However, the appropriate measure for an analysis of the contribution of infrastructure (highway) capital is gross output. Gross output includes purchases of intermediate inputs, along with primary inputs private capital and labor. Because highways are used to transport intermediate inputs, the relationship between public capital and intermediate purchases can be taken into account.

   Use of value-added data can be justified if there is no substitution between intermediate inputs such as materials and energy and the primary factors of production like capital and labor. If intermediate input prices are relatively stable, the use of value added in productivity analysis can be justified on practical grounds. However, oil price shocks substantially affected the course of the U.S. economy in the 1970's and 1980's. Similar effects to a lesser extent were associated with price increases in other intermediate inputs. Therefore, it is important to explicitly include energy and material inputs in the productivity analysis.

5. Studies at the industry level are generally confined to the manufacturing sector or a specific subset of this sector. Infrastructure capital, however, may have important effects on other industries outside the manufacturing sector as well. It is very important to undertake a comprehensive study that includes all sectors of an economy in order to study the role and degree of externalities generated by publicly financed infrastructure capital such as highway capital.

Moreover, all these studies have been challenged on conceptual and econometric grounds. Hulten and Schwab (1994) proposed a number of considerations to guide future research:

- Public investment and economic performance in the private sector are inter-related and the simultaneous relation between the two at least at the aggregate level must be specifically considered.
- Public capital may be subject to congestion and therefore the intensity of use as well as the size of infrastructure capital must be taken into account.
- Disaggregation along various dimensions is very important. Some industries may benefit while others may not from an increase in infrastructure. Similarly, some types of infrastructure may be more productive than others.
- Externalities should be modeled explicitly and carefully.
- Econometric work should use flexible functional forms to take account of the complex relationship between infrastructure capital and private sector output and inputs.
- Spurious correlation, because of common trend, should be seriously considered.

In this study, we attempt to explicitly take into account these considerations. We consider a comprehensive set of industry data that cover the entire economy and we obtain the aggregate results for the total economy from the industry estimates. We examine the possibility of spurious correlation by estimating our model in first difference form. We use a flexible form for the cost function to allow interaction between highway capital and private sector output and inputs. We do not impose *a priori* any restrictions, such as constant returns to scale, on the parameters of the functional form -- rather, we test for such restrictions. The issue of simultaneity is addressed by estimating the model using appropriate econometric techniques. The demand function for each industry is estimated separately and the estimated output price and income elasticities are used with the cost function estimates to decompose the sources of output and productivity growth. We define a general analytical model that identifies the sources of TFP growth at the industry level as well as the total economy level and the contribution of highway capital is evaluated in the context of competing determinants of TFP growth at each industry. Finally, we aggregate the individual industry estimates of the demand and cost parameters to obtain the corresponding "aggregate" parameter estimates. These "aggregated" parameter estimates and those obtained by estimating the model directly using aggregate data are then employed to calculate the rate of return to the optimal level of highway capital as well as its contribution to the output and TFP growth for the overall US economy.

III. ANALYTICAL FRAMEWORK: THE ROLE OF DEMAND, RELATIVE PRICES, AND INFRASTRUCTURE CAPITAL

Our analytical framework follows previous work by Nadiri and Schankerman (1981a,b) and Nadiri and Mamuneas (1992), and identifies the contribution of output demand, relative input prices, technical change and publicly financed capital to total factor productivity growth. Analyzing the relative contribution of these factors in the context of a comprehensive framework may provide reasonable answers to policy questions regarding the extent and significance of public capital's effect on the growth of output and productivity.

To begin the discussion of total factor productivity and its component elements, let the production function of an industry be given by

$$Y = F(X, S, T) \tag{1}$$

where Y is the output of the industry, X is an n-dimensional vector of traditional private inputs, S is an m-dimensional vector of infrastructure capital services, and T denotes the level of disembodied technology.

The traditional measure of total factor productivity growth is defined by the path-independent Divisia index:

$$\dot{TFP} = \dot{Y} - \sum_{i=1}^{n} \Pi_i \dot{X}_i \tag{2}$$

where the dot denotes rate of growth, for example, $\dot{Y} = \frac{\partial Y}{\partial t}\frac{1}{Y}$; and $\Pi_i = P_i X_i / P_y Y$ is the revenue share of the ith private input.

Differentiating (1) with respect to time, and dividing by output, we obtain

$$(3) \qquad \dot{Y} = \sum_{i=1}^{n} \frac{\partial F}{\partial X_i} \frac{X_i}{Y} \dot{X}_i + \sum_{k=1}^{m} \frac{\partial F}{\partial S_k} \frac{S_k}{Y} \dot{S}_k + \frac{1}{Y} \frac{\partial F}{\partial T}$$

Assuming cost minimization of all inputs, public capital included, and letting P_i be the price of the ith private input and Q_k the shadow price of public input k, we obtain the following first-order conditions:

$$(4) \qquad \frac{\partial F}{\partial X_i} = \frac{P_i}{\mu} \quad \forall\, i \qquad \text{and} \qquad \frac{\partial F}{\partial S_k} = \frac{Q_k}{\mu} \quad \forall\, k$$

where μ is the Lagrangian multiplier, together with the envelope conditions

$$(5) \qquad \frac{\partial C^*}{\partial Y} = \mu \qquad \text{and} \qquad -\frac{\partial C^*}{\partial t} = \mu \frac{\partial F}{\partial T}$$

where $C^* = \sum_i P_i X_i + \sum_k Q_k S_k = C^*(Y, P, Q, T)$ is the total cost function including the shadow cost of public capital. Eliminating μ from (4) and (5) and substituting (4) and (5) in (3), we obtain:

$$(6) \qquad \dot{Y} = \sum_i \frac{P_i \; X_i}{\frac{\partial C^*}{\partial Y} Y} \dot{X}_i + \sum_k \frac{Q_k \; S_k}{\frac{\partial C^*}{\partial Y} Y} \dot{S}_k + \frac{-\frac{\partial C^*}{\partial Y}}{\frac{\partial C^*}{\partial Y} Y}$$

Firms, however, do not adjust the public capital stocks - they are exogenously given. What actually is observed is that firms minimize their private production cost subject to the production function (1). Let the optimal private cost of production, given the output level and public capital, be $C = \sum_i P_i X_i = C(Y, P, S, T)$. Then the marginal benefit of an increase of public capital at equilibrium will be given by

(7) $$-\frac{\partial C}{\partial S_k} = Q_k \ .$$

It is not difficult to show using comparative statics that the total cost elasticity, η^*, is given by

$$\eta^* = \frac{\partial \ln C^*}{\partial \ln Y} = \frac{\partial \ln C}{\partial \ln Y} \Big/ B = \eta \Big/ B \text{ where}$$

$B = 1 - \sum_k \left(\partial \ln C \ / \ \partial \ln S_k\right) = 1 - \sum_k \eta_{ck}$ and η_{ck} is the private cost elasticity with respect to public inputs, and η is the private cost elasticity. The cost diminution due to technical change is

$$\dot{T} = \frac{\partial \ln C^*}{\partial T} = \frac{\partial \ln C}{\partial T} \Big/ B.$$

Following Caves et al. (1981), total returns to scale of the production function is defined as the proportional increase in output due to an equiproportional increase of all inputs (private and public, holding technology fixed), and is given by the inverse of η^*. Private returns to scale, i.e., the proportional increase in output due to an equiproportional increase in private inputs, holding public inputs and technology fixed, is given by the inverse of η. Thus, we identify two scale effects in our study, one internal and the other total, which is the sum of internal and external scale effects. Substituting (7) in (6) and then in (2) we have

(8) $$T\dot{F}P = \left(\frac{\kappa - \eta^*}{\kappa}\right) \dot{Y} - \frac{1}{\kappa B} \sum_k \eta_{ck} \dot{S}_k - \frac{1}{\kappa B} \dot{T}$$

where $k = (P_Y Y)/C^* = P_Y / AC^*$ is the ratio of output price, P_Y, to average total cost, AC^*.

According to equation (8), TFP growth is decomposed into three components: a gross total scale effect given by the first term; a public capital stock effect given by the second term; and the technological change effect given by the last term.

The next step is to further decompose the scale effect. We assume the output price is related to private marginal cost in the following manner:

$$P_Y = (1 + \theta)\,\frac{\partial C}{\partial Y}$$

where θ is a markup over marginal cost. The markup depends on the elasticity of demand as well as on the conjectural variations held by the firms within an industry. Using the definition of output elasticity, η, along with the private cost function, we obtain

$$(9) \qquad P_Y = (1 + \theta)\,\eta\,\frac{C}{Y}.$$

After time differentiating (9), the pricing rule implies

$$(10) \qquad \dot{P}_Y = \dot{(1 + \theta)} + \dot{\eta} + \dot{C} - \dot{Y}$$

Differentiating the private cost function with respect to time and using Shephard's lemma yields

$$(11) \qquad \dot{C} = \eta\dot{Y} + \sum_i \hat{\Pi}_i \dot{P}_i + \sum_k \eta_{ck}\dot{S}_k + \dot{T}$$

where $\hat{\Pi}_i = \dfrac{P_i\,X_i}{\sum_i P_i\,X_i}$ is the share of the ith input in private cost, C.

In order to obtain the equilibrium of output growth we assume a log linear demand function (see Nadiri and Schankerman (1981a)) in growth rate form:

$$(12) \qquad \dot{Y} = \lambda + \alpha\,(\dot{P}_Y - \dot{P}_g) + \beta\,\dot{Z} + (1 - \beta)\,\dot{N}$$

where Z and N are real aggregate income and population, respectively, and λ reflects a demand time trend, and P_g is the GNP deflator. Substituting (11) in (10) and the result in (12), we obtain the reduced form function for the growth rate of total factor productivity:

$$(13) \qquad T\dot{F}P = A[\,\alpha\dot{\eta} + \alpha\overset{\bullet}{(1+\theta)}\,] + A\alpha\,[\sum_i \hat{\Pi}_i \dot{P}_i - \dot{P}_g] + A[\,\lambda + \beta\dot{Z} + (1-\beta)\dot{N}\,]$$

$$+ A\alpha\sum_k \eta_{ck}\,\dot{S}_k - \frac{1}{\kappa B}\sum_k \eta_{ck}\dot{S}_k + A\alpha\dot{T} - \frac{1}{\kappa B}\dot{T}$$

where $A = \dfrac{\kappa - \eta^*}{\kappa} / [1 - \alpha(\eta - 1)\,]$.

Equation (13) decomposes TFP growth into the following components:

(i) a factor price effect $A\alpha[\sum_i \hat{\Pi}_i\,\dot{P}_i - \dot{P}_g]$;

(ii) an exogenous demand effect $A[\,\lambda + \beta\dot{Z} + (1-\beta)\dot{N}\,]$;

(iii) a public capital effect $[\,A\alpha - \dfrac{1}{\kappa B}\,]\sum_k \eta_{ck}\,\dot{S}_k$; and

(iv) disembodied technical change $[\,A\alpha - \dfrac{1}{\kappa B}\,]\,\dot{T}$.

The public capital and disembodied technical change effects can be further decomposed into direct and indirect effects. The direct effect of infrastructure k, for instance, is given by $(\eta_{Ck} / kB)\dot{S}_k$ while the indirect effect is given by $A\alpha\eta_{Ck}\dot{S}_k$. Thus, an increase in public infrastructure initially increases total factor productivity by reducing the private cost of production, which in turn leads to a lower output price and higher output growth. Changes in output growth in turn lead to changes in TFP growth.

The important parameters in (13) are the price and income elasticities of demand and the cost elasticities of the private cost function. Note that if the demand function is completely inelastic ($\alpha = 0$) then shifts in the cost function due to real factor price changes, public capital, or disembodied technical change have no effect on output and hence no indirect effect on TFP.

Also, if there are constant returns to scale including public inputs, $\eta^* = \kappa = 1$, then (13) collapses to $\dot{\text{TFP}} = -\frac{1}{B}\sum_{k} \eta_{ck} \dot{S}_k - \frac{1}{B}\dot{T}$.

IV. ECONOMETRIC SPECIFICATION AND DATA DESCRIPTION

A. Model Specification

The above model has been specialized to trace the effects of highway capital on TFP growth and factor demand. The decomposition of TFP growth into its various components, as indicated by (13), requires two sets of parameter estimates:

- Parameter estimates of the output demand function given by equation (12), which relate growth of output demand to changes in price of output and per capita income; and
- Estimates of the cost elasticities of infrastructure capital and other parameters of the cost function.

The output demand equation for each industry, *f*, can be written as

$$(14) \qquad \dot{Y}_f = \lambda_f + \alpha_f (\dot{P}_{Yf} - \dot{P}_g) + \beta_f \dot{Z} + (1 - \beta_f) \dot{N}$$

If the cost of production in the private sector is affected by public sector capital services, the traditional cost functions must be modified to include externalities associated with these capital services. We write the cost function for the *f*th industry as $C_f = C(P_f, Y_f, u_f, t; S)$ where C_f is twice continuously differentiable, normalized cost function; P_f is an n - 1 dimensional vector of relative variable factor prices, Y_f is quantity of output, u_f is the capacity utilization rate, t is an index of time representing disembodied technical change , and S is an m-dimensional vector of public capital services.

Public capital services affect the cost structure of an industry in two ways. First, a larger quantity (or better quality) of public capital services shifts the cost per unit of output downward in an industry. This can be called the "productivity effect". Second, firms will adjust their demand for labor, intermediate inputs, and physical capital stock if public sector capital services are either substitutes for, or complements to, the factors of production in the private sector. That is, the effects of public sector services may not be neutral with respect to private sector input demand decisions.

We assume that the technology of the industry can be represented by a cost function which can be approximated by a continuous, twice differentiable, and linearly homogeneous function in private input prices of the following form:

$$
\begin{aligned}
C\,(Y_f, P_f, u_f, t; S) = \{ &.5 \sum_i \sum_j a_{ij}\, P_{if}\, P_{jf} \,/\, [\sum_i \theta_i\, P_{if}\,] + \sum_i b_{ii}\, P_{if} + [\sum_i c_{it}\, P_{if}\,]\; t \;+ [\sum_i c_{iu}\, P_{if}\,] u_f \\
&+ b_{yy}[\sum_i \gamma_i\, P_{if}\,] Y_f + [\sum_i c_{iS}\, P_{if}]\; S + d_{SS}\; [\sum_i \phi_i\, P_{if}\,]\; S^2 \;\}\; Y_f \\
(15) \qquad &+ \sum_i b_i\, P_{if} + c_S \Big[\sum_i \psi_i\, P_{if}\Big]\; S\,, \quad i, j = 1,.., n,
\end{aligned}
$$

where $a_{ij} = a_{ij}$, and the parameters $\theta_i, \gamma_i\ \phi_i\ \psi_i$, are assumed to be exogenously given. We have introduced the time trend variable, t, to capture autonomous technological change and the capacity utilization rate, u_f, to capture business cycle effects; *f* is the industry identification index. This functional form is the symmetric generalized MacFadden cost function introduced by Diewert and Wales (1987), augmented to include infrastructure services. The cost function is dual to a well-behaved production function if it is nonnegative, monotonically increasing, homogeneous of degree one, and concave in input prices. If, in addition, for some reference point P*>>0, Y*>0, S*>0, the following restrictions are satisfied

$$\sum_i a_{ij}\ P_i^* \ = 0,$$

$$\sum_i \theta_i\ P_i^* \neq 0,\ \sum_i \gamma_i\ P_i^* \neq 0,\ \sum_i \phi_i\ P_i^* \neq 0 \ \text{ and } \ \sum_i \psi_i\ P_i^* \neq 0$$

then $C(\cdot)$ is a flexible, linearly homogeneous in input prices, cost function. The advantage of this functional form over the translog cost function is that if the estimated matrix $A = [a_{ij}]$ is negative semidefinite, then the cost function will be concave in input prices. However, if the A is not negative semidefinite, we can impose concavity in input prices globally by a Cholesky factorization, without destroying the flexibility property of the cost function (See Diewert and Wales (1987) for further discussion).

The system of estimating equations can be derived by applying Shephard's Lemma ($X_i = \partial C / \partial P_i$):

$$(16) \quad X_{if} / Y_f = \sum_j a_{ij} P_{if} / \Big[\sum_i \theta_i P_{if} \Big] - .5 \sum_i \sum_j a_{ij} P_{if} P_{jf} \theta_i / \Big[\sum_i \theta_i P_{if} \Big]^2$$

$$+ c_{it}\, t + c_{iu}\, u_f + b_{ii} + b_{yy} \gamma_i Y_f + c_{is} S + d_{ss} \phi_i S^2$$

$$+ b_i / Y_f + c_s \psi_i S / Y_f + \varepsilon_{if}, \;\; i,j = l,.., n, \qquad f = 1,.., F.$$

where $\varepsilon_f = (\varepsilon_{lf}, \dots, \varepsilon_{nf})$ have zero mean and constant covariance matrix Ω. This assumption seems reasonable enough since by dividing each input by the output reduces the degree of heteroskedasticity of errors.

We require the system of equations (16) to satisfy the usual regularity conditions. In particular, for the cost function to be concave in price inputs, its Hessian matrix $[\partial^2 C / \partial p_i \, \partial p_j]_{ij}$ of second-order derivatives with respect to variable input prices should be negative semi-definite. Also, the cost function should be nondecreasing in output and linearly homogenous in input prices. Finally, in order for public capital to have a meaningful context, the cost function should be nonincreasing in S.

The marginal benefit of highway capital services can be calculated by taking the derivative of the cost function with respect to infrastructure service S:

$$(17) \quad -\partial C_f / \partial S = - \Big\{ \sum_i c_{iS} P_{if} + 2\, d_{SS} \Big[\sum_i \phi_i P_i \Big] S \Big\} Y_f - \Big[\sum_i \psi_i P_{if} \Big] c_S .$$

Note that if the estimated parameter d_{SS} is positive, condition (17) can be interpreted as the demand for highway capital. Also, if the user cost of infrastructure is known, say equal to Q_s , then condition (17) can be imposed on the estimation. Condition (17) is the shadow value or marginal benefit of highway capital services to industry *f*. By knowing the marginal cost of public capital (ignoring consumption), we can also directly estimate the optimal amount of public capital that equates the sum of marginal benefits to its marginal cost. That is,

$$\sum_f - \frac{\partial C_f}{\partial S} = Q_s$$

where Q_s is the marginal cost of highway capital.

Finally, the indirect effect of highway capital on private inputs like capital and employment is given by

$$(18) \quad \partial X_{if} / \partial S = \left\{ c_{iS} + 2\, d_{SS}\, \phi_i\, S \right\} Y_{ft} + \psi_i\, c_S\, .$$

Thus we can test the so-called "public capital hypothesis" and estimate the effect of public infrastructure on private capital and labor.

An industry utilization rate is included in equation (16) to capture the utilization of both private inputs and public infrastructure capital. From the voluminous productivity studies and factor demand analysis, it is clear that short-term fluctuations in output demand significantly affect the demand for labor, materials and investment in plant and equipment. The utilization rate also affects the behavior of productivity growth. The appropriate measure of inputs in the production and cost functions is the service level provided by the respective factor of production. This means the stock of inputs must be adjusted by the utilization rate to obtain the necessary services. The same reasoning applies to infrastructure (highway) capital. Hulten (1990) argued that there are significant swings in the intensity with which public capital is used. There are variations in the utilization of highways, evidenced for example, by the ratio of vehicle miles traveled to the capital stock of roads. Also, public capital is a collective input which firms must share with others and therefore is subject to congestion (see Deno (1988)). Firms might have some control over the use of the public stock (see Shah (1992) and Fernald (1992)). For instance, a firm may have no influence on the level of highways provided by the government, but it can vary its use of existing highways by choosing routes.

In principle, each input including highway capital should be adjusted by input specific utilization rates. However, data limitations preclude such an option. We use the industry specific utilization rate as an independent variable in the cost function to capture, to the extent possible, the utilization rate of both private and public inputs.

B. Data Construction and Description of Industry Price and Cost Structure

The model detailed in the previous section is estimated using data for 35 two-digit industries of the US economy for the period 1947 to 1989. The industry coverage, given in Appendix Table 0-1, is derived from a detailed 80 industry classification that Jorgenson, Gollop and Fraumeni carefully aggregated into 35 larger categories.[4] Data for the value of gross output and costs of labor, capital services and intermediate inputs as well as their price indices for all industries are from Jorgenson, Gallop and Fraumeni.[5]

Labor and capital inputs have been adjusted for quality changes and material (or intermediate input) are constructed by subtracting value added from gross output. The primary source of data for capital is from Jack Faucett Associates and the Bureau of Labor Statistics (BLS). Investment series for each industry is obtained from *Annual Survey of Manufactures, Census of Manufacturers*, and from various issues of *The Survey of Current Business*. Data for

---

[4] See Appendix Tables 0-1 and 0-2.

[5] For a description of data construction, see Jorgenson, Gallop, and Fraumeni (1987). Also see Jorgenson (1990).

labor input have been obtained from *NIPA* and from *Census of Population* and *Current Population Survey*. Data on gross output are from Jack Faucett Associates, BLS and BEA.

Jorgenson and Fraumeni divide labor input into hours worked and average labor quality. NIPA provides hours worked by industry. Household survey data are used to disaggregate total hours into hours worked by different types of workers classified by demographic variables such as sex, age, and education. Assuming that workers are paid proportionately to the value of their marginal products, Jorgenson and Fraumeni calculated labor input as a weighted sum of hours worked by different workers, weighted by relative wage rates. Annual growth in the labor input for economy as a whole from 1947-1985 averaged 1.81 percent; hours grew an average 1.18 percent per year; and labor quality increased an average of 0.63 percent.

Jorgenson and Fraumeni also adjusted capital input stocks for quality changes by their relative efficiencies. For this quality adjustment the rental sales of various types of capital are required. Because the rental price is not directly observable they obtain total payments to capital as property compensation, a residual after all other inputs have been paid (see Fernald (1992)). Using this data, they derive the implied rental rates for each type of capital based on knowledge of this stock and depreciation rates for each type, and tax parameters such as the corporate income tax and investment tax credits.

The construction of data on intermediate inputs of energy and materials by industry is a difficult problem. The difficulty is mainly the low quality of the underlying data. Intermediate inputs into any sector includes inputs for all sectors. To obtain the proper measure of this input, the disaggregated intermediate inputs must be weighted by their marginal products in order to calculate the composite intermediate input. This requires consistent annual input-output tables in current and constant prices that are not available. The Bureau of Economic Analysis (BEA) compiles comprehensive input-output tables only about every five years, the latest is for 1987.

Jorgenson-Fraumeni, for these benchmark years, adjust the data to make them consistent over time and then aggregate to the 35-industry level. The benchmarks are then connected into shares of industry output and the shares are then interpolated from benchmark to benchmark. This gives an estimated input-output table for each year which in turn allows creation of an appropriate price deflator for nominal payments to intermediary factors in each year.

Data on net highway capital stock are from Apogee Research, Inc., based upon Federal Highway Administration expenditure data from 1921 to 1990. Total net highway capital and non-local net highway capital (NLS) are constructed using the perpetual inventory method with the economic decay with an efficiency factor equal to 0.9.[6] Capital expenditures are distributed in the following way; 52 percent to paving, 26.5 percent to grading, and 21.5 percent to structures. The average lives of paving, grading, and structures are assumed to be 14, 80, and 50 years, respectively. The growth rate of total highway capital is shown in Figure 1. After an initial decline between 1950 and 1951, the growth rate of highway capital surged, growing at the average rate of 6.2 percent during 1952-1959. From 1960 onward, the growth rate declined continuously until 1979. It grew very little during 1979-1981. Since 1982 the highway capital stock has been growing at an average rate of 1.2 percent per annum.

Data on capacity utilization rate for the manufacturing industries for the period 1950 - 1966 have been obtained from Klein and Summers (1966) and for the period 1967 - 1989 from the WEFA group (1992). These series are linked using the capacity utilization rate of total manufacturing in 1967 obtained from Citibase. Capacity utilization for the remaining industries is the total economy series obtained from the Economic Report of the President 1992, and does not vary by industry. The capacity utilization series is normalized to equal one in 1987.

---

[6] Total highway stock is based upon capital outlays by all levels of government. The non-local component is an estimate of the federal aid highway system from 1921 through 1992, excluding secondary rural roads.

Data on real GNP and population, used to estimate the demand functions, are obtained from the Bureau of Economic Analysis and the Bureau of the Census, respectively.

Table 3 provides selected descriptive statistics of the underlying data for the period 1950-1989. For each two-digit industry, the average value over the 1950-1989 period is provided for the following variables:

- Total cost (C), constructed as the sum of the value of labor (L), private capital (K) and materials (M), in billions of current dollars;
- The share of total cost attributable to factor inputs -- labor (S_L),capital (S_K), and materials (S_M);
- The value of output relative to total cost (S_Y);
- The growth rates of labor $(\dot{L})$, capital $(\dot{K})$, materials $(\dot{M})$, and output $(\dot{Y})$;
- The growth rates in the price of labor $(\dot{p}_L)$, capital $(\dot{p}_K)$, materials $(\dot{p}_M)$, and output $(\dot{p}_Y)$; and
- The growth rates of highway capital $(\dot{S})$, gross domestic product $(\dot{Z})$, population $(\dot{N})$, and the GDP price deflator .

Figure 1
Growth Rate of Highway Capital (%)
1950-1989

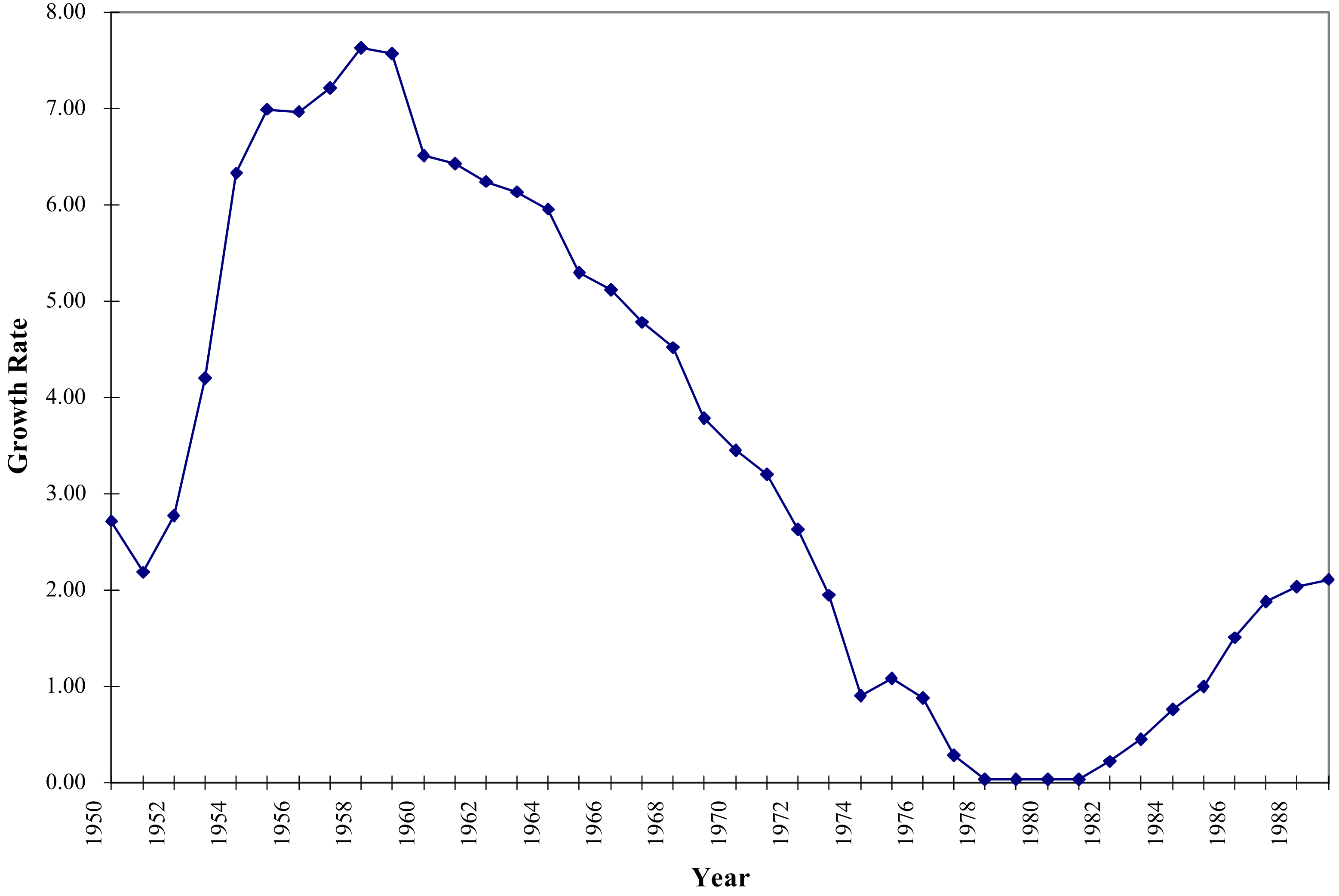


Table 3: Descriptive Statistics
Mean Values: 1950 - 1989

Ind. Code	C	S_L	S_K	S_M	S_Y	$\dot{L}$	$\dot{K}$	$\dot{M}$	$\dot{Y}$	$\dot{P}_L$	$\dot{P}_K$	$\dot{P}_M$	$\dot{P}_Y$
1	104.581	0.249	0.184	0.567	0.975	-0.013	0.004	0.013	0.018	0.055	0.047	0.033	0.027
2	4.024	0.271	0.233	0.496	1.003	-0.008	0.021	0.022	0.012	0.058	0.031	0.041	0.045
3	10.636	0.407	0.180	0.413	1.017	-0.020	0.028	0.024	0.018	0.063	0.039	0.040	0.039
4	42.187	0.195	0.433	0.373	1.017	0.013	0.027	0.027	0.012	0.056	0.033	0.044	0.054
5	5.397	0.331	0.253	0.416	1.003	0.005	0.019	0.034	0.029	0.057	0.042	0.040	0.037
6	232.262	0.340	0.075	0.584	1.000	0.023	0.029	0.029	0.028	0.056	0.047	0.040	0.045
7	138.312	0.151	0.065	0.785	1.040	0.005	0.015	0.020	0.023	0.053	0.047	0.032	0.030
8	8.015	0.122	0.212	0.666	1.376	-0.006	0.012	0.008	0.007	0.069	0.077	0.038	0.044
9	24.950	0.220	0.084	0.696	1.002	-0.010	0.006	0.017	0.022	0.050	0.031	0.029	0.022
10	36.619	0.310	0.040	0.650	1.001	0.004	0.028	0.014	0.025	0.045	0.036	0.028	0.020
11	26.243	0.275	0.115	0.610	1.003	0.003	0.021	0.030	0.026	0.053	0.049	0.037	0.038
12	13.530	0.345	0.081	0.574	1.002	0.018	0.032	0.033	0.034	0.050	0.036	0.038	0.036
13	41.186	0.250	0.134	0.617	1.002	0.014	0.032	0.040	0.036	0.056	0.045	0.039	0.040
14	45.106	0.369	0.111	0.520	1.003	0.023	0.034	0.039	0.032	0.046	0.047	0.041	0.044
15	74.529	0.198	0.194	0.608	0.955	0.018	0.031	0.041	0.046	0.057	0.043	0.038	0.034
16	63.941	0.066	0.067	0.868	1.068	0.011	0.035	0.019	0.028	0.058	0.033	0.049	0.041
17	42.026	0.330	0.061	0.609	1.021	0.026	0.045	0.056	0.052	0.053	0.034	0.035	0.033

Table 3: Descriptive Statistics (Cont'd)
Mean Values: 1950 - 1989

Ind. Code	C	S_L	S_K	S_M	S_Y	$\dot{L}$	$\dot{K}$	$\dot{M}$	$\dot{Y}$	$\dot{P}_L$	$\dot{P}_K$	$\dot{P}_M$	$\dot{P}_Y$
18	6.104	0.325	0.058	0.617	1.001	-0.022	0.003	-0.014	-0.011	0.050	0.031	0.036	0.036
19	27.299	0.325	0.130	0.545	1.003	0.011	0.022	0.029	0.026	0.054	0.033	0.040	0.040
20	72.056	0.231	0.097	0.672	0.995	-0.002	0.016	0.016	0.009	0.057	0.025	0.043	0.047
21	57.894	0.321	0.095	0.584	1.002	0.011	0.029	0.026	0.026	0.052	0.044	0.043	0.041
22	86.788	0.347	0.111	0.542	1.005	0.020	0.044	0.040	0.044	0.055	0.012	0.039	0.032
23	68.465	0.373	0.098	0.529	1.010	0.029	0.059	0.044	0.054	0.051	0.021	0.038	0.026
24	77.782	0.196	0.104	0.700	1.030	0.008	0.032	0.033	0.032	0.060	-0.002	0.039	0.034
25	55.191	0.375	0.049	0.576	0.991	0.029	0.044	0.048	0.046	0.056	0.040	0.040	0.041
26	29.179	0.386	0.101	0.512	1.003	0.042	0.067	0.054	0.061	0.053	0.007	0.038	0.031
27	13.843	0.321	0.096	0.583	1.009	0.004	0.022	0.024	0.030	0.049	0.044	0.040	0.031
28	103.799	0.433	0.159	0.408	1.010	0.009	0.011	0.032	0.030	0.055	0.052	0.041	0.037
29	49.513	0.404	0.346	0.250	1.075	0.016	0.057	0.049	0.060	0.060	0.045	0.042	0.027

Table 3: Descriptive Statistics (Cont'd)
Mean Values: 1950 - 1989

Ind. Code	C	S_L	S_K	S_M	S_Y	$\dot{L}$	$\dot{K}$	$\dot{M}$	$\dot{Y}$	$\dot{P}_L$	$\dot{P}_K$	$\dot{P}_M$	$\dot{P}_Y$
30	53.109	0.206	0.385	0.410	0.993	0.012	0.037	0.042	0.047	0.064	0.048	0.042	0.037
31	33.606	0.139	0.228	0.633	1.025	0.008	0.030	0.043	0.029	0.061	0.050	0.051	0.057
32	365.820	0.510	0.155	0.335	1.108	0.016	0.036	0.037	0.034	0.054	0.017	0.042	0.037
33	357.637	0.260	0.270	0.470	1.014	0.033	0.036	0.048	0.042	0.055	0.042	0.044	0.044
34	371.102	0.436	0.222	0.342	0.990	0.040	0.039	0.059	0.048	0.061	0.045	0.041	0.050
35	37.343	0.389	0.237	0.373	0.805	0.028	0.032	0.047	0.031	0.056	0.045	0.039	0.054

$\dot{S}$	$\dot{Z}$	$\dot{N}$	$\dot{P}_g$
0.034	0.033	0.013	0.042

Taking Agriculture, Forestry, and Fisheries (industry code 1) as an example, the average total cost of production from 1950-1989 is 104.581 billion dollars. Share of labor, S_L, constitutes 24.9 percent of total cost, while material's share (S_M) is 56.7 percent and capital's share (S_K) is 18.4 percent. The average value of output relative to total cost is 97.5 percent (S_Y). Over the period 1950-1989, output grew at the rate of 1.8 percent per year, labor declined at a rate of 1.3 percent per year, while material and private capital increased at a rate of 1.3 and 0.4 percent per year, respectively. Over the same period, output prices rose 2.7 percent per year, labor costs 5.5 percent per year, material costs 3.3 percent per year, and capital costs 4.7 percent per year.

As is clear from the descriptive statistics shown in Table 3, the size of the industries, measured by total cost, varies considerably. Food and kindred products, construction, transportation and warehousing trade, finance and other services which includes water supply, hotels, business services, health, social services, and agriculture are among the largest sectors in the economy. Other industries such as mining, tobacco, furniture and fixtures, and leather and leather products are relatively small.

In addition, factor cost shares vary considerably among the 35 industries. For example, labor’s share ranges from a low of about 0.06 in petroleum refining to a high of 0.51 in trade. Capital’s share of total cost also differs considerably among industries, ranging from 0.04 in apparel and other textile products to 0.38 in crude petroleum and natural gas. Generally, capital’s share of total cost, with few exceptions, is less than labor’s share. Material inputs on the other hand, have the largest share in total cost in almost all sectors or industries, ranging from 0.86 in petroleum refining to 0.25 in other transportation equipment.

The size and cost structure of the 35 industries under consideration vary considerably.[7] The level of their technology, as we shall observe, differs a great deal as well. Because of this degree of heterogeneity in our sample, the magnitude of the response of each industry to exogenous variables like aggregate income, population and the stock of highway capital will be quite different. In our estimation we explicitly account for industry differences in both cost and output demand. The final section of Table 3 provides the average growth rate of four national level variables that enter the industry demand and cost functions: highway capital stock, real GNP, U.S. population, and GNP price deflator, respectively.

---

[7] Some of the differences in size arise because some of the "industries" in our sample such as construction and trade are sectors unto themselves, while the manufacturing sector is composed of 21 two digit industries.

V. MODEL ESTIMATION

A. Cost and Demand Function Estimates

Both industry cost and demand functions are estimated to provide a direct link between the cost function and the aggregate economy. Estimates are obtained from equation (14), the demand function, and the system of factor demand equations (16) derived from the cost function (15). Two versions of the system of factor demands are estimated: in the first, Model A, public capital, S, is measured by total highway stock; in the second, Model B, S is measured by capital stock associated with the non-local component of the highway system - NLS (approximately the Federal-Aid system).

The demand and cost equations are estimated separately and their estimated parameters are used to decompose TFP growth according to equation (13). As noted earlier, the critical estimates for this decomposition are the price and income elasticities in the output demand function and the degree of scale and input substitution derived from the cost function:

- The price elasticity of demand is measured by the coefficient α in equation (14); $\alpha=0$ implies demand is perfectly inelastic; $\alpha=1$ implies demand is unitary elastic; and $\alpha>1$ implies demand is elastic; and
- The elasticity of demand with respect to per capita income is measured by the coefficient β.

Demand equations are estimated separately for each industry; that is, the growth rate of output within each industry is regressed on a constant, the growth rate of output price normalized by the GNP deflator and the growth rate of real income per capita. Thus, changes in quantity demanded in an industry are related to its own price movement in comparison to GNP deflator and changes in the level of aggregate income and population of the economy. Initial estimation revealed that in some industries the price or income elasticities had the incorrect sign. A different formulation of the demand functions was attempted by estimating the model with the industry panel data; we formulated alternative specifications of equation (14), introducing other variables in the demand function such as interest rate, unemployment rate, and the price of imports. The results of these alternative specifications did not differ much from those reported in Table 4.

As Table 4 indicates, the price elasticities of demand and the elasticity of demand with respect to per capita income vary across industries. The price elasticity of output demand is negative and statistically significant in almost all industries, and with the exception of a few industries, less than one. In two industries, metal mining and coal mining, the price elasticity has a positive coefficient and is statistically insignificant. These coefficients were set to zero and the demand equation was re-estimated. For several industries, construction and furniture and fixtures, for example, the demand function is price elastic (i.e., α greater than one). The magnitude of price elasticity varies considerably among the industries and in some cases is very small. Unfortunately, there are not many recent studies available to provide a basis for comparison. Houthakker and Taylor (1966) calculated price elasticities for different industries based on product classification rather than the industry classification used here. However, a comparison with their results in comparable cases indicates their estimated price elasticities are similar to ours.

The parameters of the underlying cost function are estimated using the equation system (16). This system of equations includes a labor to output equation, a capital to output equation and an intermediate input to output equation. These equations depend on private input prices P_{if}, the level of industry output Y_f, the industry's capacity utilization rate u_f, the time trend t, and the

Table 4: Estimation of Demand Function
Mean Values: 1950 - 1989

		Demand Parameters	
Industry Code	Industry Title	α	β
1	Agriculture, Forestry and Fisheries	-0.1668	0.2941
		(0.0867)	(0.2747)
2	Metal Mining	0.0000	2.6759
		(0.0000)	(0.6926)
3	Coal Mining	0.0000	0.8749
		(0.0000)	(0.5175)
4	Crude Petroleum and Natural Gas	-0.0006	0.9305
		(0.0404)	(0.2294)
5	Nonmetallic Mineral Mining	-0.3384	1.4828
		(0.2047)	(0.3567)
6	Construction	-1.0679	1.1653
		(0.3781)	(0.2522)
7	Food and Kindred Products	-0.2860	0.2083
		(0.0811)	(0.1217)
8	Tobacco Manufactures	-0.3324	0.0000
		(0.1650)	(0.0000)
9	Textile Mill products	-0.0450	1.5243
		(0.1988)	(0.3598)
10	Apparel and Other Textile Products	-0.7851	0.8606
		(0.3560)	(0.2548)
11	Lumber and Wood Products	-0.0245	1.1241
		(0.1369)	(0.3691)
12	Furniture and Fixtures	-1.5212	2.1414
		(0.4161)	(0.3014)
13	Paper and Allied Products	-0.1332	1.4088
		(0.1712)	(0.2658)

Table 4: Estimation of Demand Function Mean Values: 1950 - 1989 (Cont'd)			
		Demand Parameters	
Industry Code	Industry Title	α	β
14	Printing and Publishing	-1.2055	0.5191
		(0.3104)	(0.1761)
15	Chemicals and Allied Products	-0.1955	1.6242
		(0.1340)	(0.2434)
16	Petroleum Refining	-0.0172	0.8836
		(0.0555)	(0.2670)
17	Rubber and Plastic Products	-0.5038	2.4954
		(0.1867)	(0.3300)
18	Leather and Leather Products	-0.4701	0.8511
		(0.1820)	(0.3596)
19	Stone, Clay and Glass Products	-0.0335	2.0090
		(0.2535)	(0.2581)
20	Primary Metals	-0.5978	3.9766
		(0.2797)	(0.4857)
21	Fabricated Metal Products	-0.1782	2.3916
		(0.2400)	(0.2539)
22	Machinery, Except Electrical	-0.1635	3.1616
		(0.2767)	(0.3450)
23	Electrical Machinery	-0.7091	2.7025
		(0.4273)	(0.3449)
24	Motor Vehicles	-1.3693	3.8718
		(1.1966)	(0.9942)
25	Other Transportation Equipment	0.0000	3.2389
		(0.0000)	(0.8103)
26	Instruments	-0.1467	1.6766
		(0.3741)	(0.3051)

Table 4: Estimation of Demand Function
Mean Values: 1950 - 1989 (Cont'd)

		Demand Parameters	
Industry Code	Industry Title	α	β
27	Miscellaneous Manufacturing	-1.0034	1.0573
		(0.3009)	(0.3627)
28	Transportation and Warehousing	-0.5331	1.5610
		(0.1484)	(0.1478)
29	Communication	-0.7861	0.4414
		(0.0988)	(0.1235)
30	Electric Utilities	-0.3800	0.2740
		(0.1178)	(0.1473)
31	Gas Utilities	-0.0216	0.7539
		(0.1765)	(0.4849)
32	Trade	-0.8946	0.6612
		(0.1456)	(0.0951)
33	Finance, Insurance, and Real Estate	-0.1861	0.1032
		(0.1559)	(0.1167)
34	Other Services	-1.3969	0.2093
		(0.2313)	(0.1967)
35	Government Enterprises	-0.5275	0.2332
		(0.1498)	(0.1624)

level of total highway capital stock S. The sample consists of pooled time-series cross-section data for the 35 two-digit industries for the period 1950 - 1989. In order to capture industry specific effects we assume the parameters b_{LL}, b_{KK}, and b_{MM} are industry specific. Thus, we assume $b_{iif} = b_{ii} + h_{if} D_f$, where the parameters are normalized with respect to the k-th industry ($h_{ik}=0$), D_f is an industry dummy variable taking values either 1 or 0, and *f* is an industry identification index. Furthermore, to ensure invariant elasticity estimates, the pre-specified parameter vectors θ, γ, ϕ, and ψ were set equal to the average value of all input quantities in our sample. Estimation is carried out using an iterative seemingly unrelated regression approach (ISUR). Initial estimation revealed serial correlation in the residuals. Therefore, the equations were estimated with a correction for first order serial autocorrelation in the residuals. The serial correlation parameters are jointly estimated with other parameters of the model.

In order to account for highway capital other than NLS, we add an auxiliary equation of the form $g_2 = \alpha_0 + \alpha_1 g_1 + \alpha_2 t$ where g_1 and g_2 are respectively the NLS capital and the highway capital other than NLS, i.e., g2 equals total highway capital less NLS capital. The equation fit extremely well and the coefficient α_1 was statistically significant and highly stable with a magnitude of about 0.32. Various more complicated forms of this equation were also estimated but the estimates did not change much.

In estimating these models, we introduced interactive dummy variables to allow the slope parameters for highway capital stock services - c_{LS}, c_{KS} and c_{MS} - to vary by industry groups. In principle, we could introduce a full set of slope dummy variables (102 additional parameters) but it is not possible in an already complicated model. Rather, we classified the 35 industries into three groups - manufacturing (industry codes 7 through 27), service industries (industry codes 28 through 35), and other industries (industry codes 1 through 6). There are of course other ways to classify these industries that could be undertaken in future research.[7]

In Table 5, we present parameter estimates for both versions of the model. The estimated factor demand system in both models satisfy all the required regularity conditions: the estimated cost function is shown to be nondecreasing in output, linearly homogeneous in input prices, and concave in factor prices. The results shown in this table indicate that both models are well estimated with the parameter estimates statistically significant. Coefficients of the industry dummy variables, not shown in Table 5, were also statistically significant suggesting differences in the cost structure among industries. The square of the correlation coefficients between the actual and predicted values are high, and the standard errors of each equation are small in both versions of the model.

Comparing the coefficients of the cost function (15) for both versions of model, there is a remarkable similarity in both signs and magnitudes of the parameter estimates and their associated standard errors. The differences can be observed in the magnitudes of the parameter estimates associated with highway capital: the estimates of d_{SS}, c_S, c_{LS}, c_{KS}, and c_{MS} from Model B are approximately 1.5 times larger than those from Model A. One reason for this similarity is the high degree of correlation between the levels and variation of total highway capital and NLS capital. Even so, such stable parameter estimates in a complicated model are not necessarily guaranteed, pointing out the stability of the underlying model.

---

[7] An interesting approach is suggested by Fernald (1992). He uses "vehicle intensity" as a proxy for use of road infrastructure. It is measured as the ratio of the stock of trucks and cars in an industry to its total output. If an industry is vehicle-intense, then presumably it receives a lot of direct productive services from roads.

Table 5: Estimation of Cost Functions

Models A & B
1950 - 1989

	Model A		Model B	
Parameter	Estimate	Standard Error	Estimate	Standard Error
a_{LL}	-0.0519	(.855E-02)	-0.0528	(.857E-02)
a_{KK}	-.446E-02	(.103E-02)	-.448E-02	(.103E-02)
a_{LK}	-0.0138	(.166E-02)	-0.0138	(.166E-02)
a_{LM}	0.0657	(.827E-03)	0.0666	(.829E-02)
a_{KM}	0.0183	(.182E-03)	0.0183	(.182E-02)
a_{MM}	-0.0839	(.834E-03)	-0.0849	(.834E-02)
b_{LL}	0.2659	(.110E-00)	0.2764	(.104E-00)
b_{KK}	0.3487	(.620E-01)	0.3555	(.602E-01)
b_{MM}	0.7147	(.866E-01)	0.7316	(.823E-01)
b_{YY}	-.381E-03	(.911E-04)	-.387E-03	(.914E-04)
d_{SS}	.315E-06	(.656E-06)	.200E-06	(.124E-05)
c_{S}	.196E-03	(.125E-02)	.360E-03	(.177E-02)
b_{L}	0.5948	(.244E-00)	0.5872	(.230E-00)
b_{K}	0.9833	(.108E-00)	0.9780	(.103E-00)
b_{M}	-0.7395	(.346E-00)	-0.7588	(.326E-00)
c_{LS}	9.90E-05	(.156E-03)	1.57E-04	(.206E-03)
c_{KS}	-6.98E-05	(.766E-04)	-1.14E-04	(.102E-03)
c_{MS}	-8.44E-05	(.182E-03)	-1.57E-04	(.242E-03)
c_{LT}	-2.26E-03	(.110E-02)	-2.20E-03	(.107E-02)
c_{KT}	1.26E-03	(.587E-03)	1.37E-03	(.582E-03)
c_{MT}	3.73E-04	(.120E-02)	1.00E-03	(.112E-02)

Table 5: Estimation of Cost Functions (Cont'd)

Models A & B
1950 - 1989

	Model A		Model B	
Parameter	Estimate	Standard Error	Estimate	Standard Error
c_{LU}	-0.0644	(.865E-02)	-0.0639	(.864E-02)
c_{KU}	-0.0544	(.440E-02)	-0.0542	(.440E-02)
c_{MU}	-.385E-02	(0.0116)	-.381E-02	(0.0117)
r_K	0.9384	(.548E-02)	0.9390	(.545E-02)
r_L	0.9504	(.841E-02)	0.9520	(.811E-02)
r_M	0.9023	(.109E-01)	0.9044	(.107E-01)

Equation	Standard Error	R^2	D-W	Standard Error	R^2	D-W
Labor-Output	0.018	0.992	1.88	0.018	0.992	1.87
Capital-Output	0.009	0.992	1.942	0.009	0.992	1.95
Interm.-Output	0.024	0.981	1.85	0.024	0.981	1.85
Log of Likelihood		11546		11546		

B. Hypothesis Tests

We used the estimation results from Model A to econometrically test a number of hypotheses concerning the structure of the cost function. Log-likelihood ratios are used for the tests and the results are presented in Table 6.[8] The likelihood ratio tests suggest a decisive rejection of the joint hypothesis that the coefficients of the industry dummies are zero, suggesting that strong interindustry differences are present in the cost structure of the industries under consideration. Also, the hypothesis that the coefficient of public capital is zero in the cost function is also rejected (see Table 6, row 3). We also tested for constant returns to scale, as well as for the hypotheses of no technical change. These hypotheses were rejected as indicated by the χ^2 test statistics shown in the table (rows 4 and 5). Finally, we tested whether the contribution of the utilization rate is zero which was also rejected.

---

[8] The likelihood tests were carried out by first setting the dummies referring to individual parameters equal to zero. Then the same was done for the dummies of public input and the dummies for private inputs. The same process was also followed setting all the dummies except the public input dummies to zero, and finally, all the dummy coefficients were set to zero.

Table 6: Hypothesis Tests

Hypothesis	Parameter Restriction	Log of Likelihood	d.f.	χ^2/d.f.	$\chi^2_{c,.10}$/d. f	Test Result
No industry dummies	$\underline{h}_L=\underline{h}_K=\underline{h}_M=\underline{h}_{LS}=\underline{h}_{KS}=\underline{h}_{MS}=0$	11406.3	108	2.587	1.178	reject
No industry dummies	$\underline{h}_L=\underline{h}_K=\underline{h}_M=0$	11411	102	2.640	1.183	reject
No highway capital effects	$c_{LS}=c_{KS}=c_{MS}=c_S=d_{SS}=\underline{h}_{LS}=\underline{h}_{KS}=\underline{h}_{MS}=0$	11535.6	11	1.890	1.571	reject
Constant returns to scale technology	$b_L=b_K=b_M=b_{YY}=c_S=0$	11434	5	81.20	1.85	reject
No technical change	$c_{LT}=c_{KT}=c_{MT}=0$	11538.7	3	4.866	2.084	reject
No utilization rate effects	$c_{LU}=c_{KU}=c_{MU}=0$	11462.8	3	55.4	2.084	reject

Note: $\underline{h}$ is a vector of dummy parameters.

C. Sensitivity Tests

The infrastructure models reported in the literature, specifically those estimated using time series data, have been vigorously challenged on both conceptual and methodological grounds. The most important criticism of these types of models are identified as follows:

- Time series data on output and highway or infrastructure capital have common trends and therefore the significant positive relationship between productivity and infrastructure capital reported in the literature may be spurious (false) due to the presence of a common trend. One way to deal with this problem is to use some form of differencing of these variables. When Hulten and Schwab (1991) and Tatom (1991b) first-differenced their macroeconomic time series, the marginal product of public capital was much smaller and almost always statistically insignificant.
- Econometric models relating infrastructure and productivity are often misspecified because of missing variables. In the early 1970's energy prices rose dramatically at a time when the stock of infrastructure capital and overall productivity stopped growing. When Tatom (1991) controlled for the price of energy, the effect of infrastructure capital became weaker and statistically insignificant. However, his estimates are subject to another form of misspecification error since he introduced the price of energy as an argument of the production function. The appropriate way to test for the effect of the energy price shock is to estimate the cost function which has factor prices as one of the arguments.

- At the national level, it is not clear whether a decrease in infrastructure expenditure is due to a decrease in the level of aggregate output or vice versa. That is, whether infrastructure capital is an endogenous variable rather than an independent variable explaining the growth of output. Therefore, the issue of simultaneity between output and infrastructure (highway) capital must be dealt econometrically.

To meet these challenges, we carried out a number of experiments checking the sensitivity of our estimation results to alternative estimation procedures.

Spurious Correlation and Common Trend. The presence of common trend among variables in the time series models of infrastructure is a serious econometric issue. This criticism is equally applicable to production and cost function studies, whether they include public capital or not. It is true that private sector variables such as output, labor, materials, and private capital stock are highly correlated over time and may share a common trend. There is nothing particular about infrastructure or highway capital in this respect.

One method for removing a common trend is to estimate the model in a first-difference form. Estimation of this form eliminates a potential influence of trend which may be an over correction and not appropriate when we are seeking to trace the effect of public capital on the trend of the economy. Nonetheless, both Models A and B are estimated in “first-difference” form by setting the serial correlation parameter, ρ, to unity.[9] The parameter estimates are shown

---

[9] One way to estimate a model in “first difference” is to first difference the basic variables of the model such as$_i$, C, P u, s and then introduce these first differenced variables in equation (16). However, this approach will change the underlying cost model. For example, suppose a cost function C nonlinear in variable, i.e.

(a) $C_t = \alpha X_t + \beta X_t^2$.

We can estimate this model in first difference form in two ways:

(i) Rewrite the model as

$$C_t - \rho C_{t-1} = \alpha(X_t - \rho X_{t-1}) + \beta(X^2 - \rho X_{t-1}^2)$$

and let $\rho = 1$ That is

$$\Delta C_t = \alpha \Delta X_t + \beta \Delta X_t^2$$

(ii) First difference, the variables, C and x and rewrite model (a) as.

$$(C_t - C_{y-1}) = \alpha(X_t - X_{t-1}) + \beta(X_t X_{t-1})^2$$

in Table 7. As shown, the models fit the data very well and the estimated parameters are statistically significant. The elasticities derived from these parameter estimates have the correct sign and magnitudes similar to those when the models were estimated in level form. The fact that our results in levels, presented in Table 5, and first-difference forms, in Table 7, are quite similar is not surprising. The elasticities of output and inputs with respect to highway capital are stable in sign and magnitudes. The values of the serial correlation coefficients, ρ_l, ρ_k and ρ_m shown in Table 5 are very close to unity.

Missing Variables. The problem of missing variables, particularly the effect of the energy price increase, is accounted for in our estimation of the model. Although we have not included energy price as a separate variable, it is part of the price of intermediate inputs which is included in the cost function. In fact, one important reason why we selected the Jorgenson-Fraumeni data instead of data available from BEA is that it is constructed in the gross output framework so that it contains data on intermediate inputs while the BEA data refer to value added data. As noted earlier, a major way in which the economy benefits from public investment in the highway system is through the transportation of intermediate material inputs.

$$\Delta C_t = \alpha \Delta X + \beta [X_t^2 - 2X_t X_{t-1} + (X_{t-1})^2]$$

which implies that the basic cost function of approximately the form

$$(a')C_t = \alpha X_t + \beta X_t^2 - \beta X_t \cdot X_{t-1}$$

The difference between equations (a) and (a') will become more complex and pronounced as the degree of nonlinearity and interaction terms (as the case in equation system (16)) increases. The two cost functions will be the same if they are linear functions.

Table 7: Cost Functions Estimates: First Difference Results
1950 - 1989

	Model A		Model B	
Parameters	Estimate	Standard Error	Estimate	Standard Error
a_{LL}	-.0487	(.9077E-02)	-.0495	(.9107E--02)
a_{KK}	-.5105E-02	(.1060E-02)	-.5110E-02	(.1061E-02)
a_{LK}	-.0129	(.1757E-02)	-.0130	(.1759E-02)
a_{LM}	.0617	(.8758E-02)	.0625	(.8788E-02)
a_{KM}	.0181	(.1867E-02)	.0181	(.1869E-02)
a_{MM}	-.0798	(.8794E-02)	-.0806	(.8825E-02)
b_{YY}	-.4263E-03	(.1041E-03)	-.4276E-03	(.1039E-03)
c_{LS}	-.3146E-03	(.1221E-03)	-.3954E-03	(.1624E-03)
c_{LT}	-.4830E-02	(.9934E-03)	-.5017E-02	(.9538E-03)
c_{LU}	-.0647	(.9259E-02)	-.0642	(.9255E-02)
d_{SS}	.8415E-06	(.4803E-06)	.1420E-05	(.9074E-06)
b_L	.8971	(.2113)	.8908	(.1998)
c_S	-.2225E-03	(.1101E-02)	-.2858E-03	(.1549E-02)
c_{KS}	-.8886E-04	(.5536E-04)	-.1288E-03	(.7385E-04)
c_{KT}	.1396E-02	(.4797E-03)	.1463E-02	(.4607E-03)
c_{KU}	-.0547	(.4449E-02)	-.0546	(.4445E-02)
b_K	.9363	(.0938)	.9320	(.0896)
c_{MS}	-.2252E-03	(.1615E-03)	-.3671E-03	(.2141E-03)
c_{MT}	.7715E-03	(.1245E-02)	.1427E-02	(.1194E-02)
c_{MU}	.1070E-02	(.0116)	.1004E-02	(.0116)
b_M	-.6132	(.2839)	-.6291	(.2665)

Table 7: Cost Functions Estimates: First Difference Results (Cont'd) 1950 - 1989						
	Model A			Model B		
Equation	Standard Error	R^2	D.W.	Standard Error	R^2	D.W.
Labor-output	0.0199	0.9913	1.705	0.0199	0.9912	1.703
Capital-output	0.9667E-02	0.9920	1.916	0.0096	0.9920	1.920
Interm-output	0.0249	0.9797	1.901	0.0248	0.9796	1.901
Log of Likelihood	11299			11299		

Causality. The issue of causality between output and highway capital in the context of our time series-cross section data of a large number of industries is much less severe. An individual industry's specific needs for transportation services are not usually the dominant factor that will specifically influence investment in highways or other infrastructure capital. However, we performed a number of "causality tests" and the results suggest that aggregate highway capital can be considered as an exogenous variable in our industry cost functions. Furthermore, we re-estimated the model using a three stage least squares (3SLS) technique with lagged values of all exogenous variables as instruments. It should be noted that the problem of simultaneity between output and highway capital is more severe in production function studies than cost function studies as both output and highway capital appear as explanatory variables in the cost function. As a result, however, in the cost function approach multicollinearity between these two variables is likely to be very high.

Presentation of individual industry estimates generated by different econometric techniques would be too extensive. Rather, we present only the results for the aggregate economy based on the industry estimates. In Table 8, we present estimates of the critical parameters using different estimation techniques. Models A and B are estimated in first-difference form as noted earlier. They were re-estimated in this form using an instrumental variable maximum likelihood procedure. Models A and B were estimated in level form using 3SLS with 2 year lagged values of the independent variables as instruments. Also, a restricted form of the model where the industry utilization rates are used to convert highway capital stock into a service flow variable was estimated in both level and first difference forms.

Table 8: Alternative Model Estimation			
Model A	Scale	S	SMB
First Diff. ISUR/ML	1.05	-0.07	0.33
3SLS Inst.: X(-2)	< 1	-0.30	0.87
S^*U ISUR/ML	1.06	-0.10	0.37

Scale:	Internal Scale
S:	Cost Elasticity of Highway Capital
SMB:	Sum of Marginal Benefits

The parameters of interest are the degree of scale $1/\eta^*$, the cost elasticity with respect to highway capital and the sum of marginal benefits (SMB). One interesting feature of these results is the remarkable stability of these computed statistics across the different econometric specifications. The degree of scale is stable around 1.06 and the cost elasticity with respect to highway capital ranges from -0.06 to -0.08. The sum of marginal benefits, as we shall note later, is quite stable ranging from about 0.17 to 0.32. Of course, there are some differences in parameter estimates across different specifications arising from the number of industries involved in this study. However, the significant result is the stability of the magnitudes of the basic parameters of interest reported in Table 9 of the following section. These results suggest that it is important to develop a model that places sufficient structure on the data to obtain relatively stable parameter estimates.

VI. CONTRIBUTION OF HIGHWAY CAPITAL AT THE DISAGGREGATE INDUSTRY LEVEL

One of the most important properties obtained from the estimated cost function from the perspective of this study is the effect of highway capital stock on productivity and the cost structure of each industry. To calculate the direct productivity effect of highway capital stock, we need an estimate of the cost elasticity with respect to highway capital, S, and derive the contribution of S to the degree of scale in each industry. The indirect or "factor bias effect" can be measured by the impact of S on private sector input demand functions.

Using the estimated parameters shown in Table 5, we calculate the contribution of both total highway and NLS capital to:

- Cost reduction and scale of production;
- Demand for employment, private capital stock, and intermediate input;
- Marginal benefit of highway capital; and
- Total factor productivity.

A. Cost Reduction and Scale Elasticities

The industry cost elasticities with respect to total highway capital and NLS capital are shown in Table 9. Three basic elasticities of interest are reported:

- η_{CS} represents the private cost elasticity with respect to total highway capital or NLS capital. It is defined as $(\partial C/\partial S)\ C/S$ where $\partial C/\partial S$ is given by equation (17) and S refers to either total highway capital or NLS capital;
- η is the cost elasticity with respect to output, defined as $(\partial C/\partial Y)\ C/Y$. The marginal cost is $\partial C/\partial Y$ and is derived from the cost function (15). That is $(\partial C/\partial Y)_f = .5\sum_i \sum_j a_{ij} P_{if} P_{jf} / [\sum_i \theta_i P_{if}] + \sum_i b_{ii} P_{if} + [\sum_i c_{it} P_{if}]t + [\sum_i c_{iu} P_{if}]u_f + 2b_{yy}[\sum_i \gamma_i P_{if}]Y_f + [\sum_i c_{iS} P_{if}]\ S + d_{SS}\ [\sum_i \phi_i P_{if}]\ S^2$; and

- η^* is the cost elasticity of all inputs, including highway capital, with respect to output and is defined as $\eta/(1-\eta_{CS})$.

As shown in Table 9, an increase in either type of highway capital does not reduce the cost in all industries. Total highway capital and NLS capital reduce costs in all manufacturing industries (industry codes 7 to 27) but increase costs in all non-manufacturing industries. The magnitudes of the cost elasticities vary among the industries. In Model A, the cost elasticities in manufacturing industries range from -0.146 to -0.220 while in the non-manufacturing industries they range from +0.02 to +0.06. When we look at cost elasticities of NLS capital, a similar picture emerges. In fact, the pattern of these elasticities is quite similar to those for total highway capital except that the magnitudes of the cost elasticities are about 50 to 60 percent smaller with respect to NLS capital than with respect to total highway capital.

As will be discussed later, positive cost elasticities may imply that highway capital services are over-supplied in these industries. This does not mean that these industries do not have a demand for highway capital services. What is implied is these industries face “excess capacity” in highway capital, a situation similar to the notion of excess capacity in private capital stock in a private firm. If the firm cannot freely dispose of this capacity and is instead required to keep its capital stock fully utilized, regardless of changes in demand for its product, the cost to the firm will rise. In the case of highway capital, the entire capital stock enters the cost function of each industry. If industries are free to determine the optimum amount of highway capital services, they will choose a level where the marginal benefit of an additional unit of highway capital services is zero.

Table 9: Cost Function Elasticities - Models A & B Averages: 1950 - 1989							
		Cost Elasticities Model A			Cost Elasticities Model B		
Industry Code	Industry Title	η_{CS}	η	η^*	η_{CS}	η	η^*
1	Agriculture, Forestry and Fisheries	0.0531	0.9573	1.0122	0.0460	0.9568	0.9499
2	Metal Mining	0.0458	0.8049	0.8484	0.0402	0.8067	0.7867
3	Coal Mining	0.0488	0.9271	0.9775	0.0425	0.9279	0.8983
4	Crude Petroleum and Natural Gas	0.0615	0.9302	0.9953	0.0539	0.9296	0.8899
5	Nonmetallic Mineral Mining	0.0591	0.9231	0.9843	0.0513	0.9245	0.9148
6	Construction	0.0683	0.8280	0.8889	0.0593	0.8254	0.8144
7	Food and Kindred Products	-0.1677	0.9204	0.7911	-0.1432	0.9193	0.7871
8	Tobacco Manufactures	-0.2245	0.9801	0.8040	-0.1916	0.9807	0.8004
9	Textile Mill products	-0.1502	0.9742	0.8494	-0.1286	0.9743	0.8458
10	Apparel and Other Textile Products	-0.1463	0.9743	0.8521	-0.1251	0.9742	0.8492
11	Lumber and Wood Products	-0.1640	0.9758	0.8401	-0.1400	0.9759	0.8376
12	Furniture and Fixtures	-0.1585	0.9639	0.8334	-0.1353	0.9644	0.8319
13	Paper and Allied Products	-0.1678	0.9642	0.8273	-0.1432	0.9641	0.8244
14	Printing and Publishing	-0.2024	0.9562	0.7972	-0.1726	0.9560	0.7971
15	Chemicals and Allied Products	-0.1558	0.9557	0.8295	-0.1334	0.9553	0.8261
16	Petroleum Refining	-0.1740	0.9480	0.8096	-0.1486	0.9476	0.8070
17	Rubber and Plastic Products	-0.1625	0.9585	0.8262	-0.1388	0.9585	0.8234

Table 9: Cost Function Elasticities - Models A & B (Cont'd) Averages: 1950 - 1989							
		Cost Elasticities Model A			Cost Elasticities Model B		
Industry Code	Industry Title	η_{CS}	η	η^*	η_{CS}	η	η^*
18	Leather and Leather Products	-0.1676	0.9095	0.7805	-0.1429	0.9102	0.7798
19	Stone, Clay and Glass Products	-0.1771	0.9607	0.8174	-0.1509	0.9607	0.8155
20	Primary Metals	-0.2164	0.9166	0.7544	-0.1838	0.9158	0.7525
21	Fabricated Metal Products	-0.1728	0.9561	0.8169	-0.1475	0.9557	0.8147
22	Machinery, Except Electrical	-0.1553	0.9464	0.8206	-0.1323	0.9460	0.8177
23	Electrical Machinery	-0.1520	0.9534	0.8297	-0.1299	0.9531	0.8265
24	Motor Vehicles	-0.1897	0.9341	0.7872	-0.1620	0.9334	0.7843
25	Other Transportation Equipment	-0.1658	0.9599	0.8248	-0.1414	0.9596	0.8224
26	Instruments	-0.1876	0.8941	0.7528	-0.1601	0.8946	0.7497
27	Miscellaneous Manufacturing	-0.1469	0.9686	0.8464	-0.1256	0.9691	0.8446
28	Transportation and Warehousing	0.0287	0.9318	0.9593	0.0250	0.9309	0.9472
29	Communication	0.0264	0.9607	0.9870	0.0230	0.9606	0.9763
30	Electric Utilities	0.0354	0.9559	0.9916	0.0308	0.9556	0.9763
31	Gas Utilities	0.0209	0.9452	0.9672	0.0184	0.9450	0.9602
32	Trade	0.0209	0.7303	0.7431	0.0186	0.7263	0.7355
33	Finance, Insurance, and Real Estate	0.0242	0.7530	0.7689	0.0212	0.7493	0.7600
34	Other Services	0.0315	0.7548	0.7762	0.02730	0.7512	0.7647
35	Government Enterprises	0.0240	0.9698	0.9940	0.0208	0.9699	0.9858

The optimal level of these services can be estimated from the model which is the level at which the marginal benefit of highway capital is equal to an industry's marginal cost or willingness to pay. As we shall discuss later, estimates based on Models A and B imply a set of subsidies and taxes that would allow industries to use the optimum amount of highway capital services.

A reduction in the cost of production due to an increase in highway capital does not necessarily lead to a reduction in the output price paid by final consumers. How the reductions in production costs are passed through to consumers depends on the market structure within each industry. If, for example, an industry were perfectly competitive, cost reductions are fully passed to consumers in the form of lower prices. If, however, industries are not competitive, we expect at least that producer surplus is increased.[10] In addition, these elasticity measures are point estimates based upon the time period of the data. They do not imply the same level of cost savings will be achieved at every point in time.

Elasticities η and η^* shown in Table 9 have a returns to scale interpretation. The inverse of η, or $1/\eta$, represents internal returns to scale, or the effect on output of an equal proportional increase in all inputs except highway capital. That is, an equal proportional increase in labor, capital, and materials, holding highway capital fixed, yields a $1/\eta$ proportional increase in output. For example, in agriculture using the results of Model A, this proportional increase in output equals 1/0.958, or 1.0437. Similarly, the inverse of η^* represents total returns to scale, meaning that an equal proportional increase in all inputs, including highway capital, yields a $1/\eta^*$ proportional increase in output. Using the agriculture example, the proportional increase in

---

[10] In other words, as long as there is cost reduction from an increase in highway capital the producer surplus will increase independently from the market structure. However, consumers can also benefit depending on the structure of the market.

output equals 1/1.012, or .98. The results show that both η and η^* are less than one for all industries, except agriculture, in both models, indicating increasing internal and total returns to scale. These scale elasticities are not sensitive to whether we use total highway capital or NLS capital. They are of similar magnitudes in the same industries. The degree of internal returns to scale in each industry is smaller, as expected, compared with the degree of total returns to scale which accounts for the contribution of highway capital. Degree of scale ranges from 1.06 to about 1.2 in both Model A and Model B. These estimates are quite different and very much smaller than those estimated by Hall (1988). While our estimates suggest close to constant or a slight degree of scale, those estimated by Hall for the same industries are often quite large.

B. Effects of Highway Capital Stock on Demands for Labor, Capital and Materials

Highway capital has both direct and indirect effects on the productivity of the private sector. The direct effect arises from the assumption that the marginal product of public capital is positive, i.e., an increase in public capital services decreases private sector production costs. This in turn leads to an increase in the private sector output. The indirect effect arises from the notion that private and public capital are complements in production, i.e., the partial derivative of the marginal product of private capital with respect to public capital is positive. If private and public capital are complements, this hypothesis asserts that an increase in public capital raises the marginal productivity of private capital, and, given the rental price of capital, private capital formation increases, further raising private sector output.

In the cost function framework the direct effect of infrastructure capital is measured by the magnitude of the cost reduction due to an increase in public capital. The indirect effect is given by the magnitude of its effect on the demand for private sector factors of production. If all private inputs are substitutes with public capital, then an increase in public capital is always cost saving. The inverse, of course, is not true. The review of literature on the cost function supports the hypothesis that cost savings are associated with an increase of public capital. Hence, if one of the private inputs is a complement to public capital then cost savings can arise only if the substitution effects of the other private inputs outweigh the complementary effect (see also Seitz (1992b)).

It is clear, *a priori*, that no sign can be assigned to the indirect effect of public capital on the inputs of production. The direction and magnitude of the effect is an empirical question. Estimates in the literature support the hypothesis that labor and public capital are substitutes while the relationship between public capital and private capital is not clear cut. For instance, Conrad and Seitz (1992), Seitz (1992a,b) and Lynde and Richmond (1992) find that public capital and private capital are complements, while Shah (1992) and Nadiri and Mamuneas (1991) and Morrison and Schwartz (1991) find they are substitutes.

In Table 10, average values of the elasticities of conditional input demands with respect to total highway capital and NLS capital are presented. Conditional input demands refer to the demand for labor, capital, and intermediate inputs holding output constant. These elasticities (η_{is} for i=L, K, M) are calculated based on equation (18), with alternative measures of highway capital (S).

Elasticities of employment, private capital and intermediate inputs with respect to highway capital based on Models A and B produce the same signs and similar magnitudes. The magnitudes of these elasticities vary considerably across industries in both models. In Model A

Table 10: Elasticities of Conditional Input Demand
Mean Values: 1950 - 1989

		Model A			Model B		
Industry Code	Industry Title	η_{LS}	η_{KS}	η_{MS}	η_{LS}	η_{KS}	η_{MS}
1	Agriculture, Forestry and Fisheries	0.2736	-0.0594	0.0067	0.2362	-0.0508	0.0062
2	Metal Mining	0.2569	-0.1367	0.0188	0.2212	-0.1156	0.0168
3	Coal Mining	0.1974	-0.1628	0.0127	0.1703	-0.1379	0.0118
4	Crude Petroleum and Natural Gas	0.5295	-0.0994	0.0064	0.4557	-0.0844	0.0072
5	Nonmetallic Mineral Mining	0.2185	-0.0750	0.0196	0.1884	-0.0640	0.0175
6	Construction	0.2398	-0.2583	0.0075	0.2062	-0.2200	0.0070
7	Food and Kindred Products	-0.3937	-0.3147	-0.1124	-0.3376	-0.2687	-0.0958
8	Tobacco Manufactures	-0.5759	-0.0946	-0.2022	-0.4932	-0.0806	-0.1725
9	Textile Mill products	-0.2415	-0.2390	-0.1107	-0.2076	-0.2045	-0.0945
10	Apparel and Other Textile Products	-0.1723	-0.4646	-0.1141	-0.1478	-0.3946	-0.0974
11	Lumber and Wood Products	-0.2282	-0.1429	-0.1416	-0.1958	-0.1217	-0.1206
12	Furniture and Fixtures	-0.1749	-0.2336	-0.1389	-0.1499	-0.1989	-0.1183
13	Paper and Allied Products	-0.2387	-0.1777	-0.1384	-0.2046	-0.1514	-0.1179
14	Printing and Publishing	-0.2395	-0.1985	-0.1790	-0.2050	-0.1689	-0.1522
15	Chemicals and Allied Products	-0.2858	-0.1164	-0.1273	-0.2457	-0.0996	-0.1087
16	Petroleum Refining	-0.9757	-0.5934	-0.0852	-0.8370	-0.5042	-0.0728
17	Rubber and Plastic Products	-0.1797	-0.5934	-0.0852	-0.1544	-0.3701	-0.1105
18	Leather and Leather Products	-0.1731	-0.5370	-0.1308	-0.1478	-0.4554	-0.1114

Table 10: Elasticities of Conditional Input Demand (Cont'd)
Mean Values: 1950 - 1989

		Model A			Model B		
Industry Code	Industry Title	η_{LS}	η_{KS}	η_{MS}	η_{LS}	η_{KS}	η_{MS}
19	Stone, Clay and Glass Products	-0.1977	-0.2239	-0.1547	-0.1692	-0.1907	-0.1315
20	Primary Metals	-0.2786	-0.7365	-0.1255	-0.2383	-0.6224	-0.1067
21	Fabricated Metal Products	-0.2043	-0.2513	-0.1444	-0.1750	-0.2136	-0.1231
22	Machinery, Except Electrical	-0.1386	-0.3511	-0.1259	-0.1188	-0.2985	-0.1072
23	Electrical Machinery	-0.1400	-0.2932	-0.1345	-0.1202	-0.2492	-0.1149
24	Motor Vehicles	-0.3163	-0.4222	-0.1201	-0.2715	-0.3594	-0.1023
25	Other Transportation Equipment	-0.1593	-0.4394	-0.1476	-0.1365	-0.3731	-0.1257
26	Instruments	-0.1368	-0.6157	-0.1447	-0.1174	-0.5206	-0.1235
27	Miscellaneous Manufacturing	-0.1868	-0.1748	-0.1236	-0.1604	-0.1492	-0.1054
28	Transportation and Warehousing	-0.0763	-0.0716	0.1703	-0.0653	-0.0611	0.1464
29	Communication	-0.0648	-0.0345	0.2460	-0.0558	-0.0294	0.2119
30	Electric Utilities	-0.1586	-0.0321	0.1804	-0.1362	-0.0274	0.1552
31	Gas Utilities	-0.3600	-0.0835	0.1241	-0.3087	-0.0711	0.1063
32	Trade	-0.0693	-0.1243	0.2117	-0.0593	-0.1054	0.1820
33	Finance, Insurance, and Real Estate	-0.1241	-0.0621	0.1525	-0.1058	-0.0528	0.1310
34	Other Services	-0.0753	-0.0629	0.2254	-0.0642	-0.0536	0.1936
35	Government Enterprises	-0.0743	-0.0446	0.1749	-0.0632	-0.0378	0.1501

the magnitudes of the labor elasticity ranges generally from 0.06 in industry 29 to a high of 0.97 in industry 16. The elasticities are generally small in industries 28 through 35 except for industry 31. The elasticities of private capital with respect to total highway capital are larger in magnitude in the manufacturing industries than in non-manufacturing industries. The magnitudes of elasticities of intermediate inputs with respect to total highway capital are generally small, particularly in industries 1 through 6. They are relatively larger and positive in transportation, trade, and services.

The pattern that emerges from the elasticities based on Model A is that highway capital is a substitute for private capital in all industries, a substitute with labor in all manufacturing (industry codes 7-27) and services (industry code 28-35) while it is a complement to labor in other industries (industry codes 1-6). Finally, highway capital and intermediate inputs are complements in non-manufacturing industries and substitutes in the manufacturing industries. The main difference between the two versions of the model is that the magnitudes of the elasticities are smaller by a third to one-half in Model B. Therefore, the pattern of factor substitution and complementarity does not change with the Model B.

The general conclusion that arises is that changes in total highway capital or NLS capital have significant effects on the demand for private sector inputs in all industries. The conditional demand for labor, private capital and material inputs in the manufacturing industries will decline when investment in highway capital is increased. In the non-manufacturing industries, however, demand for labor and material is increased while demand for private capital is decreased in response to an increase in highway capital. Another feature of these results is that the pattern of complementarity and substitution of private sector inputs with respect to highway capital does not change whether we use total highway capital or NLS capital. The magnitudes of the elasticities, however, as expected, do differ.

C. Marginal Benefits

Recall that the marginal benefit of highway capital was defined to be the negative of the partial derivative of the cost function with respect to highway capital S (see equation (17)). This derivative can be interpreted as the marginal willingness to pay function and is defined as $m_f(P_f, Y_f, u_f, t, S) = - \partial C_f(P_f, Y_f, u_f, t; S)/\partial S$, where f refers to the industry. Table 11 reports the average marginal benefit (MB) of highway capital in current dollars for each industry over the sample period. The marginal benefits indicate how much each industry is willing to pay for an additional unit of highway capital services.

The magnitudes of the marginal benefits vary considerably across industries. The signs of the marginal benefits are the same for Models A and B, while the magnitudes are generally much larger in Model B, suggesting that the marginal benefits of NLS capital are in general larger than those of total highway capital. Another feature of the marginal benefits is that these estimates are increasing over time. After taking into account price changes, however, the marginal benefits in real terms appear to increase from 1950 to 1969 but decrease from 1970 to 1989 in each industry. An interesting feature is that all manufacturing industries have positive marginal benefits, i.e., they are willing to pay a positive amount for additional highway capital services, the amounts ranging from 0.002 in the leather and leather products industry to 0.029 in primary metals. Non-manufacturing industries, on the other hand, are willing to pay negative amounts, i.e., require a

Table 11: Marginal Benefits (MB) of Highway Capital
Mean Values 1950 - 1989

Industry		Model A		Model B	
Code	Title	MB	Tax(+) / Subsidy(-)	MB	Tax(+) / Subsidy(-)
1	Agriculture, Forestry and Fisheries	-0.01174	-0.01518	-0.0153	-0.0193
2	Metal Mining	-0.00041	-0.00061	-0.0005	-0.0008
3	Coal Mining	-0.00125	-0.00163	-0.0016	-0.0021
4	Crude Petroleum and Natural Gas	-0.00483	-0.00681	-0.0063	-0.0086
5	Nonmetallic Mineral Mining	-0.00071	-0.00092	-0.0009	-0.0011
6	Construction	-0.03465	-0.04384	-0.0450	-0.0559
7	Food and Kindred Products	0.04464	0.03936	0.0580	0.0518
8	Tobacco Manufactures	0.00339	0.00295	0.0044	0.0039
9	Textile Mill products	0.00735	0.00639	0.0096	0.0084
10	Apparel and Other Textile Products	0.01059	0.00927	0.0138	0.0122
11	Lumber and Wood Products	0.00816	0.00721	0.0106	0.0095
12	Furniture and Fixtures	0.00414	0.00367	0.0054	0.0048
13	Paper and Allied Products	0.01309	0.01168	0.0170	0.0154
14	Printing and Publishing	0.01624	0.01448	0.0211	0.0190
15	Chemicals and Allied Products	0.02228	0.02007	0.0290	0.0264
16	Petroleum Refining	0.02052	0.01858	0.0267	0.0245
17	Rubber and Plastic Products	0.01301	0.01178	0.0169	0.0155
18	Leather and Leather Products	0.00200	0.00164	0.0026	0.0022

Table 11: Marginal Benefits (MB) of Highway Capital (Cont'd)
Mean Values 1950 - 1989

Industry		Model A		Model B	
Code	Title	MB	Tax (+) / Subsidy(-)	MB	Tax (+) / Subsidy(-)
19	Stone, Clay and Glass Products	0.00904	0.00791	0.0118	0.0104
20	Primary Metals	0.02850	0.02413	0.0370	0.0318
21	Fabricated Metal Products	0.01887	0.01667	0.0245	0.0219
22	Machinery, Except Electrical	0.02582	0.02308	0.0336	0.0304
23	Electrical Machinery	0.02073	0.01870	0.0269	0.0246
24	Motor Vehicles	0.02711	0.02382	0.0352	0.0313
25	Other Transportation Equipment	0.01726	0.01519	0.0224	0.0200
26	Instruments	0.01016	0.00919	0.0132	0.0121
27	Miscellaneous Manufacturing	0.00398	0.00353	0.0052	0.0046
28	Transportation and Warehousing	-0.00718	-0.01080	-0.0093	-0.0136
29	Communication	-0.00348	-0.00472	-0.0045	-0.0059
30	Electric Utilities	-0.00468	-0.00627	-0.0061	-0.0079
31	Gas Utilities	-0.00275	-0.00400	-0.0036	-0.0050
32	Trade	-0.02178	-0.03594	-0.0283	-0.0449
33	Finance, Insurance, and Real Estate	-0.02331	-0.03530	-0.0303	-0.0442
34	Other Services	-0.02805	-0.03873	-0.0365	-0.0486
35	Government Enterprises	-0.00219	-0.00328	-0.0029	-0.0041

subsidy, for additional highway capital. From the point of view of non-manufacturing industries, this implies that highway capital is over-supplied.[11]

To illustrate the difference between the manufacturing and non-manufacturing industries first note that if the second derivative of the cost function with respect to highway capital is positive (d_{SS} in equation (15)) then the willingness to pay function will be downward sloping and can be interpreted as an industry's demand for highway capital. Figure 2 illustrates the demand curves of a representative manufacturing and non-manufacturing industry for public capital services.

Let S_0 be the observed level of highway capital and let m_m and m_n be the demand functions for public capital of the manufacturing and non-manufacturing industries, respectively. It can be seen that the S_0 constraint is binding for the manufacturing industry while at S_0 highway capital is oversupplied from the view point of the non-manufacturing industry. Thus, for a given level of highway capital, the manufacturing industry is willing to pay for an additional unit m_{m0}, while the non-manufacturing industry is willing to pay a negative price m_{n0}. In other words, at this level of highway capital a non-manufacturing industry requires a subsidy in order to use the entire highway capital. However, if the free disposal property is satisfied, i.e., additional units of S do not hurt the industry, or if the highway capital needed by the industries is not necessarily the

---

[11] The sign of marginal benefits depends on the sign of elasticities shown in Table 5 while magnitudes depend on the cost elasticity with respect to highway capital and the ratio of industry cost to highway capital stock. Since the ratio of industry cost to NLS capital is larger than the ratio of the cost to total highway capital while the cost elasticities with respect to two measures of highway capital are not substantially different, the size of marginal benefits for NLS capital are larger than those with respect to total highway capital.

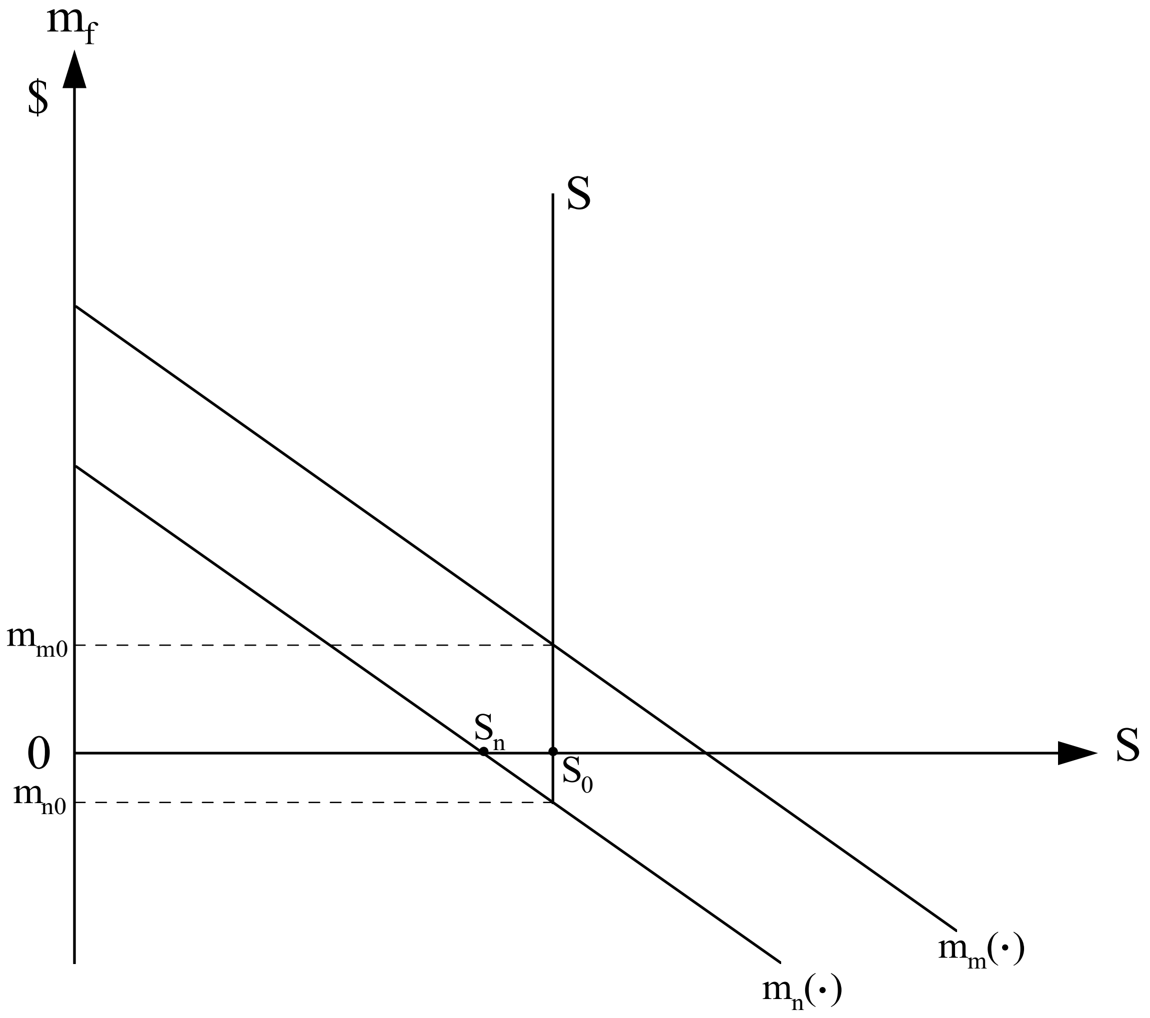


Figure 2: Demand for Public Capital Services

whole amount publicly provided, then the non-manufacturing industry will use the highway capital up to the point where the marginal cost and marginal benefit of an additional unit of highway capital are equated. Under the assumption of a free provision of highway capital this means that the non-manufacturing industry will demand S_n units.

The amount of taxes and subsidies of the various industries are shown in Table 11. These estimates are calculated at the optimal level of highway capital services demanded for both manufacturing and non-manufacturing industries.[12] The magnitudes of taxes and subsidies vary considerably. The largest taxes in manufacturing are in food and kindred products, chemicals and chemical products, primary metals, machinery except electrical, and motor vehicles. Construction, trade, finance, insurance, real estate, and other services require relatively large subsidies to encourage them to use the entire highway capital. Those that would "pay" the lowest taxes are tobacco manufacturing and leather and leather products. The lowest subsidies are in three industries: metal mining, coal mining and nonmetallic mineral mining. The magnitude of the subsidies and taxes implied by Model B are larger than those based on Model A, reflecting the larger magnitudes of the marginal benefits from NLS capital.

More careful analysis is required to examine further the size and pattern of the implied subsidies and taxes suggested by the estimates in Table 11. What is important to note is that the benefits of highway capital vary across industries. The needs of different industries for highway services diverge over time and the degree of benefits of new highway capital expansion may differ considerably among industries. That is, there is an important distributional effect of the public highway capital across industries that needs to be further examined. More careful examination and research is needed in order to ascertain the sign and magnitudes of the industry

---

[12] See Section VII(C) for discussion of optimal highway capital.

marginal benefits. There are a number of possibilities to explore in the future. One possibility is to classify industries into more detailed categories so that it can capture the diversity of industries. Another possibility is to refine highway capital data in such a way to incorporate the adjustments for quality and degree of congestion. Lastly, there is a need to take further account of missing variables, particularly the stock of infrastructure other than highway capital, in the model estimation. Other types of infrastructure do contribute to the growth of output and therefore may alter the magnitude and sign of the estimated marginal benefits.

D. Industry TFP Growth Decomposition

One of the fundamental goals in analyzing the effect of public infrastructure is to determine its contribution to productivity growth. As indicated at the outset of this report, this issue provides the rationale for much of the literature in this area. For example, in Aschauer's original study (1989), he attributes almost all of the slowdown in the rate of aggregate productivity growth to the slowdown in the growth of public infrastructure. To examine this issue further, we calculated the contribution of total highway capital to total factor productivity growth at the disaggregated industry level based on our estimated results.

The decomposition of TFP growth for Models A and B, based on their respective estimates provided in Table 5 using equation (13) are presented in Tables 12A and 12B, respectively, by individual industry. The magnitudes of the contribution of total highway capital and NLS capital differ somewhat across industries but the differences are not substantial.

Tables 12A and 12B include the factors contributing to TFP growth, reported as average annual rates of growth from 1951 through 1989:

- **Exogenous Demand**. Captures growth of real national income, aggregate population and changes in the utilization rate.
- **Relative Input Price**. Captures the growth of relative input prices.
- **Highway Capital**.[13] Captures the combined direct and indirect effects of the growth of highway capital.
- **Adjusted** $\dot{TFP}$. The effect of exogenous technical change, derived as the difference between $\dot{TFP}$, the final column in Table 12, and the exogenous demand, relative input price, and highway capital components.
- $\dot{TFP}$. Total factor productivity derived from the Jorgenson-Fraumeni data.

For brevity, the remainder of this section discusses the results obtained from Model A, although any major differences with Model B are noted. Using the agriculture sector as an illustration, total factor productivity grew at an average annual rate of 1.353 percent from 1951 through 1989.[14] Of this total, exogenous demand grew only 0.002 percent per year. Growth in relative input prices and highway capital contribute negatively to growth in total factor productivity, with an annual average of -0.052 percent and -0.107 percent, respectively. The largest contribution to agriculture's total factor productivity is exogenous technical change, which grew an average of 1.510 percent per year.

---

[13] Note in Table 12B, the contribution of highway capital is composed of the NLS (g1) and non-NLS (g2) portions. The sum of the two provides the contribution of total highway capital.

[14] This value represents the average of the annual growth rates calculated each year over the 1950-1989 period.

Table 12A: Decomposition of Total Factor Productivity Growth - Model A

Mean Values: 1951 - 1989

Industry Code	Industry Title	Exogenous Demand	Relative Input Price	Highway Capital	Adjusted $\dot{TFP}$	$\dot{TFP}$
1	Agriculture, Forestry and Fisheries	0.002	-0.052	-0.107	1.510	1.353
2	Metal Mining	0.234	0.058	-0.060	-0.432	-0.200
3	Coal Mining	0.030	0.010	-0.098	1.120	1.060
4	Crude Petroleum and Natural Gas	0.015	-0.021	-0.123	-1.243	-1.372
5	Nonmetallic Mineral Mining	0.098	-0.005	-0.105	0.883	0.856
6	Construction	0.453	0.162	-0.158	-0.345	0.092
7	Food and Kindred Products	0.399	-0.169	0.430	-0.126	0.577
8	Tobacco Manufactures	0.117	0.022	0.558	-0.421	0.209
9	Textile Mill products	0.292	-0.103	0.353	0.746	1.293
10	Apparel and Other Textile Products	0.082	-0.141	0.390	0.841	1.282
11	Lumber and Wood Products	0.330	-0.321	0.406	0.206	0.621
12	Furniture and Fixtures	0.409	-0.347	0.503	0.035	0.639
13	Paper and Allied Products	0.589	-0.426	0.420	-0.300	0.280
14	Printing and Publishing	0.684	-0.562	0.649	-0.808	-0.048
15	Chemicals and Allied Products	0.729	-0.592	0.384	0.386	0.904
16	Petroleum Refining	0.518	-0.121	0.427	0.111	0.933
17	Rubber and Plastic Products	0.827	-0.508	0.429	0.173	0.938
18	Leather and Leather Products	-0.441	0.237	0.474	0.258	0.537

Table 12A: Decomposition of Total Factor Productivity Growth - Model A (Cont'd)

Mean Values: 1951 - 1989

Industry Code	Industry Title	Exogenous Demand	Relative Input Price	Highway Capital	Adjusted $\dot{TFP}$	$\dot{TFP}$
19	Stone, Clay and Glass Products	0.419	-0.268	0.445	-0.287	0.310
20	Primary Metals	0.196	-0.146	0.667	-0.956	-0.285
21	Fabricated Metal Products	0.444	-0.246	0.440	-0.172	0.460
22	Machinery, Except Electrical	0.792	-0.427	0.400	0.298	1.072
23	Electrical Machinery	0.752	-0.409	0.406	0.722	1.512
24	Motor Vehicles	0.635	-0.355	0.645	-0.748	0.368
25	Other Transportation Equipment	0.973	-0.480	0.420	-0.364	0.548
26	Instruments	1.543	-0.750	0.469	-0.279	0.989
27	Miscellaneous Manufacturing	0.263	-0.196	0.412	0.824	1.280
28	Transportation and Warehousing	0.105	0.056	-0.043	0.927	1.060
29	Communication	0.075	0.356	-0.038	2.079	2.457
30	Electric Utilities	0.056	0.041	-0.048	1.168	1.222
31	Gas Utilities	0.125	-0.208	0.014	-0.188	-0.256
32	Trade	1.071	0.301	-0.026	-0.386	1.005
33	Finance, Insurance, and Real Estate	1.033	0.118	-0.028	-0.894	0.218
34	Other Services	0.768	0.086	-0.098	-2.169	0.091
35	Government Enterprises	0.034	-0.802	-0.044	-0.330	-1.144

Table 12B: Decomposition of Total Factor Productivity Growth - Model B
Mean Values: 1951 - 1989

Industry Code	Industry Title	Exogenous Demand	Relative Input Price	Highway Capital g1	Highway Capital g2	Adjusted $\dot{TFP}$	$\dot{TFP}$
1	Agriculture, Forestry and Fisheries	0.0019	-0.0524	-0.0990	-0.0100	1.5126	1.353
2	Metal Mining	0.2338	0.0579	-0.0570	-0.0074	-0.4268	-0.1999
3	Coal Mining	0.0284	0.0097	-0.0928	-0.0087	1.1241	1.060
4	Crude Petroleum and Natural Gas	0.0149	-0.0209	-0.1095	-0.0109	-1.2454	-1.372
5	Nonmetallic Mineral Mining	0.0979	-0.0208	-0.0969	-0.0110	0.8874	0.8563
6	Construction	0.4533	0.1353	-0.1458	-0.0150	-0.3351	0.0921
7	Food and Kindred Products	0.3996	-0.1337	0.4018	0.0331	-0.1236	0.5770
8	Tobacco Manufactures	0.1167	-0.0930	0.5204	0.0434	-0.3782	0.2091
9	Textile Mill products	0.2916	-0.0979	0.3305	0.0276	0.7415	1.2931
10	Apparel and Other Textile Products	0.0821	-0.0331	0.3648	0.0308	0.8375	1.2820
11	Lumber and Wood Products	0.3293	-0.3212	0.3800	0.0308	0.2021	0.6209
12	Furniture and Fixtures	0.4095	-0.3176	0.4701	0.0389	0.0382	0.6390
13	Paper and Allied Products	0.5886	-0.4295	0.3927	0.0323	-0.3041	0.2799
14	Printing and Publishing	0.6839	-0.5660	0.6053	0.0489	-0.8202	-0.0484
15	Chemicals and Allied Products	0.7292	-0.5887	0.3585	0.0297	0.3752	0.9037
16	Petroleum Refining	0.5185	-0.1226	0.3985	0.0323	0.1067	0.9333
17	Rubber and Plastic Products	0.8265	-0.5010	0.4007	0.0333	0.1786	0.9380
18	Leather and Leather Products	-0.4411	0.2556	0.4427	0.0360	0.2439	0.5367

Table 12B: Decomposition of Total Factor Productivity Growth - Model B (Cont'd)
Mean Values: 1951 - 1989

Industry Code	Industry Title	Exogenous Demand	Relative Input Price	Highway Capital g1	Highway Capital g2	Adjusted $\dot{TFP}$	$\dot{TFP}$
19	Stone, Clay and Glass Products	0.4192	-0.2676	0.4152	0.0336	-0.2907	0.3096
20	Primary Metals	0.1956	-0.1929	0.6225	0.0492	-0.9589	-0.2848
21	Fabricated Metal Products	0.4444	-0.2543	0.4113	0.0336	-0.1752	0.4597
22	Machinery, Except Electrical	0.7910	-0.4208	0.3742	0.0308	0.2966	1.072
23	Electrical Machinery	0.7522	-0.3866	0.3797	0.0323	0.7346	1.512
24	Motor Vehicles	0.6452	-0.2814	0.6022	0.0486	-0.6458	0.3684
25	Other Transportation Equipment	0.9730	-0.4799	0.3926	0.0315	-0.3687	0.5484
26	Instruments	1.5423	-0.7485	0.4378	0.0361	-0.2788	0.9887
27	Miscellaneous Manufacturing	0.2633	-0.2216	0.3848	0.0323	0.8217	1.280
28	Transportation and Warehousing	0.1307	0.0425	-0.0396	-0.0050	0.9312	1.060
29	Communication	0.0756	0.3378	-0.0353	-0.0046	2.0832	2.457
30	Electric Utilities	0.0557	0.0455	-0.0429	-0.0063	1.1695	1.222
31	Gas Utilities	0.1254	-0.2074	0.0140	-0.0025	-0.1860	-0.2561
32	Trade	1.071	0.34067	-0.0247	-0.0044	-0.3773	1.005
33	Finance, Insurance, and Real Estate	1.036	0.1040	-0.0256	-0.0040	-0.8916	0.2182
34	Other Services	2.7676	-0.4227	-0.0918	-0.0112	-2.1469	0.0911
35	Government Enterprises	0.0338	-0.8076	-0.0405	-0.0042	-0.3259	-1.144

In general, changes in exogenous demand contribute over half of TFP growth, mainly in the manufacturing industries. Its contribution in agriculture, extractive and mining industries and government enterprises are rather small. In construction, instruments, transportation equipment and trade and finance, the contribution of an increase in demand is relatively large.

The sign of the contribution of relative input prices could be positive or negative depending on whether industry factor price changes exceeded that of the general economy or not. When an industry's rate of input price inflation exceeds the national inflation rate, productivity growth is hampered. Generally, growth in relative input prices contributes negatively to TFP, although there are several exceptions. The magnitude of this effect varies across industries ranging from -0.750 in the instrument sector to 0.356 in the communications industry. Compared to the contribution of exogenous demand, the relative input price effects on TFP growth are relatively small.

Highway capital's contribution to TFP growth is positive in all the manufacturing industries and in some of these industries its contribution is relatively large, accounting for almost one third of TFP growth. In non-manufacturing sectors, growth in highway capital contributes negatively to productivity growth. This negativity can be explained, as noted earlier, as the result of an excess supply of highway capital in these industries. When account is taken of the effects of demand, relative input price changes, and highway capital, the rate of technical change is much smaller than conventionally calculated. In general the main causes of TFP growth in the manufacturing industries are exogenous shifts in demand, relative price changes, and highway capital, while in the non-manufacturing industries the dominant factor is the scale effect, or exogenous technological change.

Regarding the speed of change in TFP growth, highway capital plays only a minor role in the acceleration or deceleration of TFP growth at the industry level. The sample period was divided into four sub-periods: period I, 1952-1963; period II, 1964-1972; period III, 1973-1979; and period IV, 1980-1989. In several industries, the contribution of highway capital to the deceleration of TFP growth between periods II and III was fairly large, about one-third, but in the majority of industries, there was little or no systematic relationship.

The magnitudes of the contribution of highway capital between periods III and IV were generally very small. It appears that total highway capital contributes at varying degrees to the long term growth of TFP in various industries but its contribution to the acceleration or deceleration of industry TFP growth over the sub-periods is negligible.

The contribution of NLS capital to industry TFP growth is similar to that of total highway capital although some differences in magnitude appear in several industries. Generally, the size of the contributions of exogenous demand and relative prices to TFP growth remain the same as indicated in Table 12A. The contribution of NLS capital to TFP growth, however, is generally smaller than that of total highway capital. The contributions of non-NLS highway capital are similar to those of NLS in sign, but its contributions are much smaller than those of NLS. Finally, the contribution of NLS capital to the acceleration or deceleration of TFP growth was similar to that of total highway capital.

VII. CONTRIBUTION OF HIGHWAY CAPITAL AT THE TOTAL ECONOMY LEVEL

Industry specific results reported in previous sections were used to calculate the contribution of highway capital stock to the overall economy. Two different approaches were taken:

- In the first, the individual industry elasticities are averaged to obtain "*aggregated*" estimates;
- Secondly, the industry level data is summed to the national level prior to estimation of Models A and B; these models are then re-estimated with the national level data. The resulting estimates are referred to as "*aggregate*" estimates.

Parameter estimates from the national cost function using the aggregated industry data are presented in Table 13 for Models A and B.[15] Judging from the parameter estimates and goodness of fit statistics shown in the table, the models are well estimated. The coefficients are statistically significant and the elasticities generated using the estimated coefficients have the correct signs with reasonable magnitudes. When comparing parameter estimates of Model A and Model B, the only notable differences are some changes in magnitudes and signs of coefficients associated with highway capital measures d_{SS}, c_S, c_{LS}, c_{KS}, and c_{MS}. This was also the case when these models were estimated using pooled cross section data for the 35 industries (see Table 5).

In the alternative approach, national average "aggregated" elasticities are obtained from industry estimates weighted by their respective industry input and output shares of total cost. For

---

[15] Recall that the industry coverage underlying the data includes the entire US economy. Thus, the output measure includes material inputs, and, as a result, is substantially larger than GNP, which represents value-added.

Table 13: Estimates of the Aggregate Cost Function
Models A and B
1950 - 1989

	Model A		Model B	
Parameter	Estimate	Standard Error	Estimate	Standard Error
a_{LL}	-0.0334	(.181E-01)	-0.0342	(.0194)
a_{KK}	-0.896E-01	(.645E-02)	-0.803E-02	(.6189E-02)
a_{LK}	0.0173	(.675E-02)	0.0166	(.6831E-02)
a_{LM}	0.0161	(.162E-01)	0.0176	(.0175)
a_{KM}	-0.834E-02	(.475E-02)	-0.855E-02	(.4641E-02)
a_{MM}	-7.77E-02	(.118E-01)	-0.910E-02	(.0134)
b_{LL}	0.2515	(.640E-01)	0.2251	(.0602)
b_{KK}	0.1700	(.349E-01)	0.1615	(.0326)
b_{MM}	0.5766	(.699E-01)	0.6085	(.0619)
b_{YY}	-0.438E-04	(.113E-04)	-0.457E-04	(.1158E-04)
d_{SS}	0.293E-06	(.644E-06)	0.125E-06	(.1126E-05)
c_S	-0.9220	(.674E-00)	-1.744	(.8028)
b_L	7.479	(.104E+01)	7.774	(9.765)
b_K	1.507	(.540E+00)	1.675	(.5171)
b_M	0.2640	(.115E+01)	0.5495	(.1028)
c_{LS}	-0.803E-04	(.180E-03)	0.150E-04	(.2143E-03)
c_{KS}	1.79E-05	(.639E-04)	0.703E-04	(.7664E-04)
c_{MS}	-0.345E-05	(.219E-03)	0.763E-04	(.2592E-03)
c_{LT}	0.275E-02	(.894E-03)	0.257E-02	(.9163E-03)
c_{KT}	0.174E-02	(.362E-03)	0.174E-02	(.3719E-03)
c_{MT}	0.135E-02	(.108E-02)	0.107E-02	(.1104E-02)

Table 13: Estimates of the Aggregate Cost Function
Models A and B
1950 - 1989

	Model A		Model B	
Parameter	Estimate	Standard Error	Estimate	Standard Error
c_{LU}	0.0625	(.279E-01)	0.0651	(.0282)
c_{KU}	-0.0725	(.158E-01)	-0.0742	(.0154)
c_{MU}	0.0425	(.283E-01)	0.0368	(.0272)

Equations	R^2	R^2
Labor-Output	0.996	0.996
Capital-Output	0.837	0.836
Interm.-Output	0.718	0.741
Log of Likelihood	469	469

example, to find the aggregate impact of highway capital on total cost for the economy we define the cost elasticity of highway capital for industry *f* as $\eta_{csf}=(\partial C_f/\partial S)\ (S/C_f)$, and obtain the "aggregated" cost elasticity obtained from

$$\eta_{cs} = [\Sigma_f(\partial C_f/\partial S)]\ (S/\ S_fC_f)= \Sigma\eta_{csf}(C_f/\ \Sigma_fC_f).$$

That is, the "aggregated" cost elasticity is a cost weighted average of individual industry elasticities. Using the envelope condition, the output elasticity of highway capital is equivalent to the negative of the ratio of the elasticity of cost over the cost elasticity of output.[16] Thus the output elasticity of highway capital for the economy is given by $\varepsilon_{ys}=-\eta_{cs}/\eta$, where $\eta=\Sigma_f(\eta_f\ C_f/\Sigma_fC_f)$ is the cost weighted average of output cost elasticities of the industries in our sample.

A. Aggregate Output and Cost Elasticities

Tables 14A and 14B present the effect of the total highway and NLS capital stocks, respectively, on aggregate private sector cost and aggregate input demand functions based on the "aggregated" and “aggregate” estimates. The two sets of estimates based on Model A are quite similar: the "aggregated" cost elasticity is about -.044 which is virtually the same as the -.040

---

[16] Under cost minimization the Lagrangian is given by

$$L\ (Y, P, S, T;\lambda) = C\ (Y, P, S, T) + \lambda\ [F(\bullet) - Y],$$

Applying the envelope theorem, it is

$$\partial L / \partial S_k = \partial C / \partial S_k + \lambda\ F_j = 0, \forall\ j$$

$$\partial L / \partial Y = \partial C / \partial Y - \lambda = 0,$$

where $F_j = \partial Y/\partial S_k$ and λ is the Lagrangian multiplier. Multiplying the second condition by $_k$/SY and using the third, the relationship between public capital output elasticity and public capital cost elasticity is given by

$$\partial \ln Y / \partial \ln S_k = -(\partial \ln C / \partial \ln S_k) / (\partial \ln C / \partial \ln Y), \forall\ k,$$

which provides the linkage between the production function approach and cost function approach. This condition can be used to recover the public capital output elasticities from the public capital cost elasticities.

Table 14 A:
Effect of Total Highway Capital, S, on Cost and Factors of Production,
Sum of Marginal Benefit, Cost Elasticities
Average Values

Total Highway Capital	η_{CS}	η_{LS}	η_{KS}	η_{MS}	η	η^*	$\sum_{f=1}^{F} m_f$
"Aggregated"	-.044	-.083	-.122	-013	.862	.826	.18
Aggregate	-.040	-.116	.005	-.018	.719	.692	.09

Table 14 B:
Effect of NLS Capital, S, on Cost and Factors of Production,
Sum of Marginal Benefit, Cost Elasticities
Average Values

NLS Capital	η_{CS}	η_{LS}	η_{KS}	η_{MS}	η	η^*	$\sum_{f=1}^{F} m_f$
"Aggregated"	-.038	-.071	-.105	-.011	.741	.706	.234
Aggregate	-.0488	-.0939	.0636	-.0544	.7414	.7063	.2473

obtained by estimating the cost function (16) with aggregate data. The elasticity of labor with respect to highway capital is negative and somewhat higher when aggregate estimates are used. These results suggest that highway capital is labor saving at the aggregate economy level. The elasticity of private capital with respect to total highway capital is negative in the "aggregated" approach while it is positive and very small in the aggregate approach. The elasticity of intermediate inputs with respect to total highway is negative and small in both approaches.

The degree of returns to scale, the reciprocal of η and η_c*, differs in the two approaches but both suggest increasing returns to scale. The sum of marginal benefits (SMB), generated by the two approaches are not close to each other. The "aggregated" approach generates an estimate of SMB equal to 0.18, a value almost twice as large as that of the aggregate approach, 0.09.

Using the same approach, the elasticity measures for NLS capital are calculated and presented in Table 14B. The magnitudes of costs and input elasticities with respect to NLS are higher in the “aggregate” approach than those generated by the “aggregated” approach. The results are similar to those shown in Table 14A. The magnitudes of the cost and input elasticities are somewhat smaller when NLS capital is used as a measure of S. Also, the magnitude of internal scale, $1/\eta$, and total scale, $1/\eta^*$, are larger in Model B. What is important, however, is that the sum of marginal benefits using NLS capital is almost the same whether we use the “aggregated” or “aggregate” approach; they are greater than those generated using total highway capital as measure of S. This result suggests that the rate of return to NLS capital is larger than for the total highway capital, which is consistent with the individual industry results reported in Table 11.

Output elasticities of inputs and utilization rate and the rate of technical change at the aggregate economy level are shown in Tables 15A and 15B. The "aggregated" output elasticities are calculated by converting industry cost elasticities to the corresponding output elasticities and then aggregating them. For the aggregate approach, we convert the national cost elasticities to output elasticities. The results in Tables 15A and 15B are quite similar, which suggests the results are not sensitive to whether total highway or NLS capital is used as a measure of highway capital. The output elasticity of material inputs (ε_{YM}) is large, around 0.60 - 0.70, followed by that of labor (ε_{YL}), approximately 0.40 to 0.45, and the output elasticity of capital (ε_{YK}) at approximately 0.20. The rate of autonomous technical change (ε_T) is small and it has the wrong sign (negative) in the aggregate approach. The output elasticity of highway capital (ε_{YS}), in comparison to those of the private sector inputs, is relatively small, approximately 0.04 - 0.06.

It is important to note that the output elasticity of private sector capital is clearly larger than the output elasticity of highway capital. The results indicate a one percent change in private capital stock contributes almost four times as much as a one percent change in highway capital stock to growth of output of the economy. Compared to previous findings (see Table 1), our estimates of output elasticities of highway capital are small. In fact, the elasticity estimates originally reported in Aschauer (1989), Holtz-Eakin (1988) and Munnell (1990) are about eight times as large as our estimates for the aggregate economy. Our estimates are more comparable to output elasticities of public capital reported in Duffy-Deno and Eberts (1989) and Eberts (1990) for the highly disaggregate level of the Metropolitan Area.

Table 15 A: Output Elasticities of Factor Inputs, Total Highway Capital, Utilization Rate, Rate of Technical Change						
Model A	ε_{YL}	ε_{YK}	ε_{YM}	ε_{YS}	ε_{YU}	ε_{T}
"Aggregated"	.384	.185	.605	.051	.142	.001
Aggregate	.454	.219	.716	.056	-.016	-.008

Table 15 B: Output Elasticities of Factor Inputs, NLS Capital, Utilization Rate, Rate of Technical Change						
Model B	ε_{YL}	ε_{YK}	ε_{YM}	ε_{YS}	ε_{YU}	ε_{T}
"Aggregated"	.348	.185	.605	.044	.142	.001
Aggregate	.443	.214	.698	.064	-.009	-.007

B. Net Social Rates of Return

One question which has been raised in the literature and has important public policy implications is whether public capital is over- or under-supplied. The optimal provision of public capital services (highway capital) can be derived by the well-known Samuelson condition, as modified by Kaizuka (1965). This condition requires that public capital be provided at the point where the sum of marginal benefits of producers and consumers is equal to the marginal cost of providing an additional unit of public capital. Ignoring the consumption sector, an alternative means of determining whether public capital is provided optimally is to compute the rate of return to highway capital and compare it with the rate of return to private capital for the whole economy. The optimal provision of public capital requires that the rates of publicly provided and private capital be equalized. Thus, if the rate of return of highway capital is higher than that of private capital, highway capital is under-supplied and an increase of public investment is necessary.

Nadiri and Mamuneas (1993a) find that the rate of return of public infrastructures implied by the industries of the manufacturing sector is about 7 percent, while the rate of return of private capital is about 9 percent. Morrison and Schwartz (1991) take another approach. They compare the shadow price of public capital with the "user cost" of public capital, and find that Tobin's q ratio of public investment exceeds one, suggesting that infrastructure investment has been too low for social optimization for the manufacturing sector of all regions in their sample. Similarly Shah (1992) estimates a Tobin's q equal to 1.04 for the Mexican manufacturing sector, and concludes there is an indication of under-investment in public capital. Berndt and Hansson (1992), by equating the marginal benefit of public infrastructures with its ex-ante rental price, solve for the optimal capital stock and then calculate the ratio of the optimal level of the public capital stock to the actual public capital. They find that this ratio is above one for the period 1960 to 1970, below one for the period 1970-1990, suggesting over-investment.

Assume the government chooses the amount of highway capital by minimizing the present value of the costs of all the resources of the economy. That is, government selects the level of public capital such that the sum of the industry marginal benefits equals the user cost of public capital, i.e.,

$$(20) \qquad \sum_{f-1}^{F} m_f(P_f, Y_f, u_f, t, S^*) = \sum_{f-1}^{F} - \frac{\partial C_f}{\partial S} = P_s(\rho + \delta)$$

where P_s is the acquisition price, ρ is the discount factor and δ is the depreciation rate of highway capital. The optimal amount of highway capital can be found by solving equation (20) for S*.

From equation (20) the net social rate of return from public capital can be derived as the ratio of the sum of marginal benefits to cost minus the depreciation of public capital, i.e.,

$$(21) \qquad \gamma_s = \frac{\sum_{f=1}^{F} m_f(P_f, Y_f, u_f, t, S)}{P_S} - \delta.$$

This rate of return on highway capital is calculated assuming the user cost of highway capital is $Q_s = P_g(\gamma_s + \delta)(1 + \varpi)$ where P_g is government capital price deflator, δ is the depreciation rate of highway capital and ϖ is the price distortion effect of taxes levied to finance highway capital (ϖ is set to 0.46; see Jorgenson and Yun (1990)) This distortion effect arises because no country relies extensively on head taxes to finance infrastructure capital. Distortionary taxes (e.g., an income tax) are often used to fund public investments. Therefore, the social cost of additional public capital is the sum of the direct burden of the taxes needed to pay for the infrastructure and the dead weight cost associated with these taxes.

The net social rate of return to total highway capital γ_{sT} and to NLS capital γ_{sN} , the net rate of return to private capital stock γ_k and the interest rates of ρ are shown in Table 16 for four different sub-periods. The social rate of return on total highway capital, γ_{sT}, during the 1950's and 1960's was very high, reflecting the shortage of highway capital stock during the 1950's when the Interstate Highway System was under construction. This rate has declined continuously since the late 1960's and in 1989 it is barely above the level of the long term interest rate. The rate of return on NLS capital γ_{sN}, is higher than that for total capital, γ_{sT}, for the entire period.

The time profile of the net social rate of return for total highway capital is shown in Figure 3. The rate begins at a relatively high level, rising to its maximum level in 1955 and fluctuates around 37 percent until 1968. Thereafter, the net rate of return starts to decline and falls below 10 percent in 1985 to about 5 percent in 1989. When NLS is used as a measure of highway capital, Model B, the net rate of return traces the same pattern as shown in Figure 3. The estimates of γ_{sN} for NLS, however, are constantly above those for total highway capital reflecting higher marginal benefits from NLS as noted earlier. The rate of return to NLS also declined since 1970, with much lower levels in the 1980s. The value of γ_{sN} for NLS was 13 percent in 1980 and 9 percent in 1989, values higher than those for γ_{sT}. When γ_{sT} and γ_{sN} are compared with the interest rate over the period 1950 - 1989, the gap between these rates and ρ is very large from the beginning of the period until the 1970s. By 1980, the gap narrows considerably, and almost disappears in the 1980s, particularly in the case of total highway capital.

Table 16

Net Rate of Return from Total Highway Capital,

Private Physical Capital, and Interest Rates

Net Social Rate of Return	1950-1959	1960-1969	1970-1979	1980-1989	1950-1989
Total Highway Capital g_{ST}	.352	.348	.161	.100	.281
NLS Capital g_{SN}	.479	.474	.238	.161	.338
Private Capital Stock g_K	.134	.140	.120	.110	.133
Interest Rate r	.04	.05	.08	.110	.07

Table 17

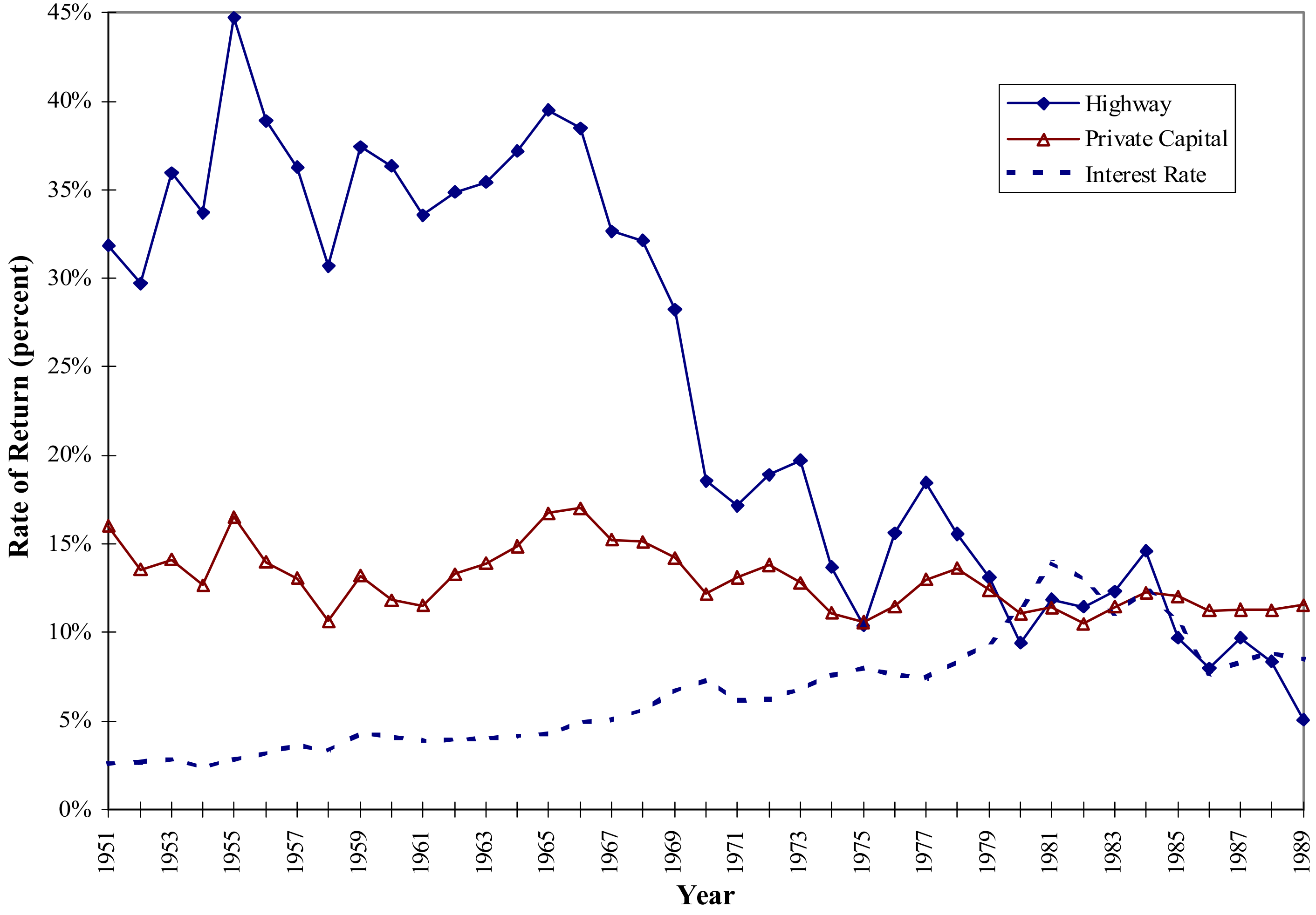
The Ratio of Optimal to Actual Stock of

Highway Capital (S*/S)

Ratio of S*/S	1950-1959	1960-1969	1970-1979	1980-1989	1950-1989
Total Highway Capital Model A	3.057	1.678	1.112	0.995	1.710
NLS Capital Model B	3.831	1.851	1.186	1.043	1.978

Figure 3

Net Rate of Return of Highway Capital, Private Capital, and Private Interest Rate (1951-1989)



The net rate of return on private capital is calculated as $\gamma_k = \frac{\partial Y}{\partial K} - \delta_k = \frac{W_k^*}{P_y} - \delta_k$ where W^*_k is the user cost of private capital ($W^*_k = P_k (\gamma_k + \delta_k) * Tax$). Table 16 indicates the net rate of return on private sector capital, γ_k, averaged approximately 14 percent from 1950-1969, and then declined in the 1970s and 1980s. This rate exceeded the interest rate over most of period as shown in Figure 3. The net social rate of return from highway capital is very high in 1950-1973 when compared to net rate of return on private capital and the interest rate. Since 1965 and in 1970-1989 period, all three rates, γ_{sT}, γ_k and ρ, converged to about 10 percent. While the rate of return on NLS capital is somewhat higher based on this set of evidence, there seems to be no excessive rate of return to highway capital since 1979 and the rates of return to public and private capital have been nearly equalized.

The results of Table 16 are much lower than previously reported in the literature. Recently, Fernald (1992) estimated the rate of return to investment in roads using essentially the same set of data as used in this study. He concluded that "a conservative statement -- is that the data strongly supports the view that roads investments are highly productive, offering rates of return of 50% to100%, perhaps more."[17] Our results suggest rates of return well below Fernald's lower bound estimated rate of return. Our average rate of return for the period 1950 - 1989 is 28 percent, about half of his rate of return of 50 percent. Even so, the rate of return, particularly to that on NLS investment, over the postwar period has been quite impressive, although in recent years the returns to highway capital have converged to those estimated for private capital stock.

---

[17] Fernald (1992) p. 26

C. Optimal Highway Capital Stock

We calculated the optimal stock of highway capital from estimates for marginal benefits obtained from both Models A and B, based upon equation (20). As previously noted, industries differ in their use of highway capital, and therefore, the magnitude and even the sign of the marginal benefit differs. Therefore, the optimal stock of highway capital, S^*, will depend on how the marginal benefit is calculated. To illustrate this point, consider the case of two industries, manufacturing and non-manufacturing. The optimal amount of highway capital, S^*, is found at the intersection of the sum of marginal willingness to pay function with marginal cost of public capital, point E in Figure 4. The ratio S^*/S_0 will imply a degree of under-investment or over-investment in the highway capital. In Figure 4, any marginal cost intersecting the sum of marginal willingness to pay functions, Sm_f, below point A implies an over-investment, while an intersection above point A suggests under-investment. Note that the difference between actual and optimal highway capital depends critically on the estimates of marginal cost of highway capital.

We calculate the optimal level of highway capital for each year using the sum of industry marginal benefits obtained from Models A and B. These optimal values are compared with the actual level of highway capital and the average ratios S^*/S are reported in Table 17. Two striking results emerge:

- For Models A and B, the ratio S^*/S is very high during the 1950s but declines dramatically thereafter.
- The ratios based on Model A are slightly lower than those derived from Model B.

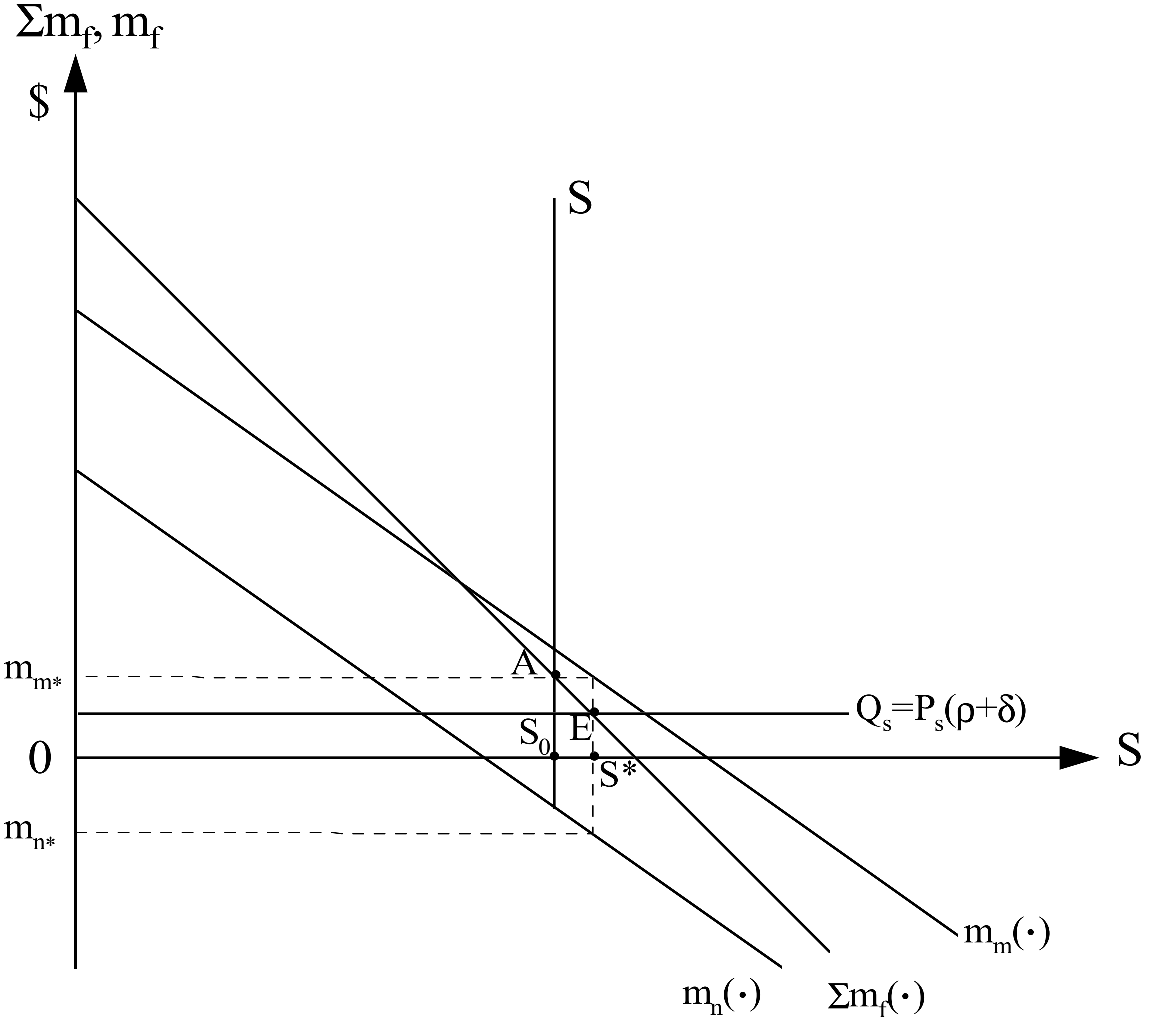


Figure 4: Optimal Highway Capital Stock

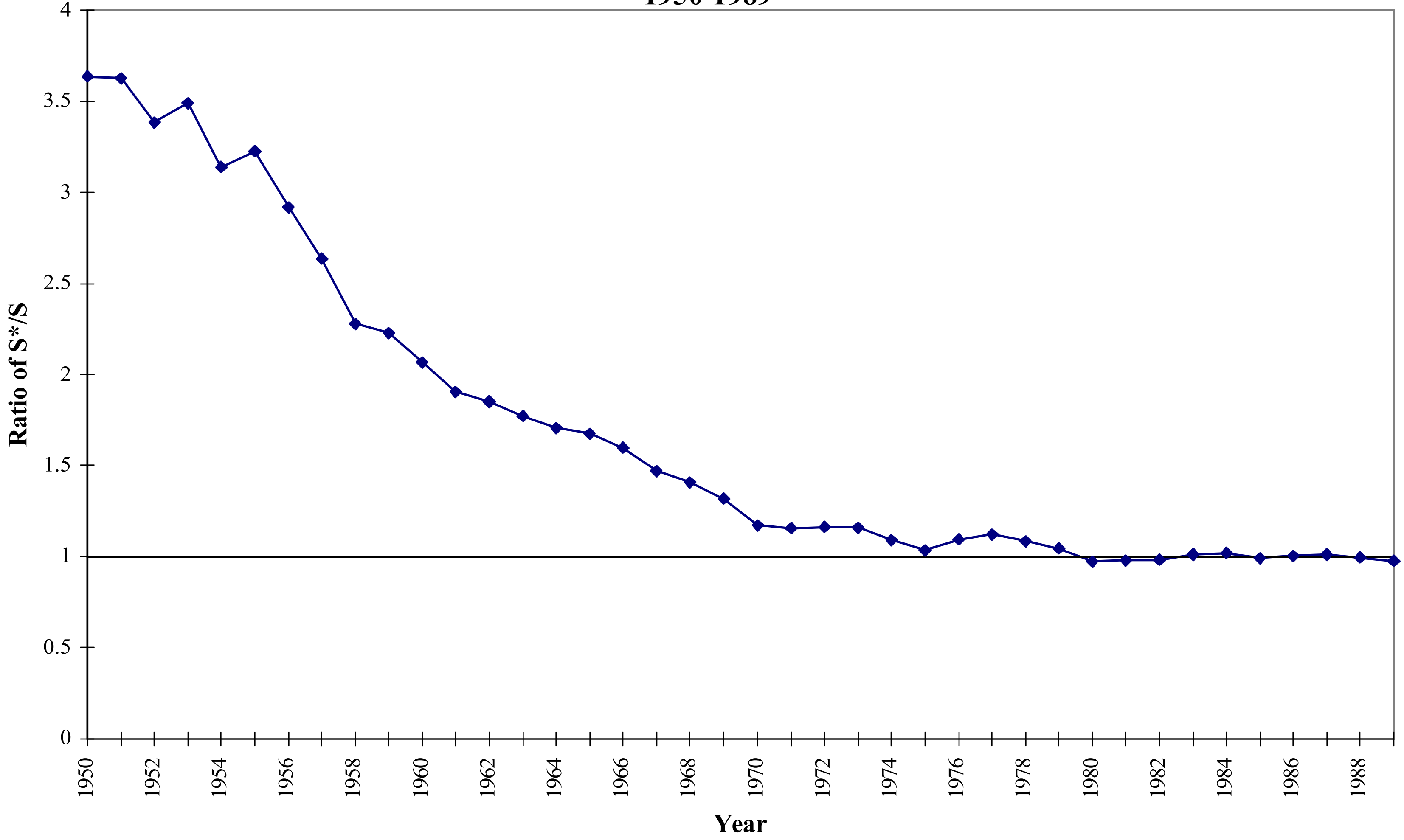
There was clearly an under-investment in highway capital immediately after World War II. However, the gap between optimal and actual capital stocks narrowed during the 1959-1969 period as the Interstate Highway System and other road systems were completed. The ratio of S^*/S declined by about 50 percent during 1960-1969 and further decreased in the 1970-1979 period.

Interestingly, this ratio in the 1980s suggests that total highway capital stock and NLS capital are close to their optimal levels and there is no significant under- or over- investment in either of the highway stocks. This result seem to be at variance with those reported in the literature summarized earlier.

The decline in the ratio of optimal to actual highway capital shown in Figure 5 is due in part to public investment decisions and to economic and demographic changes. Growth in the stock of highways and streets, shown in Figure 1, rose sharply from 1955 to 1975, the period when the US Interstate Highway System was under construction, and leveled off since that time as construction of the Interstate slowed and previously built highways depreciated. The net stock of total highway capital grew at an annual rate of approximately 5 percent from the mid-1950s to the late 1960s. It began to decline in the 1970s, reaching a minimum growth rate of 0.7 percent in 1983. Since then it has gradually increased, but the growth rate of 2.3 percent in 1993 is still less than half the average growth rate of the mid-1950s to late 1960s period.

One factor contributing to the growth rate pattern in highway capital was the sharp rise in the price of gasoline in the 1970s that increased the cost of travel significantly. Demographic changes since the 1950s may also have had an impact on demand for infrastructure and educational structures. The number of young people as a percentage of the total population rose

Figure 5
Ratio of Optimal to Actual Highway Capital
1950-1989



rapidly from 1950 to 1970 and has declined sharply since then. This decline may have contributed to a decline in demand for transportation and educational structures.

D. Highway Capital Externalities

Highway capital constitutes a network of roads and facilities that serves all the users, in our case, all industries in the economy. This network has the characteristics of a public good that cannot and probably will not be provided by the private sector. If every industry attempted to provide its own road system, the costs of duplication, management disputes, etc., would be prohibitively high for the private sector. Industry and society would be better off if the participants pooled their efforts and established a network of highways to serve all. The cost saving of such a system is enormous.

Consider the case where highway capital is not publicly provided. If a private industry k had to provide the highway capital, it would provide a level S_k , at a point where the marginal benefit and marginal cost of highway capital are equal:

$$m_k(P_k, Y_k, u_k, t, S_k) = P_s(\rho+\delta) \ . \tag{22}$$

Based on our estimates, we could solve equation (22) for S_k and calculate, for each industry, the highway capital that satisfies equation (22). It is well known (Samuelson), however, that the level of highway capital S_k chosen by each industry will be below the social optimum because private industry does not take into account the benefits that accrue to the other industries. In addition, the private sector will be unwilling to provide highway services since the cost of an additional unit of highway services will be close to zero.

Consider now the hypothetical case in which each industry builds capital stock S. Each industry bears the whole cost of investing in highway capital S, and the net rate of return from highway capital to industry f, evaluated at the actual level of capital S, will be given by

$$(23) \qquad \gamma_f = \frac{m_f(P_f,\ Y_f\ u_f,\ t,\ S)}{P_s} - \delta\,;$$

γ_f could be negative if the real gross private marginal benefit is less than the depreciation rate of δ. Individual industries possibly will not invest in highway capital since its cost will be prohibitive. However, by sharing the cost of highway capital S, the economy can achieve the maximum benefit with the minimum cost. Comparing equations (21) and (23), the following relationship exists between the social and private rates of return:

$$(24) \qquad \gamma = \sum_{f=1}^{F} \gamma_f + (F-1)\,\delta\,,$$

where F is the total number of industries sharing the cost and benefits of highway capital. If each industry had to build its own highway capital S, the cost of the duplicated network of highways would be too high for the economy due to total depreciation Fδ. By sharing highway infrastructure, the economy is saving in terms of depreciation costs (F-1) δ. Using our estimated marginal benefit functions for Model A, the sum of net private rates of return ($\sum_{f=1}^{F} \gamma_f$), under our hypothetical case is equal to -2.62 on average and the saving to the economy (F-1)δ is 2.90. Thus, the social net rate of return for total highway capital is equal to .28. The same type of calculation sets the social rate of return for NLS equal to .358.

Note that the real gross private benefit m_f/P_s, in terms of private input cost reduction will be the same whether highway capital S is built and owned by individual industries or by sharing the benefits and costs together. The net private benefit will be higher through sharing. In the simple case where all industries have the same demand for highway capital, the cost of infrastructure will be equally shared by all industries and the cost per unit of S for each industry will be equal to $t_f = P_s(\rho+\delta)/F$. Then the net private rate of return for each industry will be $\gamma'_f = m_f/P_s - \delta/F$; clearly γ_f is less than γ'_f.

The industry marginal benefits of highway capital shown in Table 11 are gross rates of return, inclusive of depreciation rate δ. The marginal benefits in each of the industries is much smaller than the actual value of the depreciation rate δ which is, on average, about .10. It is only through a shared network of highways that each industry avoids the duplicative cost of individual highway systems, each with a separate depreciation rate.

E. Decomposition of Aggregate TFP Growth

We use the "aggregated" estimates from Models A and B to decompose the sources of TFP growth in the aggregate economy. We first obtain the parameters of aggregate demand as the weighted average of the industry elasticities shown in Table 4, using relative outputs as weights. Alternatively, we estimated the demand function using the aggregated industry data. The two approaches generated almost the same values for the demand parameter estimates, as shown in Table 18.

The second step is to use the cost function elasticities shown in Tables 14 and 15 and use equation (13) to decompose aggregate TFP growth into its component parts. That is, we calculate the effect of exogenous demand, relative prices, highway capital stock, utilization rate and technical change in determining the growth rate of TFP in the US economy over the period

Table 18
Aggregate Demand
Parameter Estimates

	α	β	λ	R^2	D/W
Aggregated	-.6076	1.1178	-.0017	-	-
Aggregate	-.6307 (.1281)	1.0669 (.0916)	-.0012 (.0029)	.8061	1.9841

Table 19 A
Aggregate $\dot{TFP}$ Decomposition
Total Highway Capital Mean Values

$\dot{TFP}$	Exogenous Demand	Relative Price	Highway Capital	Capacity Utilization	Adjusted $\dot{TFP}$
.6783	.5960	-.0571	.1767	.0069	-.0484

Table 19 B
Aggregate $\dot{TFP}$ Decomposition
NLS Capital Mean Values

$\dot{TFP}$	Exogenous Demand	Relative Price	Highway Capital g1	Highway Capital g2	Capacity Utilization	Adjusted $\dot{TFP}$
0.6783	0.6029	-0.0571	0.1649	0.0118	0.0069	-0.0411

1950-1989. The sources of productivity growth for the aggregate economy are shown in Tables 19A and 19B.

These results indicate that growth in exogenous demand is the most important contributor to aggregate TFP growth -- almost 87 percent is accounted for by changes in aggregate demand. Input price movement contributes negatively to TFP growth, about 8 percent, while highway capital contributes about 25 percent. The contribution of the capacity utilization rate is relatively small, about 1 percent.

A central issue in the debate on the role of infrastructure or highway capital, as noted in Section II, is its contribution to growth of aggregate TFP and to the deceleration of TFP growth in the period 1973-1979. Aschauer (1989), Munnell (1990a) and others claimed the decline in this period was mainly, if not exclusively, due to the decline in growth of infrastructure capital. Hulten and Schwab (1991a), Gramlich (1994) and others have argued for no or minimal contribution of infrastructure capital to productively slowdown.

Figure 6 shows movements of aggregate TFP growth calculated from the industry estimates, and the contribution of growth of external demand and total highway capital. It is clear that TFP growth fluctuates considerably over the period 1952-1989, taking on both positive and negative values. These movements are highly correlated with movements in the contribution of external demand and relative prices and not to movements on growth of highway capital stock.[18]

---

[18] The contribution of highway capital is dominated by the magnitude and movement of investment in highway capital. As noted in Figure 1, growth rate of highway capital does not show year to year fluctuations. Rather, it rises continuously for several years and then declines for a number of years before it begins an upward trend in 1982.

Figure 6
Growth of TFP, Exogenous Demand and Highway(%)
(1951-1989)

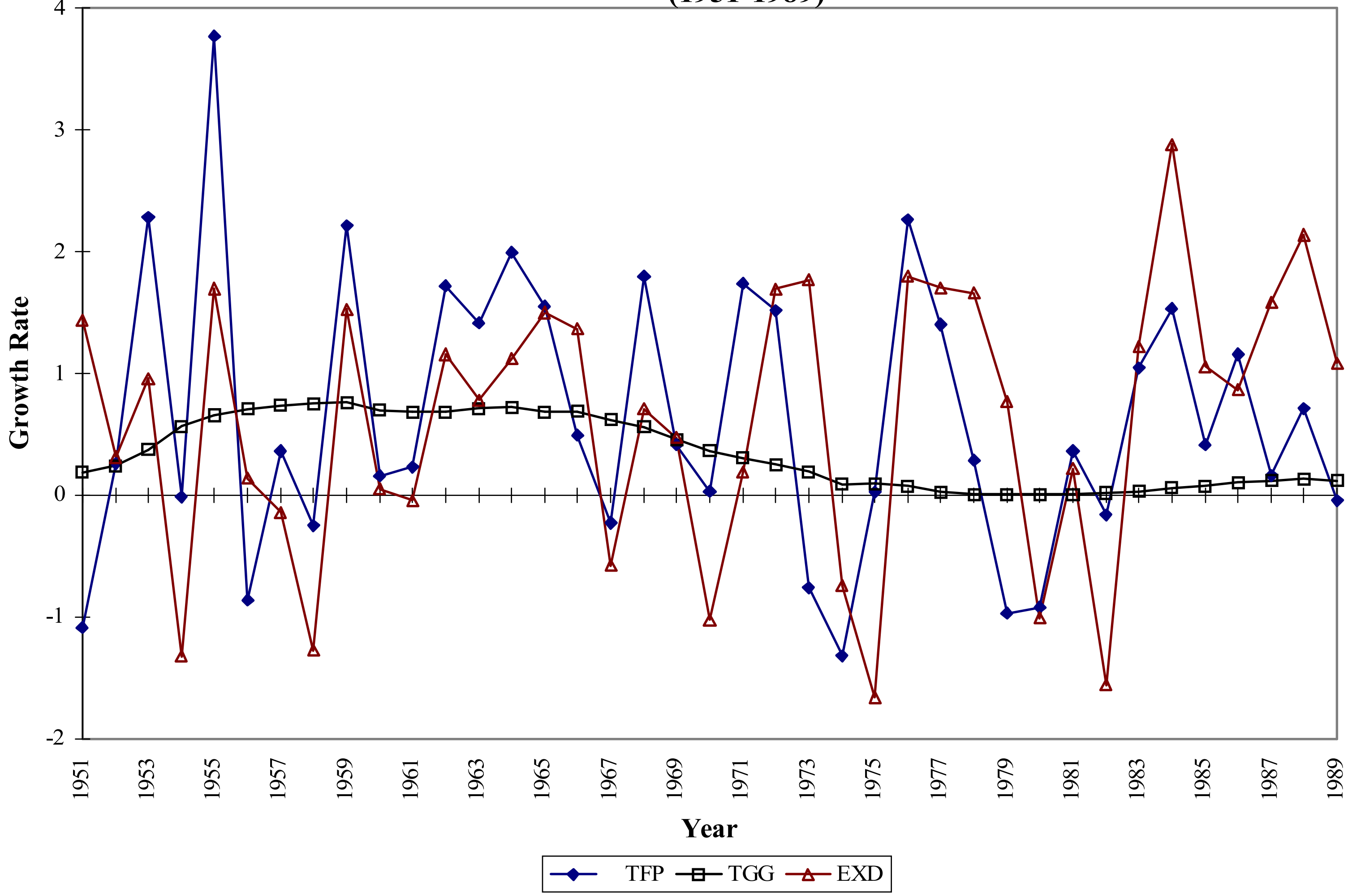


Table 20 A:

Average growth rate of $T\dot{F}P$ and contributions of exogenous demand, relative prices and total highway capital
1952-1989 and sub periods

	1952-1989	I 1952-1963	II 1964-1972	III 1973-1979	IV 1980-1989
$T\dot{F}P$	.68	.94	1.03	.13	.42
EXD	.60	.30	.60	.75	.84
TGG	.17	.30	.26	.03	.03
PFP	-.06	-.06	-.10	-.17	.07

Table 20 B:

Average growth rate of $T\dot{F}P$ and contributions of exogenous demand, relative prices and NLS capital
1952-1989 and sub periods

	1952-1989	I 1952-1963	II 1964-1972	III 1973-1979	IV 1980-1989
$T\dot{F}P$	0.6783	0.9402	1.034	0.1327	0.4255
EXD	0.6029	0.3185	0.5945	0.7392	0.8563
TGG	0.1649	0.2966	0.2463	0.0195	0.0353
TGO	0.0118	0.0188	0.0121	0.0080	0.0058
PFP	-0.0571	-0.0566	-0.1089	-0.1698	0.0678

What is important is not yearly fluctuations, however, but the trend over a specific period. Customarily, annual data are averaged to obtain measures of average rates of growth of technical change. We calculated the trend growth rate of total factor productivity growth ($T\dot{F}PT$) by fitting it as a polynomial function of time.[19] As Table 20 indicates, the contribution of exogenous demand (EXD) is the major contributor to TFP growth . Relative price movements (PFP) are not large contributors except in 1973-1979 period. Contribution of highway capital (TGG) has been about 1/3 of that of exogenous demand; its contribution has been much larger in the early period until 1972 but has declined significantly since then. This pattern of contribution reflects two sets of factors: the pattern of marginal benefits of highway capital stock; and, more importantly, the growth rate of highway capital stock exhibited in Figure 1. Highway capital's contribution was less than 0.18 until 1953 when the investment in Interstate Highway System started; its contribution rose to almost twice as much during the period 1954-1967. After 1967 it started to decline considerably until 1981 to about .001. Since 1981, there has been some increase in contribution of highway capital to TFP growth to about 0.06 in 1989.

When $T\dot{F}P$ is decomposed into trend and deviation from the trend, (i.e., DTFP= $T\dot{F}P$ - $T\dot{F}PT$), trend $T\dot{F}P$ ($T\dot{F}PT$) is highly correlated to trend contribution of highway capital ($T\dot{G}GT$), trend exogenous demand ($E\dot{X}DT$) and trend in relative factor prices ($F\dot{P}ET$). The deviation from trend of $T\dot{F}P$ is correlated to deviation of the latter two variables from their trend. The deviation from trend in contribution of highway capital stock did not have much explanatory power. The conclusion to be drawn is that highway capital stock contributes to growth of total factor productivity; its contribution is much smaller in comparison of the contribution of exogenous demand. Most of the contribution of highway capital to productivity

---

[19] A 3rd degree polynomial seem to fit the data best.

growth occurred in the 1950s and 1960s. Since 1973, highway capital has made a small contribution to trend TFP. Highway capital, whether measured by total highway capital or NLS capital, does not contribute much to the acceleration or deceleration of TFP growth.

These results stands in contrast to those reported by Aschauer, Munnell and other proponents of large contributions to infrastructure and also to those reported by researchers who have denied any role for infrastructure in enhancing the growth rate of productivity. Our analysis suggests that highway capital stock has contributed to the expansion of the productive capacity of the economy. It has contributed to TFP growth, although its contribution has been relatively small and has varied over time. Expansion of highway capital has had significant effects on the pattern of, and demand for, labor, capital and material inputs in different industries.

VIII. SUMMARY, CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

A. Summary and Conclusions

The main goal of this report is to provide a general framework for analyzing and measuring the contribution of highway capital -- measured by total stock of highway and NHS capital - to private sector productivity growth. The approach developed here explicitly incorporates demand and supply forces, including the contribution of highway capital, that may affect productivity performance. The model is empirically estimated using disaggregated data composed of 35-sectors covering the entire U.S. economy for the period 1950-1989. The data include measures of gross output, material inputs (inclusive of energy), and private capital and labor. Demand and supply (cost) functions for each industry are estimated. The determinants of productivity growth for each industry including the contribution of highway capital are identified and the marginal benefit of highway capital to each industry is specifically measured.

To generate aggregate measures for the whole economy, two specific approaches are followed: the "aggregated" approach using a weighted sum of individual industry elasticities to obtain aggregate elasticity measures for the whole economy and the “aggregate” approach by fitting the model to aggregate data obtained by adding up the industry data. The results of these two approaches are compared with each other and to results reported in the literature. Using the "aggregated" and "aggregate" estimates, we decompose total TFP growth into its various components. We also calculate the net social rate of return to highway capital and the ratio of optimal to actual stock of total highway and NHS capital to examine whether there has been any over- or under-investment in highway capital or NHS capital over the postwar period.

The estimated results are quite stable and do not change substantially under the alternative measures of highway capital. The rates of return to NHS capital are generally higher than that for total highway capital and therefore the sum of marginal benefits from NHS capital is larger than that for total highway capital. They do, however, follow patterns over time similar to the rates on total highway capital.

The specific quantitative results of this report can be briefly summarized as follows:

- Total highway capital and NHS capital contribute significantly to economic growth and productivity at the industry and national economy levels. Their contribution varies across industries and over time. The magnitude of the elasticity of output with respect to total highway capital at the aggregate level is about 0.05 which is much smaller than comparable estimates reported in the literature.
- Our basic model was estimated using several alternative econometric procedures including estimating the model in first-difference form and using instrumental variable techniques. These alternative estimations were necessary to meet the criticisms of spurious correlation and simultaneity (i.e., reverse causality) between highway capital and output (cost). The results indicate that the model passes these tests and the signs and magnitudes of elasticities are stable.
- There is evidence of a mild degree of increasing returns in most industries and at the national level. The marginal products of labor, capital and intermediate inputs vary across industries and the output elasticity of labor was generally the largest, followed by that of capital and intermediate inputs. More importantly, both at the industry and national levels, the elasticity of private capital dominates that of total highway capital or NHS capital by almost four times. This result is in sharp contrast to the results found by Aschauer (1990), Canning and Fay (1993), and Fernald (1992), which imply that an additional dollar of public investment was substantially more productive than a corresponding dollar of private investment.
- Total highway capital and NHS capital have a significant effect on employment, private capital formation and demand for materials inputs in all industries. At a given level of output, an increase in highway capital and NHS capital lead to a reduction in demand for all inputs in manufacturing while in non-manufacturing the pattern is mixed. The magnitude of these effects varies among the three inputs in a given industry and among the industries. The main effect seems to be to reduce the demand for private capital and labor in the majority of industries. Reductions in demand for intermediate inputs are rather small in most industries.
- The marginal benefits of total highway capital and NHS capital at the industry level were calculated using the estimated cost elasticities. Demand for highway capital services varies across industries as do the marginal benefits. The marginal benefits are negative for all non-manufacturing industries. This suggests that for these

industries the existing stock of highway capital may be over supplied. This issue, however, requires further research.

- We calculate the net social return to total highway capital and NHS capital using the industry marginal benefit calculations and the user cost of highway capital taking into account the distortionary effects of taxation to finance highway capital. The results indicate that net social rate of return on total highway capital was high, about 35 percent in the 1950s and 1960s, then declined considerably and in 1980s to about 10 percent. The same pattern holds for NHS capital though the net social rates of return are higher for NHS. For the entire period 1950-89, the average net social rate of return for both measures of highway capital are much smaller than estimates in the literature. In 1980s the rates of return on total highway capital and private sector capital seem to have converged and basically equal to the long term rate of interest.
- Using a set of "aggregated" estimates, we calculated the "optimum" level of highway capital and compared it with its actual level over the period 1952-1989. The picture that emerges is that the ratio of the optimum to actual highway capital, measured by total or NHS, was high at the beginning of the period until the 1960s and declined thereafter as construction of the Interstate Highway System neared completion. By the end of 1980s, there appears to be no evidence of under or over-investment in highway capital.
- The contribution of highway capital to TFP growth is positive in almost all industries, except in some non-manufacturing industries. The reason is, as noted earlier, that in these industries, highway capital is over supplied. The main contribution of highway capital is in the manufacturing industries; the magnitudes of the contribution varies among industries. At the aggregate level, highway capital contribution in about .17 which compared with reported estimates in the literature is relatively small. The main contributor to productivity both at the industry and aggregate level is aggregate demand. Relative prices, the capacity utilization rate and technical change also contribute to the growth of TFP, but their contributions are generally smaller and vary across industries.

The main conclusion about the relationship between highway capital and economic productivity and growth is that it contributes to productivity by lowering production costs in each industry and influences demand for capital, labor and materials. However, its contribution to the trend in productivity growth is relatively small; and contributes little if any to short term fluctuations of TFP growth.

B. Directions for Future Research

There are a number of important issues that require further research.

Omitted Variables. One of the most important considerations is to introduce the effect of omitted variables in our analysis. Two types of adjustments are desirable: one to adjust for the quality changes in highway capital services and the other is to account for the contribution of infrastructure capital other than highway capital. The quality adjustments can take different dimensions. For example adjustments are needed for effect of congestion and other environmental factors such as noise, smog, etc. The highway capital stock needs to be adjusted for quality of roads, degree of maintenance and intensity of use. Besides these types of adjustments, the effects of infrastructure capital other than highway capital should be specifically introduced in our model. Clearly there is considerable evidence that other types of public infrastructure contribute to growth of output and productivity. Including the “other” infrastructure capital may affect the magnitudes and even sign of the elasticities and marginal benefits of highway capital (or NHS) reported in this study.

Relaxation of Assumptions. Evaluation of the productivity contribution and the effect on demand for labor, capital and materials of an increase in highway capital are estimated under the assumption that the level of output is given. This assumption needs to be relaxed to take account of output expansion induced by investment in highway capital. Highway capital investment reduces cost i.e. the average cost shifts downward (productivity effect). This in turn, given a downward sloping output demand curve, leads to a decline in output prices and an increase in output. The induced output expansion leads to increases in demand for each of the private sector inputs. This indirect expansion effect of highway capital investment will likely to offset any potential substitution effects on demand for labor, capital and materials. This issue is an important challenge to be taken up also in future research.

Depreciation of Highway Capital. Another issue is to examine more closely the depreciation rate estimates that are used to generate the total highway or NHS capital. If the depreciation rates are not will specified then the results on marginal benefit, net social rate of return and productivity contribution of highway capital reported here will be affected. Analytical models are available to estimate the depreciation rate from available investment data.[16] Also, availability of data on maintenance expenditures and other relevant data may allow estimating a more precise measure of the depreciation rate and thus better measures of total highway and NHS capital stocks.

Further Industry Detail. In the present study, industries were divided into three broad categories. A more refined classification such as that used by Fernald may be necessary to capture the industry variations in demand for highway capital services. As a result, our measures of industry marginal benefits, social rate of return and contribution to productivity at the industry and aggregate level are likely to be affected. Also, we need to improve our estimation of the output demand function. Furthermore, the demand and cost functions are estimated separately. What is required is to jointly estimate the two functions and allow for the effect of highway capital on the demand for output of an industry.

Benefits to Other Groups. Finally, in this study we have concentrated on the benefits of highway capital to private sector industries. The welfare benefits of highway capital services to the consumers have not been addressed. To do so requires modeling the consumption sector of

---

[16] See Nadiri and Prucha 1996.

the economy and integrating it with the production sector in a general equilibrium model. Such an attempt, though extremely important, at present remain outside the scope of our research.

REFERENCES

Aaron, H.J. (1990), Discussion of "Why is Infrastructure Important?" in A. Munnell, ed. *Is There a Shortfall in Public Capital Investment?* Federal Reserve Bank, Boston, 51-63.

Apogee Research, Inc. (1989), *Current Literature on Highway Investment and Economic Development*, prepared for the Federal Highway Administration.

Arrow, K. J. and M. Kurz (1970), *Public Investment, the Rate of Return, and Optimal Fiscal Policy,* Baltimore: The Johns Hopkins Press.

Aschauer, David Alan (1989a), "Does Public Capital Crowd Out Private Capital?" *Journal of Monetary Economics* 24, 171-188.

_______ (1989b), "Is Public Expenditure Productive?" *Journal of Monetary Economics* 23, 177- 200.

_______ (1993), "Infrastructure and Productive Efficiency: A Literature Review," mimeo.

Berndt, Ernst R. and B. Hansson (1991), "Measuring the Contribution of Public Infrastructure Capital in Sweden," Paper Presented at IUI, Sweden, March.

Bernstein, Jeffrey I. and M. Ishaq Nadiri (1991), "Product Demand, Cost of Production, Spillovers, and the Social Rate of Return to R&D," NBER Working Paper #3625 (February).

Caves, D. W., L. R. Christensen, and J. A. Swanson (1981), "Productivity Growth, Scale Economics, and Capacity Utilization in U.S. Railroads, 1955-1974," *American Economic Review* 71(5), 994-1002.

Chambers, R.G. (1988), *Applied Production Analysis: A Dual Approach*, New York: Cambridge University Press.

Conrad, Klaus and Helmus Seitz (1992), "The Economic Benefits of Public Infrastructure." Institut fur Volkswirtschaftslehre und Statistik Universitat Mannheim Discussion Paper 469-92.

Deno, Kevin T. (1988), "The Effect of Public Capital on U.S. Manufacturing Activity: 1970 to 1978," *Southern Economic Journal* 55, 400-411.

Diewert, W.E. (1974), "Application of Duality Theory," in M.D. Intriligator and D.A. Kendric (eds.), *Frontiers of Quantitative Economics*, vol. II, Amsterdam: North-Holland.

_________ (1986), *The Measurement of the Economic Benefits of Infrastructure Services*, New York: Springer Verlag.

_________ and T.J. Wales (1987), "Flexible Functional Forms and Curvature Conditions," *Econometrica*, 55 (1), 43-68.

Duffy-Deno, K.T. and R.W. Eberts (1991), "Public Infrastructure and Regional Economic Development: A Simultaneous Equations Approach," *Journal of Urban Economics*30, 329-43.

Eberts, Randall W. (1986), "Estimating the Contribution of Urban Public Infrastructure to Regional Growth," *Federal Reserve Bank of Cleveland Working Paper 8610,* December.

_______ and M. Fogerty (1987), "Estimating the Relationship Between Local Public and Private Investment." Working Paper 8703, Federal Reserve Bank, Cleveland, OH.

Eisner, Robert (1991), "Infrastructure and Regional Economic Performance: Comment," *New England Economic Review*, Sept./Oct., 47-58.

Federal Highway Administration (1992), "Assessing the Relationship Between Transportation Infrastructure and Productivity: Summary of Current Research: Part of a Highways and Economic Productivity Agenda," Searching for Solutions: A Policy Discussion Series, Number 4 (August). Office of Policy Development, Federal Highway Administration, Washington, D.C.

Fernald, John (1992) "How Productive Is Infrastructure" Distinguishing Reality and Illusion with a Panel of US Industries." mimeo.

Gramlich, E. (1994) "Infrastructure Investment: A Review Essay," *Journal of Economic Literature*, September, 1176-1196.

Grossman, Herschel I., and Robert Lucas (1974) "The Macro-Economic Effects of Productive Public Expenditures", *The Manchester School of Economics and Social Studies*, 42, 162-170.

Hall, R.E. (1988) "The Relationship between Price and Marginal Cost in U.S. Industry," *Journal of Political Economy*, 96(5), 921-947.

Hauthakker, H.S., and L.D. Taylor (1966) "Consumer Demand in the United States 1929-1970," Cambridge Mass., Harvard.

Holtz-Eakin, D. (1991), "New Estimates of State-Local Capital Stocks by State," Syracuse University, mimeo.

_____ (1992), "Public-Sector Capital and the Productivity Puzzle," NBER Working Paper #4122.

Hulten, Charles R. (1990) "Infrastructure: Productivity Growth and Competitiveness", Committee on Banking, Finance and Urban Affairs, Serial No. 101-117.

Hulten, Charles R. and Robert M. Schwab (1984), "Regional Productivity Growth in U.S. Manufacturing: 1951-1978," *American Economic Review* 74, 152-162.

______ (1991a), "Public Capital Formation and the Growth of Regional Manufacturing Industries," mimeo, March.

Jorgenson, D., F. Gollop and B. Fraumeni (1987*) Productivity and U.S. Economic Growth*, Cambridge, MA: Harvard University Press.

Jorgenson, D. (1990) "Productivity and Economic Growth," in Berndt, E. and J. Triplett, (eds) *Fifty Years of Economic Measurement*, *NBER Studies in Income and Wealth Volume 54*, Chicago: The University of Chicago Press.

Jorgenson, D.W. and Kun-Young Yun (1990) "The Excess Burden of Taxation in the U.S.," Harvard University Discussion Paper #1528.

Kaizuka, K. (1965), "Public Goods and Decentralization of Production," *Review of Economics and Statistics* 47, 118-120.

Keeler, T.E. and J. Ying (1988), "Measuring the Benefits of a Large Public Investment: the Case of the U.S. Federal-aid Highway System," *Journal of Public Economics* 36 (1), 64-86.

Klein, L. and R. Summers (1966) "The Wharton Index of Capacity Utilization," *Studies in Quantitative Economics*, No. 1, University of Pennsylvania.

Lynde, Catherine and James Richmond (1992), "The Role of Public Capital in Production," *Review of Economics and Statistics* 74, 37-44.

_____ (1993), "Public Capital and Long-Run Costs in U.K. Manufacturing," *The Economic Journal* 103 (July), 880-893.

McGuire, T. (1992), "Highways and Macroeconomic Productivity: Phase Two." Final Report to Federal Highway Administration, Washington, D.C.

Morrison, Catherine and Amy Ellen Schwartz (1991), "State Infrastructure and Productive Performance," mimeo.

Munnell, A. H. (1990a), "Why Has Productivity Growth Declined? Productivity and Public Investment," *New England Economic Review*, Jan./Feb., 3-22.

_____ (1990b), "How Does Public Infrastructure Affect Regional Economic Performance," *New England Economic Review*, Sept./Oct.

_____ (1991), "Comments on 'Is There Too Little Capital? Infrastructure and Economic Growth,' by Charles R. Hulten and Robert M. Schwab," American Enterprise Institute Conference on Infrastructure Needs and Policy Options for the 1990's, February.

Nadiri, M. Ishaq and Theofanis P. Mamuneas (1993a), "The Effects of Public Infrastructure and R&D Capital on the Cost Structure and Performance of U.S. Manufacturing Industries," C.V. Starr Center RR #91-57.

_____ (1993b), "Publicly-Financed Infrastructure, Human and R&D Capital, and Aggregate Productivity Growth," in progress.

_____ (1993c), "Infrastructure and Public R&D Investments and the Growth of Factor Productivity in U.S. Manufacturing Industries," NBER Working Paper #4845.

Nadiri, M. I. and I. Prucha (1986), “Estimation of the Depreciation Rate of Physical and R&D Capital in the U.S. Total Manufacturing Sector,” *Economic Inquiry*, forthcoming.

Nadiri, M. I. and M. Schankerman (1981a), "Technical Change, Returns to Scale and Productivity Slowdown," *American Economic Review* 71 (2), 314-19.

_____ (1981b), "The Structure of Production, Technological Change, and the Rate of Growth of Total Factor Productivity in U.S. Bell System," in *Productivity Measurement in Regulated Industries*, G. Cowing and R.E. Stevenson (eds.), Academic Press, New York.

Nienhaus, M. (1991), "Highways and Macroeconomic Productivity: Phase One: The Current State of Research." Volpe National Transportation Systems Center Final Report, Federal Highway Administration, Washington, D.C.

Seitz, Helmut (1992a), "A Dual Economic Analysis of the Benefits of the Public Road Network," mimeo.

_____ (1992b), "Public Capital and the Demand for Private Inputs," mimeo.

Shah, A. (1992), "Dynamics of Public Infrastructure, Industrial Productivity and Profitability," *The Review of Economics and Statistics*, 28-36.

Tatom, John A. (1991a), "Public Capital and Private Sector Performance," mimeo.

_____ (1991b), "Should Government Spending on Capital Goods Be Raised," mimeo.

Varian, H.R. (1984), *Microeconomic Analysis*, New York: W.W. Norton and Company.

WEFA Group, (1990), *Industrial Analysis Quarterly Review*, July.

APPENDIX

Table 0-1: Industry Classifications

Industry Code	Industry Title
1	Agriculture, Forestry and Fisheries
2	Metal Mining
3	Coal Mining
4	Crude Petroleum and Natural Gas
5	Nonmetallic Mineral Mining
6	Construction
7	Food and Kindred Products
8	Tobacco Manufactures
9	Textile Mill products
10	Apparel and Other Textile Products
11	Lumber and Wood Products
12	Furniture and Fixtures
13	Paper and Allied Products
14	Printing and Publishing
15	Chemicals and Allied Products
16	Petroleum Refining
17	Rubber and Plastic Products
18	Leather and Leather Products
19	Stone, Clay and Glass Products
20	Primary Metals
21	Fabricated Metal Products
22	Machinery, Except Electrical
23	Electrical Machinery
24	Motor Vehicles
25	Other Transportation Equipment
26	Instruments
27	Miscellaneous Manufacturing
28	Transportation and Warehousing
29	Communication
30	Electric Utilities
31	Gas Utilities
32	Trade
33	Finance, Insurance, and Real Estate
34	Other Services
35	Government Enterprises

Table 0-2: Industry Classification

RELATIONSHIP OF DGEM AND 80-SECTOR I-O CATEGORIES (12/15/87)

1	AGRICULTURE, FORESTRY AND FISHERIES	01	LIVESTOCK AND LIVESTOCK PRODUCTS
		02	OTHER AGRICULTURAL PRODUCTS
		03	FORESTRY AND FISHERY PRODUCTS
		04	AGRICULTURAL, FORESTRY AND FISHERY SERVICES
2	METAL MINING	05	IRON AND FERRO ALLOY MINING
		06	NONFERROUS METAL MINING
3	COAL MINING	07	COAL MINING
4	CRUDE PETROLEUM AND NATURAL GAS	08	CRUDE PETROLEUM AND NATURAL GAS
5	NONMETALLIC MINERAL MINING	09	STONE AND CLAY MINING
		10	CHEMICAL AND FERTILIZER MINING
6	CONSTRUCTION	11	NEW CONSTRUCTION
		12	MAINTENANCE AND REPAIR CONSTRUCTION
7	FOOD AND KINDRED PRODUCTS	14	FOOD AND KINDRED PRODUCTS
8	TOBACCO MANUFACTURES	15	TOBACCO MANUFACTURES
9	TEXTILE MILL PRODUCTS	16	BROAD AND NARROW FABRICS, YARN AND TREAD MILLS
		17	MISCELLANEOUS TEXTILES AND FLOOR COVERINGS
10	APPAREL AND OTHER TEXTILE PRODUCTS	18	APPAREL
		19	MISCELLANEOUS FABRICATED TEXTILE PRODUCTS
11	LUMBER AND WOOD PRODUCTS	20	LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS
		21	WOOD CONTAINERS
12	FURNITURE AND FIXTURES	22	HOUSEHOLD FURNITURE
		23	OTHER FURNITURE AND FIXTURES
13	PAPER AND ALLIED PRODUCTS	24	PAPER AND ALLIED PRODUCTS, EXCEPT CONTAINERS
		25	PAPERBOARD CONTAINERS AND BOXES
14	PRINTING AND PUBLISHING	26	PRINTING AND PUBLISHING
15	CHEMICALS AND ALLIED PRODUCTS	27	CHEMICALS AND SELECTED CHEMICAL PRODUCTS
		29	DRUGS, CLEANING AND TOILET PREPARATIONS
		30	PAINTS AND ALLIED PRODUCTS

Table 0-2: Industry Classification (Cont'd)

RELATIONSHIP OF DGEM AND 80-SECTOR I-O CATEGORIES (12/15/87)

16	PETROLEUM REFINING	31	PETROLEUM REFINING AND RELATED INDUSTRIES
17	RUBBER AND PLASTIC PRODUCTS	28	PLASTICS AND SYNTHETIC MATERIALS
		32	RUBBER AND MISCELLANEOUS PLASTIC PRODUCTS
18	LEATHER AND LEATHER PRODUCTS	33	LEATHER TANNING AND FINISHING
		34	FOOTWEAR AND OTHER LEATHER PRODUCTS
19	STONE, CLAY AND GLASS PRODUCTS	35	GLASS AND GLASS PRODUCTS
		36	STONE AND CLAY PRODUCTS
20	PRIMARY METALS	37	PRIMARY IRON AND STEEL
		38	PRIMARY NONFERROUS METALS
21	FABRICATED METAL PRODUCTS	39	METAL CONTAINERS
		40	HEATING, PLUMBING AND FABRICATED STRUCTURAL METAL
		41	SCREW MACHINE PRODUCTS AND STAMPINGS
		42	OTHER FABRICATED METAL PRODUCTS
22	MACHINERY, EXCEPT ELECTRICAL	43	ENGINE AND TURBINES
		44	FARM AND GARDEN MACHINERY
		45	CONSTRUCTION AND MINING EQUIPMENT
		46	MATERIALS HANDLING MACHINERY
		47	METALWORKING MACHINERY
		48	SPECIAL INDUSTRY MACHINERY
		49	GENERAL INDUSTRIAL MACHINERY
		50	MISCELLANEOUS MACHINERY, EXCEPT ELECTRICAL
		51	OFFICE, COMPUTING AND ACCOUNTING MACHINES
		52	SERVICE INDUSTRY MACHINES
23	ELECTRICAL MACHINERY	53	ELECTRICAL INDUSTRIAL EQUIPMENT
		54	HOUSEHOLD APPLIANCES
		55	ELECTRIC LIGHTING AND WIRING EQUIPMENT
		56	RADIO, TV AND COMMUNICATION EQUIPMENT
		57	ELECTRONIC COMPONENTS AND ACCESSORIES
		58	MISCELLANEOUS ELECTRICAL MACHINERY AND SUPPLIES
24	MOTOR VEHICLES	59	MOTOR VEHICLES AND EQUIPMENT
25	OTHER TRANSPORTATION EQUIPMENT	13	ORDNANCE AND ACCESSORIES
		60	AIRCRAFT AND PARTS
		61	OTHER TRANSPORTATION EQUIPMENT

Table 0-2: Industry Classification (Cont'd)

RELATIONSHIP OF DGEM AND 80-SECTOR I-O CATEGORIES (12/15/87)

26	INSTRUMENTS	62	SCIENTIFIC AND CONTROLLING INSTRUMENTS
		63	OPTICAL, OPHTHALMIC AND PHOTOGRAPHIC EQUIPMENT
27	MISCELLANEOUS MANUFACTURING	64	MISCELLANEOUS MANUFACTURING
28	TRANSPORTATION AND WAREHOUSING	65	TRANSPORTATION AND WAREHOUSING
29	COMMUNICATION	66	COMMUNICATIONS, EXCEPT RADIO AND TV
		67	RADIO AND TV BROADCASTING
30	ELECTRIC UTILITIES	68.01	ELECTRIC SERVICES (UTILITIES)
		78.02	FEDERAL ELECTRIC UTILITIES
		79.02	STATE AND LOCAL ELECTRIC UTILITIES
31	GAS UTILITIES	68.02	GAS PRODUCTION AND DISTRIBUTION (UTILITIES)
32	TRADE	69	WHOLESALE AND RETAIL TRADE
		74	EATING AND DRINKING PLACES
33	FINANCE, INSURANCE AND REAL ESTATE	70	FINANCE AND INSURANCE
		71	REAL ESTATE AND RENTAL
34	OTHER SERVICES	68.03	WATER SUPPLY AND SEWERAGE SYSTEMS
		72	HOTELS, PERSONAL AND REPAIR SERVICES
		73	BUSINESS SERVICES
		75	AUTOMOBILE REPAIR AND SERVICES
		76	AMUSEMENTS
		77	HEALTH, EDUCATION, SOCIAL SERVICES, NONPROFIT ORG.
35	GOVERNMENT ENTERPRISES	78.01	U.S. POSTAL SERVICE
		78.03	COMMODITY CREDIT CORPORATION
		78.04	OTHER FEDERAL GOVERNMENT ENTERPRISES
		79.01	LOCAL GOVERNMENT PASSENGER TRANSIT
		79.03	OTHER STATE AND LOCAL GOVERNMENT ENTERPRISES