On the Role of Public Capital in Production

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ABSTRACT

This thesis examines the role of public capital, in particular "core infrastructure", in private sector production in the United States. The underlying theme is the importance of the individual infrastructure stocks, in particular highways and streets, water and sewer systems and "other structures". Two different empirical approaches are used to shed light on a number of issues. In the first study in Chapter 3, two cost function models are estimated using data for the total private business sector, one using aggregate infrastructure data and the other using disaggregated infrastructure. The parameter estimates are used to calculate optimal infrastructure stocks (the optimal total infrastructure stock and the optimal individual stocks). The results reveal that, despite the fall in infrastructure investment from 1968-82, none of the infrastructure stocks was undersupplied over the sample period. The estimated output elasticities of the different infrastructure stocks are significantly lower than those obtained in previous research. In the second study in Chapter 4, use is made of recent developments in the productivity literature to construct a measure of manufacturing total factor productivity (TFP) that takes account of varying returns to scale and variable labour and capital utilisation over the cycle. The adjusted TFP measure is used to shed light on the causal relationship between infrastructure (total, core and disaggregated core) and productivity using a selection of autoregressive model-building techniques and causality testing procedures. Contrary to the stated view of many infrastructure researchers, there is no evidence of "reverse causality", ie, productivity causing infrastructure investment. There is, however, evidence that infrastructure has a small but statistically significant positive effect on TFP. Highways and other roads are the most productive types of infrastructure, followed by "other structures". When the TFP data is disaggregated, the finding is that core infrastructure affects some industries more than others, especially those that are capital intensive and have the largest motor vehicle shares. The results obtained using the adjusted TFP measure differ in several respects to those obtained using the standard Solow residual: the Solow residual produces evidence of reverse causality; infrastructure is found to have a relatively larger (thought not as statistically significant) effect on TFP and the results are not robust to the use of disaggregated data.

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Introduction:

Motivation, Definitions, and Thesis Structure

1. Background

In many countries the public sector owns most of the physical infrastructure, the absence or neglect of which means private economic activity would be either impossible or greatly hindered. In a broad sense physical infrastructure contributes to the provision of all public services, from national defence, maintenance of law and order and fire prevention to education, health care and environmental protection, and the supply of power, water, waste disposal and transportation networks. This type of capital often accounts for a significant portion of the national wealth. In the United States, for example, over a third of the total capital stock is publicly owned.

The purpose of this thesis is to examine the role of public capital in private sector production, in particular the role of "core" infrastructure – the large capital-intensive "natural monopolies" such as highways, water and sewer lines and mass transit. These types of capital arguably have the most direct and instantaneous effect on private production. The most general characteristic of core infrastructure is that services are supplied through a networked delivery system, designed to serve a large number of users.

It is not difficult to see why infrastructure matters. One need only imagine the difficulties encountered by firms operating in countries which lack adequate communications networks and basic amenities. It is also not difficult to envisage the contribution of infrastructure at the margin. Because most publicly provided goods exhibit at least some degree of consumption rivalry, new capital expenditures are required to meet increased demand and, as time passes, to support changes in the nature and geographic location of economic activity.

The importance of infrastructure to the regional and urban economic development process has long been recognised. For example, studies have analysed whether public capital crowds out or crowds in private capital and thus whether infrastructure is a useful tool for inter-regional competition for private investment. However, since the late 1980s, a considerable amount of research has focused on the importance of public capital as a macro policy instrument; not for the type of demand management that was popular during the Great Depression, but for stimulating the supply-side of the economy by enhancing private factor productivity. Analysis of the link between public capital and private sector productivity was originally motivated by the finding that the slowdown in many countries' productivity growth rates in the early 1970s coincided with an "infrastructure slowdown" of comparable severity, as government spending was redirected towards the provision of consumption goods.

The focus in this thesis is on the importance of infrastructure capital to private production in the United States (U.S.). The U.S. was chosen as the economy of focus partly because a wealth of public capital data is available for this country and partly so that the results of the empirical research could be compared with existing studies, most of which use U.S. data. Despite the significant increase in macro infrastructure research in recent years, there remain many unanswered questions. Firstly, there has been very little investigation of the importance of the different types of infrastructure to private producers. In the U.S. the public sector owns many different types of capital. It is possible that some types (eg, courthouses and fire stations) have no effect on productivity, while others have either an indirect effect (eg, schools and hospitals) or direct effect (eg, highways and water mains). With the analysis of the different types of infrastructure as the underlying theme, the thesis takes a somewhat eclectic approach, using two different empirical approaches, each of which sheds light on a number of unresolved issues. The first approach involves estimating a series of cost function models, the second involves estimating autoregressive models and conducting causality tests.

2. Thesis Structure

The thesis is divided into four chapters: the first two provide background information on the infrastructure literature and the history of public investment in the U.S.; the second two consist of the empirical studies that make up the majority of the research. In the next few pages a summary is provided of the techniques employed in each of the chapters and the contributions they make to the infrastructure literature.

Chapter 1: Review of the Literature

The main empirical approaches, findings and criticisms of the existing body of infrastructure research are summarised and discussed in this chapter. Its primary purpose is to highlight opportunities for new research. The main empirical approaches in the infrastructure literature are the production function and duality approaches. The latter involves estimating cost and profit functions. The cost function approach has been used by a host of researchers in recent years to determine whether infrastructure reduces private sector costs and to establish the nature of the relationship between public capital and private inputs. In motivation of the empirical analysis conducted in Chapter 3, reasons are provided why the cost function approach is preferred to the production function approach, in particular the fact that private inputs are treated as endogenous variables and the availability of a richer menu of analytical statistics. The main results of the various studies are summarised. It is clear that several issues have not been addressed, in particular concerning optimality, the role of the different infrastructure stocks and the effect of input prices on the demand for infrastructure.

The catalyst for the upsurge in infrastructure's macro effects was the observation that, in the U.S. and other countries, the slowdown in productivity growth coincided with a slowdown in infrastructure investment. However, some authors have argued that infrastructure may not cause productivity, rather the relationship runs in the opposite direction: because infrastructure is a normal good, productivity gains that lead to increases in income lead to increases in the demand for infrastructure services. In motivation of the empirical analysis conducted in Chapter 4, attention is drawn to the fact that there has been very little formal analysis of the causal relationship between the two variables. More importantly, those studies that use a direct measure of total factor productivity (TFP) have not made use of recent developments in the productivity literature that, by accounting for variable factor utilisation over the cycle, allow researchers to get closer to the true relationship between infrastructure investment and productivity.

Chapter 2: Analysis of the Severity and Causes of the Infrastructure Slowdown

This chapter makes use of the wealth of public capital data available from the U.S. Bureau of Economic Analysis. It is used to illustrate what researchers refer to as the "infrastructure slowdown" – the period of falling public investment from 1968-82. The slowdown is also illustrated by comparing public investment with a variety of measures of private economic activity (private investment, GDP, growth of the labour force and TFP). The public capital data is divided into its chief components in order to identify those types of capital that suffered most severely from the spending cuts and those that were relatively unaffected. This information is useful in interpreting the results of the main studies in Chapter 3 and Chapter 4. The causes of the infrastructure slowdown are then examined and particular attention is paid to the way that higher levels of economic depreciation, caused by changes in the composition of the public capital stock, may have contributed to the slowdown.

Chapter 3: Calculating Optimal Public Capital Stocks

One of the advantages of the cost function approach is that it provides a convenient framework for the estimation of optimal capital stocks. To date, however, the quantity of public capital that is optimal to U.S. private production has not been calculated. Calculating this measure is useful because the finding that public capital has a significant output or cost elasticity does not necessarily mean more investment is required. The benefits have to be weighed against the cost of providing the additional capital. This is done using shadow value techniques.

An examination of the literature also reveals that none of the cost function studies compare the benefits of the different types of infrastructure. To redress this, the optimal quantities of the different types of core infrastructure (roads, water and sewer systems and other structures) are estimated. This exercise is worthwhile because, just as a finding that infrastructure has a large output or cost elasticity does not imply that more investment is required, a finding that the overall stock of infrastructure is sub-optimal does not imply that there should be more of every type of public capital. Also, most of the cost function studies focus only on the importance of public capital to the manufacturing sector. While it is possible that infrastructure provides more benefits to manufacturers than to other sectors, it is also likely that the benefits enjoyed by many other sectors are by no means insignificant. The transportation industry, for example, is likely to benefit from an increase or improvement in roads (which make up the majority of the core infrastructure stock). Thus, omitting non-manufacturing from the analysis will lead to inaccurate estimation of the optimal capital stocks. In this chapter data is used for the total non-farm private business sector which includes the mining, manufacturing, construction, transportation, utility and service sectors.

Two cost function studies are carried out, using the Generalised Leontief specification. The parameter estimates obtained from each are inserted into optimal capital stock equations, along with a series of private sector variables, and the resulting optimal capital stocks are compared with the actual capital stocks over the period 1959-94. The first study uses aggregate infrastructure data to determine whether the overall stock of core public capital is under or oversupplied. In the second study, the stock of core infrastructure is disaggregated and the optimal amount of each type of capital (roads, water and sewer systems, and "other structures") is estimated.

The study contains a number of additional innovations. Optimal infrastructure elasticities, which show the responsiveness of the optimal capital stocks to changes in factor prices and output, are also calculated using the parameters from the two models. Using techniques developed by Dale Jorgenson and Zvi Griliches, a measure of aggregate public capital input is computed by Divisia quantity aggregation. The public capital index takes account of the fact that some types of capital are more productive than others – assets with high user costs are more productive in equilibrium than assets with lower user costs. To my knowledge, none of the U.S. infrastructure studies has employed these techniques.

To estimate the optimal capital stocks, data is required on the prices of labour, private capital and public capital. The studies in the infrastructure literature differ considerably in their treatment of these variables for tax purposes. The optimal capital stock estimates are compared under a number of different taxation scenarios. To start, pre-tax user costs of capital are used. The rental price of private capital is then adjusted to account for various investment incentives and the system of taxing corporate profits. The rental price of public capital is adjusted to take account of the excess burden of taxation. The labour wage rate is also converted into an after-tax measure. Other more minor innovations are discussed in the chapter itself.

The results reveal that, despite the slowdown in the growth rate of the core infrastructure stock, this type of capital was never underprovided over the sample period. Using disaggregated data the finding is also that none of the three types of core infrastructure was suboptimal. However, there were times when one type of infrastructure would be moving towards a state of underprovision while another was becoming increasingly oversupplied.

Chapter 4: Using Adjusted Measures of Productivity to Resolve the Causality Issue

The research in this chapter is motivated by the fact that most studies in the infrastructure literature that use a direct measure of total factor productivity have ignored developments in the productivity literature. The aim is to analyse the relationship between infrastructure investment and U.S. manufacturing using two alternative measures of total factor productivity; one based on Robert Solow's famous derivation and another based on developments by Robert Hall and Susanto Basu to take account of possible increasing returns to scale and variable factor usage over the cycle. The adjusted TFP measure is constructed using manufacturing materials usage data, which measures the degree to which labour and capital usage vary during expansions and contractions. Each of these measures is used to answer a number of questions: does infrastructure investment cause TFP or, as several authors have argued, does the relationship run in the opposite direction? Which types of infrastructure, if any, are the most productive? If infrastructure is productive does it account for much of the variation in the TFP growth rate? Which manufacturing industries benefit the most from infrastructure investment?

The original Solow residual is used in the analysis for comparative purposes and because it is the preferred measure of TFP in a considerable amount of econometric research, including the infrastructure literature. The adjusted TFP measure is employed because it arguably reflects "true" efficiency changes more accurately than the Solow residual. The NBER manufacturing productivity database is used to construct a variety of standard and adjusted residuals: the first set is constructed from aggregate data for total, durable and nondurable manufacturing; the second set uses disaggregated data for each of the 20 two-digit SIC industries. The latter is used to determine which industries benefit most from infrastructure investment. While it would be preferable to calculate an adjusted TFP measure for the entire private business sector, data limitations preclude such an exercise. Nevertheless interesting insights into infrastructure's role are derived by comparing the results obtained using the adjusted measure of TFP with the Solow residual and the results of other infrastructure studies.

The productivity measures are put to a number of uses. Several authors have alluded to the possibility that infrastructure does not Granger cause productivity but rather that productivity gains result in new public investment. However, very little empirical analysis has been conducted to determine the relationship between the variables. To establish whether there is evidence to support the "reverse causality" hypothesis, autoregressive models that introduce dynamic effects from infrastructure investment are constructed using Akaike's Final Prediction Error Criterion and other statistical lag-length selection criteria. A number of causality tests are conducted within this framework and extensive diagnostic tests are conducted to confirm the robustness of the causality test results and the adequacy of the models.

The original and adjusted TFP measures produce very different results concerning infrastructure's impact on productivity. While the original Solow residual produces some evidence of reverse causality, the adjusted residual produces evidence of uni-directional causality from infrastructure to productivity. Causality tests are performed using a variety of different infrastructure and productivity measures. The Solow residual produces inconsistent results at different levels of aggregation. However, the results obtained using Basu's measure of TFP are far more satisfactory. No evidence of reverse causality is found using either aggregate or disaggregated infrastructure data. Disaggregated infrastructure data reveals that investment in roads, utilities, and transit systems affect productivity. When individual industry TFP measures are included in the analysis the finding is that infrastructure investment affects some industries but not others

Once the causality issue has been resolved the next step is to estimate the magnitude of the relationship between public investment and TFP. Again the different TFP measures produce different results. Whether use is made of aggregate or disaggregated infrastructure data, the autoregressive estimates obtained using the adjusted productivity measure are relatively smaller but more significant than those obtained using the Solow residual. Thus it is not possible to agree with certain infrastructure researchers that at least a quarter of the productivity growth slowdown can be explained by the fall in infrastructure investment. Nor, however, is it possible to agree with other researchers that the relationship between the variables is purely spurious. It is likely that infrastructure investment has a positive effect on private productivity but this effect is quite small.

The approaches followed in the two studies in Chapters 3 and 4 are quite different, the one making use of a formal specification incorporating infrastructure's impact on variable costs; the other using no formal specification, treating each variable as endogenous within an autoregressive framework. Furthermore, the one chapter makes use of data for the whole private business sector; the other uses manufacturing data only. A common finding in both studies is that infrastructure has a significant effect on the private production process and the different infrastructure stocks vary in importance. The results of both studies yield caution against exaggerating infrastructure's importance, however. The cost function approach reveals that at no time over the sample period was the infrastructure stock seriously undersupplied. The autoregressive framework reveals that infrastructure investment has only a small effect on the productivity growth rate. Each of the empirical approaches has a number of advantages and disadvantages which are discussed in greater detail in each of the chapters and the conclusion to the thesis.

3. Concluding Comments

Before proceeding it is also necessary to mention some of the important issues that are not analysed in this thesis. First, it is obvious that many of the benefits provided by the public capital stock are enjoyed by consumers rather than producers. While some of these benefits, eg, improved health and leisure facilities, accrue indirectly to producers, others do not. An analysis of consumption benefits falls outside the scope of this thesis.

Another important issue is the relative role of the private and public sectors in the provision of infrastructure services. In the infrastructure literature, the terms "infrastructure" and "public capital" are used interchangeably. However, it is necessary to point out that in the U.S. some of the capital owned by the private sector can be classified as infrastructure. Examples include electric and gas utilities, communication networks, educational institutions and certain transportation networks. Similarly, the public sector owns certain types of capital that are not part of the country's infrastructure. A good example is state-owned equipment which is made up of a variety of private goods ranging from power tools and garden equipment to computers and motor vehicles.

In recent years there has been growing interest in the U.S. in the role of the private sector in the provision of infrastructure services. While markets work best in providing pure private goods or services, many types of infrastructure are, arguably, as much private goods as they are public goods. For example, most of the services infrastructure provides are excludable in a specific sense – their use depends on gaining access to a facility or network, for example by connection to piped water and gas or access to a section of the highway network, and service use may be metered and charged for. Once a user is connected to the network or transport facility, the degree of rivalry depends on the costs (including congestion) imposed on existing users or on the service supplier when an additional service unit is consumed. It has in the past been common in many countries not to charge users for the volume of some utility services consumed because the marginal supply cost has been considered negligible, congestion has been absent, or because technological constraints have prevented volume pricing. However, growing congestion as networks' capacities become fully utilised and technical innovations in metering consumption have made it possible and desirable to price many infrastructure services like other private goods. Where regulation is required because a particular type of infrastructure produces negative externalities, it can be narrowly focused on market imperfections while permitting wide scope for competition in other components of the sector. While the sunk costs that characterise the provision of many infrastructure services are a potential source of natural monopoly, technological and other differences make it possible to "unbundle" the components of a sector that involve natural monopoly from those that can be provided more competitively.

In conclusion, the fact that many infrastructure services are as much private goods as they are public goods arguably paves the way for a meaningful role for the private sector in future years. Other services may remain in the public domain. The above comments are provided for background information purposes only. A rigorous analysis of the relative roles of the public and private sector falls outside the scope of this thesis.

Chapter 1

The Role of Public Capital in Private Production: A Review of the Literature

1. Introduction

The number of studies focusing on public infrastructure has ballooned since Aschauer (1989a,b) and Munnell (1990a,b) uncovered a positive and statistically significant relationship between this variable and private productivity.[1] Several reviews of the infrastructure literature have already been carried out[2] so, rather than simply listing the main results of previous empirical work, the purpose of this chapter is to highlight opportunities for new research and provide a platform for the two studies that account for the majority of the research in this thesis. Some of the results of previous work are also provided as background information.

[1] Although Aschauer and Munnell sparked off the public capital debate, a number of studies (eg, Ratner, 1983) had previously analysed infrastructure's effect at the national level. The link between public investment and economic activity was analysed analytically by Arrow and Kurz (1970) and the role of infrastructure has for a long time been an important area of research in the literature on regional and urban development. Nevertheless, Aschauer's and Munnell's work attracted policymakers' attention to the fact that infrastructure may be a macroeconomic policy instrument.
[2] For example, those by the Federal Highway Administration (1992), Gillen (1996), Gramlich (1994), Hurst (1994) and Munnell (1993).

The infrastructure literature is almost entirely empirical in nature. Broadly, two approaches have received the most attention: the production function approach and the duality approach. The latter involves the estimation of cost and profit functions. Early work involved estimation of aggregate Cobb-Douglas production functions, with public capital included as an input. The implausible results obtained in these studies led to the use of more complex functional forms, richer data sets consisting of data across time and space and econometric techniques that account for non-stationary variables. In reviewing this literature a point that has to be stressed is that many of the results of the various studies are not comparable and it is often difficult, without replicating, to know to what innovations differences in results should be attributed: the use of a different geographic dataset, economic sector, functional form, econometric technique, adjustment to variables, *etc.*

Developments in the production function literature were accompanied by work using the duality approach by a number of authors such as Berndt and Hansson (1992), Lynde and Richmond (1992), and Nadiri and Mamuneas (1994). These studies address some of the problems encountered in the estimation of production functions and, by allowing for adjustments in firms' decision variables, provide a richer menu of analytical statistics that allows researchers to investigate how firms benefit from an expansion of the public capital stock.

Despite the significant increase in infrastructure research in recent years there remain many unanswered questions. First, the finding that various measures of public capital have a significant effect on productivity does not answer the question as to whether the benefits outweigh the cost of providing additional capital. Public capital contributes independently to firms' output in the sense that it is not purchased on a per unit basis. Local governments, for example, supply infrastructure in return for lump sum property tax payments and the amount of public capital supplied is determined by a political process over which firms have no direct control. Although most studies in the infrastructure literature treat infrastructure capital as a fixed unpaid factor of production, new public projects impose a cost to society in the form of higher tax payments. Thus the optimal infrastructure stock can be derived by balancing the cost savings enjoyed by the private business sector against the cost to society of providing the additional capital. Much of the recent research using the duality approach also focuses on the importance of infrastructure to the manufacturing sector, either in the U.S. or in other countries. This is justifiable in the sense that a more complete set of input data is available for this sector and manufacturing is, arguably, the sector that derives most benefits from this type of capital. However, there are other sectors that are likely to benefit from infrastructure investment either directly or indirectly and so more investigation is needed into the extent of infrastructure's impact on total private business production possibilities.

Second, it is also clear that studies that make use of a direct measure of total factor productivity (TFP) rely on standard constructions based on Solow (1957).[3] However, as Malley *et al.* (1998) point out, the standard Solow residual ignores considerations pertaining to market power, returns to scale and variable factor utilisation over the business cycle. If the Solow residual does not measure "true" productivity growth, it is possible that conclusions drawn about the relationship between productivity and infrastructure based on this residual are invalid. It is for this reason that in Chapter 4 the focus moves from infrastructure to issues relating to

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[3] These include production function studies, studies that use a growth accounting framework and studies in which causality tests are carried out.

productivity measurement. There are a number of uses to which alternative measures of productivity can be put. For example, many surveys of the infrastructure literature raise the question of "reverse causation" (productivity gains generating increases in public investment). However, there has been very little empirical investigation of the causal relationship between the two variables.

Third, regardless of the empirical approach, more work is needed on the importance of the different types of public capital. For example, do increases in the different types of public capital have opposite effects on the demand for labour and capital? Are some types of infrastructure optimal and others suboptimal? Do some types of infrastructure Granger cause TFP and others not?

This chapter is divided up as follows. In Section 2 a brief overview is provided of the different ways in which public capital is hypothesised to affect private production. In Section 3 an outline is provided of the production function approach and the results of the various national-level and state-level studies are summarised. The main criticisms of this approach are also highlighted. In Section 4 the advantages of the cost function approach are reported and the wide variety of infrastructure impacts that can be uncovered using this approach are derived. Finally, the main results of the various studies are reported. In Section 5 a brief summary is provided of the second duality approach which involves estimation of profit functions. In Section 6 avenues for new research (most of which receive attention in the remaining chapters of the thesis) are highlighted.

2. The Transmission Mechanism

It is important to distinguish between infrastructure effects that reveal themselves on the demand side and those that reveal themselves on the supply side. The immediate impact of an increase in infrastructure spending is to stimulate demand for construction workers, engineers and other types of labour and factor inputs required for the actual building of a road or facility. The increased demand for such resources has a prompt and positive effect on output and growth. Public works projects were used aggressively in the U.S. during the Great Depression to provide employment and stimulate income growth. Policies adopted in Japan and proposed in the European Community in recent years have also been motivated on these grounds.[4] Stimulating demand, however, offers only one channel, and rather a short-lived one, through which public capital affects private economic activity. The more important and longer-lasting effects occur on the supply side.

According to Meade (1952), there are two ways in which public capital can affect private production. One is as an "environmental" factor that enhances the productivity of private inputs. In terms of this hypothesis, infrastructure investment produces positive production externalities.[5] As shown by Hulten and Schwab (1991b), if these externalities augment all inputs to the same degree, a change in the quantity of public capital acts like a Hicks-neutral shift in the production function:

$$Q_t = \Theta(G_t, t) \cdot F(L_t, K_t), \tag{1}$$

where Q_t is value-added output, $\Theta(.)$ is an index of Hicks-neutral technical change, G_t

[4] See *IMF* (1993, p. 34) and *EC* (1993) for discussions of the Japanese proposals of August 1992 and April 1993 and the June 1993 EC summit proposals respectively.
[5] The benefits are similar to those discussed by Romer (1986).

represents services from the public capital stock, L_t is labour input and K_t is private capital. In the Hicks-neutral world, an increase in public investment raises the marginal products of labour and private capital. For example, an uncongested transportation network allows firms to deliver products faster, reduce inventories, centralise work to take advantage of economies of scale and hire a broader range of people from a wider geographical area.

The other way in which public capital affects private output is if it enters the production function as a direct but unpaid factor of production. The correct specification of the production function in this case is

$$Q_t = \Theta_t \cdot F(L_t, K_t, G_t). \tag{2}$$

The public good has the characteristics of a private good though it is not supplied through a market-clearing process. Public capital does not augment the productivity of the private sector but increases in G lead to increases in Q if the marginal product of public capital is positive. It is likely that certain types of infrastructure may enter the production function as a direct input as well as enhance the productivity of other inputs.

The third way in which infrastructure can increase output (as opposed to productivity) is by attracting private inputs into a region or country and thereby shifting the production function outwards. If more or better infrastructure provides cost savings (or some other benefit), one would expect firms to relocate from regions with a low quantity or poor quality of infrastructure to regions with a large quantity or high quality of infrastructure capital. This is why Seitz and Licht (1995) argue that public capital may be a strategic weapon for inter-regional (and maybe international) competition.

With public investments that reduce travel time (roads, highways, airports and mass transit) many of the time savings accrue directly to consumers or workers and not to firms. Reduced commuting time could lead to more time being spent at work but this would add to both output and hours paid for, not necessarily to output per hour. It is more likely that reduced commuting time increases the amount of leisure time and hence improves welfare. However, to the extent that workers are compensated for the cost of their travel, increased public spending on transport infrastructure should lower the cost of producing a given level of output.[6]

3. The Production Function Approach

3.1 Introduction

Production function studies are divided into two main groups: those that use national data and those that use state or regional data. Studies using state-level production functions have generally concluded that public capital has a positive effect on productivity, but the effect is smaller than that uncovered by studies using national-level data. The Cobb-Douglas production function is the most popular functional form in these studies. Following (2), public capital enters the production function as a fixed unpaid factor of production:

$$Q = \Theta\, L^{\beta_L} K^{\beta_K} G^{\beta_G}, \tag{3}$$

[6] To the extent that workers are employed up to the point where, at the margin, productivity is equal to real wages, the increased public investment could lead to *lower* productivity. Hence there are conceptual reasons why one would not expect public infrastructure investment to increase productivity.

where β_L, β_K, and β_G are the output elasticities of labour, private capital and public capital respectively and time subscripts are omitted for simplicity. Taking logarithms of both sides the equation can either be estimated with output as the dependent variable (eg, Munnell, 1993) or after transforming Q into a measure of capital, labour or total factor productivity (eg, Aschauer 1989a and Munnell 1990a).

3.2 Aggregate Production Function Studies

Aschauer (1989a) estimated a transformed version of (3) using national data for the U.S. from 1949 to 1985. His basic premise is that:

> "Expansions of public investment spending should have a larger stimulative impact on private sector output than equal-sized increases in public consumption expenditure. Specifically, public investment is argued to induce an increase in the rate of return to private capital and, thereby, to stimulate private investment expenditure." (p.178)

Rather than crowding out private investment, Aschauer argues that public investment stimulates private investment by increasing the rate of return to private capital. To transform the left-hand side into output per unit of capital a number of assumptions are made about returns to scale. The first specification of technology Aschauer considered was increasing returns to scale over L, K and G but constant returns to scale (CRS) over private inputs ($\beta_L + \beta_K = 1$). This assumption is broadly consistent with the argument that industries with increasing returns to scale are likely to be publicly operated.[7] In this case, private factors may be paid according to their marginal productivities and private output will be exhausted. Under this assumption (3) becomes

$$q-k=\theta+\beta_L(l-k)+\beta_G g, \tag{4}$$

where lower-case letters denote logarithms and $q-k=\ln(Q/K)$, the average product of capital. Assuming competitive product and factor markets, Aschauer also derives the following measure of total factor productivity

$$p=q-\alpha_L l-\alpha_K k=\theta+\beta_G g, \tag{5}$$

where α_L and α_K are the shares of labour and capital in total product respectively. Otto and Voss (1994) point out that (5) has important implications for standard calculations of the Solow residual. If aggregate production is correctly described by (2) then the variable p cannot be interpreted as a measure of total factor productivity. This requires removing the contribution of public capital $\beta_G g$. In this case total factor productivity, θ, is measured properly as $(p - \beta_G g)$ and the variable p is by definition positively related to the level of public capital.

If it is argued that the assumption of increasing returns is unrealistic (eg, due to congestion effects) over the relevant range, then $\beta_L + \beta_K + \beta_G = 1$. The residual is the implicit rent earned by the public service. The productivity of private capital becomes

$$q-k=\theta+\beta_L(l-k)+\beta_G(g-k). \tag{6}$$

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[7] One rationale behind public provision of infrastructure arises from economies of scale in production. The acquisition and distribution of water, for example, may allow for substantial decreases in cost along with increases in the scale of production. While pricing mechanisms can be developed to ensure an efficient allocation of resources, it is also necessary in such cases to allow a monopolist to engage in the whole of the production. It can be argued that the most efficient or most easily monitored producing entity is the government itself.

In this case if private factors are paid according to their marginal products, private output will not be fully distributed. Note that (4) and (6) are nested in the following more general specification

$$q-k=\theta+\beta'_K k+\beta_G g+\beta_L(l-k), \tag{7}$$

where $\beta'_K=\beta_K+\beta_L-1$. Equation (7) is the basis of Aschauer's (1989a) and other researchers' empirical analyses. If the estimate of β_G is positive and statistically significant, the conclusion is that public capital enhances the productivity of private capital. If the estimated coefficient for β'_K were not significantly different from zero, the hypothesis of increasing returns to scale in all three inputs would not be rejected and (4) would become the focus of the analysis. However, if the estimated coefficient for β'_K is not significantly different from that estimated for β_G, with the opposite sign (ie, $\beta'_K = -\beta_G$), then the hypothesis of constant returns to scale in all three inputs would not be rejected and (6) would be the equation to estimate.[8]

Aschauer obtained an estimate of 0.39 for β_G, the output elasticity of the public/private capital output ratio. This means that a 1 per cent increase in the ratio of public capital to private capital raises productivity – output per unit of private capital – by 0.39 per cent.[9] Aschauer also found that "core infrastructure" contributes most to productivity growth. The core includes highways and streets, mass transit, airports, electrical and gas facilities and water and sewer systems. The core has an output elasticity of 0.24 which, given its size, implies a rate of return of almost 150 per cent.

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[8] Other variables are also added to the estimating equation such as time trends and the capacity utilisation rate to control for business cycle effects.

[9] Ratner (1983) found an output elasticity of 0.058 with data from 1949 to 1973. However, the data has been substantially revised since then. Tatom (1991) re-estimated Ratner's model using the new data and obtained an output elasticity of 0.28.

Public capital's rate of return is calculated by differentiating (3) with respect to G:

$$\frac{\partial Q}{\partial G} = \beta_G \Theta L^{\beta_L} K^{\beta_K} G^{\beta_G - 1} = \beta_G \frac{Q}{G}, \tag{8}$$

where $\partial Q/\partial G$ is the marginal product of government capital. In 1994 the total infrastructure stock was \$2.1 trillion and output for the private business sector was \$4.6 trillion, thus an estimate of 0.39 implies a rate of return of 85 per cent.

Munnell's (1990a) results supported Aschauer's finding of a significant and large effect of public capital on productivity. The dependent variable was transformed to output per unit of labour and regressed on a constant, private capital per hour, public capital per hour and capacity utilisation. The production function was constrained to constant returns to scale. An output elasticity of 0.33 was obtained for output per hour with respect to public capital. A number of other production function studies have been conducted using aggregate data for other countries (eg, Bajo-Rubio and Sosvilla-Rivero, 1993, for Spain and Otto and Voss, 1994, with Australian data). These studies obtain estimates of infrastructure's output elasticity ranging from 0.19 to 0.45.

3.3 Criticisms of the Production Function Approach

3.3.1 The Estimates are Sensitive to the Choice of Dataset

The production function studies have attracted criticism from a number of authors. The estimated output elasticities for public capital and the rates of return implied by them have been criticised as being "implausible" (Aaron, 1990; McGuire, 1992), "grossly inflated" (Schultze, 1990) and for "straining credulity" (Montgomery, 1990). Aaron

Table 1. *Sensitivity Testing of the National Aschauer & Munnell Specifications.*

Aschauer equation:

Data set used	**Public capital coefficient**
Aschauer data (1949-85)	0.39
Munnell data (1949-85)	0.42
Munnell data (1949-87)	0.24

Munnell equation:

Data set used	**Public capital coefficient**
Munnell data (1949-87)	0.35
Munnell data (1949-85)	0.64
Aschauer data (1949-85)	0.34

Note: The first set of coefficients result from regressing output divided by private capital (all variables in logs) on a constant, time trend, labour divided by private capital, public capital divided by private capital, and capacity utilisation. The second set result from regressing output divided by employment on a constant, employment, private capital, public capital and the capacity utilisation rate.

points out that, based on Aschauer's estimated elasticities, the stock of core infrastructure would have to increase over five-fold to equalise the marginal productivity of private capital and core infrastructure. Nienhaus (1991) conducted several tests on the effects of mixing the data sets and equations used by Aschauer (1989a) and Munnell (1990a,b). The results of these sensitivity tests are reported in Table 1. The coefficient estimates vary considerably, which leads Nienhaus to conclude that the two authors' national level results lack robustness. Using Munnell's data Nienhaus (1991) also tested a different split of the sample (1951-69 and 1970-87) and found that for the period to 1969 the public capital output elasticity was 0.54 and significant. However, for the period 1970-87 the public capital coefficient is insignificant. Nienhaus notes that this insignificant result is all the more important because this is the period (1970-87) in which the decline in the rate of public capital growth occurred. His conclusion is that although a very high elasticity for output with respect to public capital or core public capital is obtained when estimating aggregate

U.S. production functions using annual post-World War II data (0.25 to 0.50), this relationship seems to have disappeared or weakened since 1970. When Berndt and Hansson (1992) estimated one of the equations of Aschauer (1989a) and Munnell (1990a) using Swedish data, they obtained a number of unrealistic coefficient estimates.[10] The authors are critical of aggregate production function studies for a number of reasons:

> "The highly restrictive Cobb-Douglas functional form is hardly ever employed anymore; more flexible functional forms are used instead. Second, there is a serious issue of what is endogenous and what is exogenous, and the extent to which the production function estimates – Cobb-Douglas or translog – suffer from a simultaneous equations bias. Specifically, the right-hand variables in the various equations estimated by Aschauer and Munnell include measures of labour input and utilisation (either capacity utilisation or the state unemployment rate) and strong arguments have been made that in this type of a context such variables should be treated as endogenous, not exogenous; in such a case estimation by OLS produces biased and inconsistent parameter estimates." (p. S155)

It is for these reasons that many authors have chosen to estimate cost functions instead of production functions. I will return to the relative merits of each approach in Section 4.

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[10] For example, for the Aschauer specification the coefficient estimates for G and L are greater than 1 and the estimate on K is -1.67, implying a negative marginal product for private capital since the implicit estimated elasticity of output is -0.67.

3.3.2 The Relationship Between Output and Public Capital is a Coincidence

Several authors have pointed out that the data used in a number of studies is not stationary and that the relationship between public capital and private sector productivity is spurious. For example, Tatom (1993b) states that the level of the public capital stock and the level of business sector output per hour have correlations of roughly 0.95 but, when first differences are taken the two series have correlations that are essentially zero.

Tatom (1991, 1993a) calculates the degree of integration of the data, finding that the dependent variable $\ln(Q/K)$ is integrated of degree one, while the variable $\ln(G/K)$ is integrated of degree two. Using first differences and including a time trend Tatom finds that the effect of public capital becomes insignificantly different from zero. Ford and Poret (1991) also use differenced data to carry out their production function study on a selection of OECD countries and find that the relationship between public capital and productivity is not robust for all countries. When public capital is significant, the coefficients for private inputs are often implausible. Hulten and Schwab (1991a) and Jorgenson (1991) also find that the relationship between public capital and productivity is not found when first differencing is used. Munnell (1993) counters these findings, arguing that first differencing produces problems of its own:

> "No one would expect growth in capital stock, whether private or public, in one year to be correlated with the growth in output in that same year. In fact, equations estimated in this form often yield implausible coefficients for labour and private capital as well as for public capital (Evans and Karras, 1994; Hulten and Schwab, 1991a). None of the critics concludes from these

> mis-specified equations, however, that private capital and labour lack a significant effect on private sector output." (p. 32)

Against first-differencing it is also argued that it destroys any long-term relationship in the data. Instead it should be tested whether the variables are cointegrated, adjust them and estimate accordingly. Duggal *et al.* (1995) also argue that there are specification problems in all of the studies that use first-differenced data.[11]

3.3.3 The Relationship Runs in the Opposite Direction

Several surveys of the infrastructure literature[12] have questioned whether public capital affects productivity or whether the relationship runs in the opposite direction.[13] However, very little research has been conducted into the causality issue. An exception is Tatom (1993c), whose point is that:

> "Many researchers have noted that regions of the United States and countries that have relatively high income and productivity have relatively more public capital per worker and per person. Such an observation suggests that infrastructure boosts private-sector productivity, but others view that observation as simply confirmation that higher-income voters normally demand more of all goods, including the services of public capital stocks." (p. 13)

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[11] As Lynde and Richmond (1993a) point out many studies ignore the effect of energy price changes on productivity.

[12] For example, those by the Federal Highway Administration (1992), Gillen (1996), Gramlich (1994) and Hurst (1994) and Munnell (1993).

[13] Causality from productivity to infrastructure is referred to as reverse causality in the rest of the thesis.

To the extent that the productivity slowdown led to lower real incomes, growth in the demand for infrastructure services may have slowed. Furthermore, the productivity slowdown may have squeezed government budgets, leading to less infrastructure spending. Causality may in fact run in both directions: more public capital may help produce more output and the subsequent rise in income may lead voters to demand more infrastructure.

There is some evidence that public capital is a normal good. Borcherding and Deacon (1972) calculated large and statistically significant income elasticities for highways and water and sewer system expenditures in the United States. These two types of infrastructure account for roughly 47 per cent of the total non-military public capital stock. According to Tatom (1993c), there is strong evidence of reverse causality. He finds that the growth rate of the public capital stock does not Granger cause total factor productivity in the private business sector and the reverse test fails to reject causation from total factor productivity growth to public capital growth. Due to the focus on causality and related issues in Chapter 4 it is worth outlining Tatom's methodology briefly. Tatom tests for causality between the logarithm of total factor productivity[14], θ_t, and two infrastructure variables: the change in the logarithm of the constant dollar net non-military public capital stock, Δg_t, and the log of the constant dollar flow of public investment, $\ln I_t$. Up to 4 lags of each variable were added to the estimating equations and examined for a statistically significant effect.

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[14] According to Tatom (1993c), TFP for the total business sector is output divided by a weighted average of labour and private capital, ie. the standard Solow residual.

The following results were obtained using a sample period from 1949-1990 (t-stats in parentheses):

$$\begin{aligned} &\theta_t = 0.094 - 0.019 \ln I_{t-1} \\ &\quad\;\; (2.11) \quad (1.81) \\ &\bar{R}^2 = 0.05 \;\; DW\ 1.79 \end{aligned} \tag{9}$$

Because the estimate on $\ln I_{t-1}$ is statistically insignificant, Tatom concludes that there is no evidence that public capital formation causes the growth of TFP.[15] The following are the results of the reverse causality tests, first using the growth rate of public capital:

$$\begin{aligned} &\Delta g_t = \underset{(1.11)}{0.001} + \underset{(7.31)}{1.057}\Delta g_{t-1} + \underset{(0.48)}{0.109}\Delta g_{t-2} - \underset{(2.19)}{0.266}\Delta g_{t-3} + \underset{(2.59)}{0.059}\theta_{t-1} + \underset{(2.73)}{0.060}\theta_{t-2} \\ &\qquad\qquad \bar{R}^2 = 0.97 \;\; DW = 1.85 \end{aligned} \tag{10}$$

and, second, using the logarithm of investment:

$$\begin{aligned} &\ln I_t = \underset{(1.42)}{0.173} + \underset{(8.15)}{1.169}\ln I_{t-1} - \underset{(1.54)}{0.209}\ln I_{t-2} + \underset{(2.58)}{0.893}\theta_{t-1} + \underset{(2.17)}{0.732}\theta_{t-2} \\ &\qquad\qquad \bar{R}^2 = 0.97 \quad DW = 1.98 \end{aligned} \tag{11}$$

According to Tatom, the results reported in (10) and (11) provide evidence that TFP causes public capital formation. However, there are several points worth making about this causality testing procedure. First, Tatom does not specify whether the TFP variable is in levels or differences (ie, the growth rate of total factor productivity). It appears that data in both levels and differences was used without checking for stability. Second, Tatom does not specify how lag-lengths were selected. It would appear that this was on the basis of t-stat significance. Third, the empirical adequacy of the equations was not investigated sufficiently.[16] However, the most important criticism of

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[15] Similarly, no statistically significant relationship was found using lags of Δg_t.

[16] For example, the Durbin Watson test for serial correlation is unreliable when the estimating equation contains lagged dependent variables.

Tatom's approach is his use of the standard Solow residual to represent productivity growth. This issue is discussed in Section 6.

There are other causality studies in the infrastructure literature but most attempt to identify the nature of the relationship between public investment and *private investment*, rather than TFP and thus establish whether public investment crowds out or crowds in private investment. Like so many studies in the infrastructure literature the results are not directly comparable due to differences in econometric technique and the various variables. For example, Ramirez (1994) concludes that changes in public investment precede and add significantly to the explanation of variations in private investment expenditures along the U.S.-Mexico border. However, he uses a rather simplistic Granger causality testing procedure, adding lags on an ad hoc basis. Erenburg and Wohar (1995) adopt a more rigorous approach: the multivariate Granger causality testing procedure is combined with Akaike's Final Prediction Error Criterion. A battery of diagnostic tests is then performed to check the adequacy of the results. Although econometrically rigorous, a possible drawback of this study is the use of public *equipment* investment as the relevant infrastructure variable. This measure of public capital, consisting of assets such as lawn and garden equipment, computers and vehicles is unlikely to have as direct an effect on private production as Aschauer's measure of core infrastructure.[17]

3.4 Regional and State Level Production Functions

Munnell (1993) concedes that the output elasticities obtained from aggregate production functions are "too large to be credible". It does not make sense for private

[17] See Katz and Herman (1997), Table A, for a list of the components of the public equipment stock.

capital to have a smaller impact than public capital. As an alternative, several researchers have estimated production functions using more geographically disaggregated data (at the state or regional level). On balance, these studies provide evidence of a role for public infrastructure in boosting private productivity, albeit a much reduced one compared with estimated output elasticities of the aggregate studies. The use of pooled data sets such as these, it is argued, provide more observations with inherent variation because of the difference in size and structure of the various states' economies. By supplementing variation over time with variation across space any criticism of spurious correlation across time is mitigated. It must be borne in mind that some of these papers contain potential biases. For example, if the measure of public capital that enters the state production function is the own public capital stock, this implies that an additional road in Texas affects output in Texas alone, and ignores the productivity benefits of Texan roads that accrue to other states. Furthermore, many of the results cannot be compared directly with the national-level studies. Apart from using data disaggregated at the geographic level, many of the state-level and regional-level studies use data for just one sector (ie, manufacturing) and incorporate other econometric innovations.

Munnell (1990b), using state level data for 1970-86, obtains a lower estimate of public capital's output elasticity compared with her aggregate study (0.15 compared with 0.33). The elasticities for private capital and labour are 0.31 and 0.59 respectively. Public and private capital were calculated for the state level using investment spending profiles. Eisner (1991) did further work with Munnell's data and found that public capital is still significant when the data are arranged to allow for cross-sectional variation. This, however, disappears when the data are arranged to allow for time series variation. States with more public capital per capita have a higher

Table 2. *Sensitivity Tests of Munnell's 1990b State-level Study.*

Dummy Variable	Public Capital Coefficient
Munnell, no dummies	0.15*
State Dummies included	-0.02
Regional dummies	0.09*
Regional estimates	Public Capital Coefficient
East	0.11*
South	0.17*
Midwest	0.14*
West	0.08*

* Denotes statistical significance
Source: Nienhaus (1991)

level of per capita output but state infrastructure spending does not increase output in the same year. Eisner regards the direction of causation as undecided and argues that a lag structure is needed to understand the true relationship between output and public capital. Holtz-Eakin (1994) estimates production functions that control for unobserved, state-specific characteristics and obtains results that indicate no role for public capital at the margin. Estimates obtained by other authors (eg, Garcia-Mila and McGuire, 1992 and Munnell, 1990b, 1993) did not control for these effects in this manner. Nienhaus (1991) replicated Munnell's (1990b) results and also included a number of dummy variables. When state dummy variables are included the public capital variable becomes insignificant and with regional dummy variables the public capital coefficient is smaller but significant. Nienhaus also runs separate regressions for groups of states, obtaining significant coefficients throughout. A summary of some of these results is contained in Table 2.

McGuire (1992) tests the robustness of the results obtained by Munnell (1990b) and Garcia-Mila and McGuire (1992) using variables from both studies. Several production functions are estimated: Cobb-Douglas with no control for state effects. Cobb-Douglas with control for state fixed and random effects, and translog

Table 3. *Production Function Estimates of the Output Elasticity of Public Capital by Level of Geographic Aggregation*

Author	Aggregation	Output elasticity
Aschauer (1989a)	National	.39
Holtz-Eakin (1989)	National	.39
Munnell (1990a)	National	.34
Moomaw & Williams (1991)	States	.25
Costa, Ellson & Martin (1987)	States	.20
Eisner (1991)	States	.17
Garcia-Mila & McGuire (1992)	States	.04
Mera (1973)	Japanese regions	.20
Munnell (1990b)	States	.15
Duffy-Deno and Eberts (1991)[1]	Metropolitan	.08
Eberts (1986)	Metropolitan	.03

[1]The authors use personal income as the dependent variable instead of estimating a production function.
Source: Munnell (1993)

with no control for state effects. Public capital is found to have a strong and statistically significant effect on gross state product (elasticities ranging from 0.035 to 0.394). A summary of some of the production function estimates of the output elasticity of public capital is contained in Table 3. The coefficients at each level of aggregation tend to be similar. As the geographic focus narrows, so too does the output elasticity of infrastructure. This is perhaps because it is not possible to harness all the benefits of a specific infrastructure project by looking simply at the area in which it exists. There are spillover effects as well. The studies cannot be compared solely on the basis of the geographic focus, however.

4. Cost Functions

4.1 Cost Functions versus Production Functions

A number of authors have suggested that cost functions may be more appropriate for analysing the relationship between public infrastructure capital and the private production process. Morrison and Schwartz (1992) favour the cost function approach because:

> "Estimating equations result from direct differentiation of the function, and the endogeneity of the resulting dependent variables is consistent with intuition." (p. 4)

Cost function models usually consist of at least two estimating equations: the cost equation and the input demand equation for labour and, in the case of long-run cost functions, the input demand equation for private capital. Thus in the cost function approach labour and private capital are dependent variables. The input prices are exogenous variables. In contrast, in production functions the input levels are independent variables, raising questions about endogeneity and exogeneity. Friedlander (1990) agrees that production functions suffer from an important problem of mis-specification:

> "In particular, since input prices affect factor utilisation and thus where firms are positioned on their transformation function, omitting them in an econometric analysis of technology could lead to substantial biases in the estimated technological coefficients. Of course, if relative input prices are constant over the sample, this is not a problem. A substantial variation in input prices over the sample probably would be a legitimate cause for concern, however." (p. 109)

Estimating a cost function rather than a production function incorporates input price effects into the analysis. The differences between econometric implementation of cost and production functions are summarised in Table 4.

Table 4. *Cost and Production functions: Endogenous and Exogenous Variables*

Variable	Cost function	Production function
Output	Exogenous	Endogenous
Input quantities	Endogenous	Exogenous
Input costs	Endogenous	Exogenous
Input prices	Exogenous	Endogenous

Berndt and Hansson (1992) add that estimation of a cost function allows economic content to be added to the analysis. This is because it incorporates the assumption of cost minimisation. Firms choose quantities of inputs (including public capital) to minimise their production costs. Declines in the cost of producing a particular level of output (given constant input prices) represent an increase in firms' productivity. As Gillen (1996) notes, there are several other reasons why cost functions are preferred:

> "The production function approach imposes the minimal modelling structure on the data and therefore the estimates of the underlying production technology are more likely to be biased and not be robust. The production approach is a purely technical specification between inputs and outputs and not a behavioural one. The notion of an expansion path is not considered to simultaneously determine inputs and outputs. Other reasons for moving to a cost function approach are the richer menu of analytical statistics, the explicit characterisation of optimising behaviour of the firm and the lack of any loss in information by abandoning the production function approach." (p. 49)

As the dual to the production function the cost function reflects technology. It can also represent the dependence of costs on the level of output (scale economies) and inputs that are fixed in the short run, such as private and public capital (fixity). If public capital is included as an argument in a variable (short-run) cost function it becomes a factor explaining observed external scale effects. This, according to Morrison and Schwartz (1997), is consistent with intuition as infrastructure may affect the shape of the long-run average cost curve. The impact of infrastructure, fixity and internal scale economies on costs can be specified in terms of the elasticity of costs with respect to output. External scale economies that arise from outside forces with public good characteristics will cause output and total cost changes to be non-proportional. In Section 4.2 a brief look is taken at the various "analytical statistics" that can be computed using the cost function approach.

4.2 Cost Functions: The Theoretical Framework

Infrastructure's effect on private costs can be illustrated by solving the firm's cost minimisation problem subject to a Cobb-Douglas production technology:

$$Min \quad P_L L + P_K K - \lambda(L^{\beta_L} K^{\beta_K} G^{\beta_G} - Q), \tag{12}$$

where P_K and P_L are the prices of private capital and labour respectively. The necessary conditions are:

$$P_L - \lambda\beta_L L^{\beta_L - 1} K^{\beta_K} G^{\beta_G} = 0, \text{ and} \tag{13}$$

$$P_K - \lambda\beta_K L^{\beta_L} K^{\beta_K - 1} G^{\beta_G} = 0. \tag{14}$$

Solving for L and K gives

$$L^* = \left(\frac{P_K}{P_L}\frac{\beta_L}{\beta_K}\right)^{\frac{\beta_K}{\beta_L+\beta_K}} G^{-\frac{\beta_G}{\beta_L+\beta_K}} Q^{\frac{1}{\beta_L+\beta_K}}, \text{ and} \tag{15}$$

$$K^* = \left(\frac{P_L}{P_K}\frac{\beta_K}{\beta_L}\right)^{\frac{\beta_L}{\beta_L+\beta_K}} G^{-\frac{\beta_G}{\beta_L+\beta_K}} Q^{\frac{1}{\beta_L+\beta_K}}. \tag{16}$$

Equations (15) and (16) are the conditional input demand equations for labour and private capital. They determine the quantities of labour and capital that minimise firms' costs. The optimal quantities depend partly on the quantity of public capital. Using the cost-minimising quantities of L and K, total costs are given by

$$C^* = G^{-\frac{\beta_G}{\beta_L+\beta_K}} Q^{\frac{1}{\beta_L+\beta_K}} P_K^{\frac{\beta_K}{\beta_L+\beta_K}} P_L^{\frac{\beta_L}{\beta_L+\beta_K}} \left[\left(\frac{\beta_L}{\beta_K}\right)^{\frac{\beta_K}{\beta_L+\beta_K}} + \left(\frac{\beta_K}{\beta_L}\right)^{\frac{\beta_L}{\beta_L+\beta_K}} \right]. \tag{17}$$

Assuming constant returns to scale in private inputs (ie, $\beta_L+\beta_K = 1$), the impact of G on costs can be expressed solely in terms of its own output elasticity, ie, $G^{-\beta_G}$. How do changes in G or β_G affect C^*? The higher is the output elasticity of G the lower are costs and the higher is G the lower are costs. Unless constant returns to scale are assumed, the importance of government infrastructure depends on $\beta_L + \beta_K$, the output elasticities of labour and private capital. The bigger they are the smaller is the exponential term in absolute terms. The larger are $\beta_L + \beta_K$ the smaller is the shift down in cost from an increase in public infrastructure capital, *ceteris paribus*. The duality existing between the production function and the cost function is called Shephard's duality. What this duality suggests is that, given a production function, it is always possible to derive a cost function that reflects the same production technology. Irrespective of functional form the cost function depends on the level of output, the prices of labour and private capital and the quantity of public capital:

$$C^* = F(Q, P_L, P_K, G). \tag{18}$$

As Silberberg (1990) notes:

> "If a cost function satisfies some elementary properties, ie, linear homogeneity and concavity in the factor prices, then there in fact is some real, unique underlying production function." (p. 313)

Although the Cobb-Douglas functional form is popular with researchers estimating production functions, its dual cost function is not popular in the infrastructure literature. This is because it incorporates restrictive assumptions regarding input substitutability. Flexible cost functions, such as the translog cost function, which allow for the effect of a change in input prices on the cost-minimising mix of inputs are preferred. Below, the methodologies of some of these studies and their results are discussed. First a general look is taken at the direct and indirect effects of public capital. The direct effect is the impact of G on costs; the indirect effect is the effect of G on the firm's demand for labour and capital. Differentiating (18) with respect to G leads to:

$$Z_G = -\frac{\partial C(Q, P_L, P_K, G)}{\partial G}, \tag{19}$$

where Z_G is the change in private production cost if public capital increases by one unit. Z_G is called the shadow price of public capital or the willingness to pay for public services.[18] Infrastructure's cost elasticity is

$$\varepsilon_{CG} = \frac{\partial C}{\partial G}\frac{G}{C} = \frac{\partial \ln C}{\partial \ln G}. \tag{20}$$

If $\partial F/\partial G$ is defined as the marginal product of public capital, application of the Envelope Theorem provides a link between the monetary measure Z_G and the marginal product of public capital[19]:

$$\frac{\partial F}{\partial G} = \frac{-\dfrac{\partial C}{\partial G}}{\dfrac{\partial C}{\partial Q}} = \frac{Z_G}{P_Q}, \tag{21}$$

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[18] The negative sign converts the shadow value to a positive number.
[19] See Chambers (1988).

that is, the marginal product of infrastructure is equal to the ratio of the shadow price of G to marginal production cost, P_Q. This relation provides a connection between the primal (the production function) and the dual (the cost function). The indirect effects can be illustrated as follows. Applying Shephard's lemma to the cost function (18) yields the cost-minimising factor demand equations for labour, L^*, and capital, K^*:

$$L^* = \frac{\partial C}{\partial P_L}, \text{and}$$
$$K^* = \frac{\partial C}{\partial P_K}. \tag{22}$$

These cost-minimising factor demand equations depend on the same variables as the cost function (P_L, P_K, Q and G). Differentiating (22) with respect to G it is possible to see how the demand for labour and capital varies as G is increased. For example,

$$\frac{\partial L^*}{\partial G} = \frac{\partial^2 C}{\partial P_L \partial G}, \tag{23}$$

where $\partial L^*/\partial G$ is the labour saving ($\partial L^*/\partial G<0$) or extra labour demanded ($\partial L^*/\partial G>0$) if G is expanded by one unit. If $\partial L^*/\partial G>0$ the public capital stock and labour are complements and if $\partial L^*/\partial G<0$, they are substitutes. Similarly for private capital:

$$\frac{\partial K^*}{\partial G} = \frac{\partial^2 C}{\partial P_K \partial G}.$$

Substituting the cost-minimising factor demand equations from (22) into the cost equation $P_L L + P_K K$, the cost function can be expressed as

$$C = P_L L^* + P_K K^*. \tag{24}$$

Differentiating (24) with respect to G yields:

$$\frac{\partial C}{\partial G} = P_L \frac{\partial L}{\partial G} + P_K \frac{\partial K}{\partial G}. \tag{25}$$

In (25) the cost-saving effects of G are decomposed into adjustment effects on the demand for labour and private capital. Further ways of analysing the relationship between G and private production are explored in Chapter 3.

4.3 Summary of Empirical Results

A great deal of cost function research has been conducted in recent years. Researchers have experimented with aggregate and disaggregated private data (manufacturing and/or regional), alternative functional forms and data for a variety of countries. In what follows some of the most widely reported results are discussed. These and others are summarised in Table 5.

Lynde and Richmond (1992) analyse the impact of public capital on the production costs of the U.S. non-financial corporate sector using share equations derived from a translog cost function. The marginal product of capital is found to be positive, implying that an increase in the stock of G reduces costs. This is one of the few cost function studies that uses total private business data. Nadiri and Mamuneas (1994) estimate a translog cost function using data for 12 U.S. manufacturing industries and find that public capital significantly reduces manufacturing costs. The magnitudes of the average cost elasticities range from -0.11 to -0.21, implying that infrastructure has a significant effect on private production but a smaller effect than that implied by the aggregate production function studies. Public capital is adjusted for capacity utilisation and R&D expenditures are included in the cost function. Seitz and Licht (1995) obtain slightly higher elasticities in a study using West German manufacturing data. The average cost elasticity is -0.22 but they range from -0.02 in

Table 5. *Key Results of Cost Function Studies*

Author	Data set	Specification	*G* Variable	Direct Effect	Indirect Effect
Berndt & Hansson (1992)	Swedish private business sector 1960-88	Variable cost function	Core public capital	Infrastructure Surplus	L = Complement & Substitute
Conrad & Seitz (1994)	West German manufacturing, construction, trade and transport 1960-88	Translog	Core, adjusted by capacity utilisation rate	Cost savings, $\partial C/\partial G$ = -0.142	L = Substitute K = Complement M = Substitute
Holleyman (1996)	U.S. manufacturing, 4-digit level, 1969-86	Translog	Highway stock, H	Cost increases, $\frac{\partial C}{\partial H}\frac{H}{C} = 0.022$	L = Substitute K = Substitute M = Complement
Keeler & Ying (1988)	U.S. trucking 1960-88, regional pooled	Translog	Highway stock	Cost savings	
Lynde & Richmond (1992)	U.S. non-financial corporate business sector 1958-89	Translog	Total non-military	G has positive marginal product	L = Substitute K = Complement
Lynde & Richmond (1993b)	U.K. manufacturing, 1966-90, value-added	Translog, adjustments for non-stationarity	Total non-military	G/L contributes to Q/L	K = Substitute
Morrison & Schwartz (1997)	U.S. manufacturing, pooled by region, 1971-87	Variable Cost Generalised Leontief P_Q=MC	Core (highways, sewers and water)	Cost savings, $\frac{\partial C}{\partial G}$ = -0.16-0.31	
Nadiri & Mamuneas (1994)	12 U.S. manufacturing industries at 2-digit level 1955-86	Translog, CRS for private inputs	Total, adjusted by capacity utilisation rate	Cost Savings, $\frac{\partial C}{\partial G}\frac{G}{C} = 0 - 0.21$	L = Substitute K = Substitute M = Complement
Seitz (1993)	31 West German 2-digit industries, 1970-89	Generalised Leontief	Public roads, length of motorway system	Cost savings	L = Substitute K = Complement
Seitz (1994)	31 West German 2-digit industries, 1970-89	Generalised Leontief	Total and core	Total: $\partial C/\partial G$ = -0.002 Core: $\partial C/\partial G$ = -0.004	L = Substitute K = Complement
Seitz & Licht (1995)	West German manufacturing, regional level	Translog	Total, lagged 1 year	Cost savings, $\frac{\partial C}{\partial G}\frac{G}{C} = 0.216$	L = Substitute K = Complement
Shah (1992)	26 Mexican manufacturing industries, 3-digit level, 1970-87	Translog variable cost function	Total, adjusted by industries' proportion of output	Cost savings	L = Complement K = Complement M = Substitute

Source: Gillen (1996) and original papers.

Bremen to -0.36 in Nordrhein-Westfalen.[20] Shah (1992) applies the cost function approach using data for 26 industrial sectors in Mexico. He calculates the rate of return on public capital to be 5-7 per cent compared with 14-18 per cent for private capital. Lynde and Richmond (1993b) estimate share equations derived from a translog

[20] The authors note that the cost reducing effects are largest in those regions which have the largest areas. This might be because almost 50 per cent of the public capital stock consists of road capital and for large areas a well-developed road network is of crucial importance.

cost function using data for UK manufacturing and conclude that public capital plays a significant role in the production of value-added output. Decomposition of TFP reveals that from 1966-79 the contribution of growth in the ratio *G/L* accounted for approximately 17 per cent of the growth in labour productivity. However, in the 1980s the contribution became negative. Keeler and Ying (1988) focus upon the effect of investment in the inter-state highway system on costs in the inter-city trucking industry. They find that savings in trucking costs alone covered almost one third of the capital costs of the Federal-aid highway system in the period 1950-73.

An important aspect of manufacturing cost function studies is the determination of the technical relationship between public capital and private capital and between public capital and labour. There is some consensus that public capital and labour are substitutes and some types of public capital are complements to private capital (see Table 5).

4.4 Implications for Employment

Studies that have used the cost function approach have produced a lower rate of return for public capital than that derived from either national or regional production functions. Because public capital has generally been found to be a substitute for labour these studies also raise a number of employment issues. As Hurst (1994) notes, this result is not counter-intuitive:

> "Where roads are of poorer quality vehicle maintenance is greater. Equally, uncertain deliveries of goods mean that inventories must be higher. Both of these activities would imply more employment. In the long run increased private sector productivity could lead to greater investment and more

employment, but in the interim problems of unemployment could be exacerbated." (p. 67)

There has been relatively little examination of the effect of infrastructure investment on employment, although Hurst mentions a few. Botham (1983) studied the impact of transport infrastructure on regional employment in 28 regions of the United Kingdom for the period 1961-66 (the period of construction of the national highway system). The conclusion is that the impact of the highway system on the regional distribution of employment was quite small. Other studies, however, (for example, Dodgson, 1974) have found positive impacts on regional employment growth. In a study of employment in Minnesota, Stephanides and Eagle (1986,1988) found that there was no relationship between spending on state highways and employment growth. Employment went up slightly in the year following an increase in spending but dropped to its original level after three years. The regional distribution of employment could be affected, however. In regions near large cities retail sector jobs appear to be transferred to the urban area when communications infrastructure is improved. The employment impacts of public investment may be very difficult to identify. The evidence tends to suggest that public capital and labour are short-run substitutes. The long-term effect will depend upon the level and type of private investment that is "crowded-in" to a particular location by the enhanced public capital stock.

5. Profit Functions

In a few studies in the infrastructure literature a profit function is estimated to ascertain the role of public capital in production.[21] Duality work in this thesis is based on the cost function approach so the following discussion, based on Lynde (1992), is provided as background information only. Profits in the economy can be expressed as

$$\pi = P_Q Q - P_L L - P_K K, \tag{26}$$

where π is profit, $P_Q Q$ is revenue and $P_L L$ and $P_K K$ are labour and capital costs respectively. The profit rate is thus

$$\Pi = \frac{P_Q Q - P_L L - P_K K}{qK}, \tag{27}$$

where q is the private capital deflator or price of capital goods. To incorporate public capital in the analysis it is assumed that the production function includes G as an unpaid input:

$$Q = \Theta F(L, K, G). \tag{28}$$

In terms of Euler's Theorem:

$$\gamma Q = \Theta \frac{\partial F}{\partial L} L + \Theta \frac{\partial F}{\partial K} K + \Theta \frac{\partial F}{\partial G} G, \tag{29}$$

where γ measures the degree of homogeneity. Under competitive market conditions in product and factor markets the marginal products of labour and private capital equal their respective real rental prices:

$$\Theta \frac{\partial F}{\partial L} = \frac{P_L}{P_Q}, \text{ and} \tag{30}$$

[21] See Deno (1988) and Lynde and Richmond (1993a)

$$\Theta\frac{\partial F}{\partial K}=\frac{P_K}{P_Q}. \tag{31}$$

Using (31), (29) can be expressed in terms of labour's revenue share $P_L L/P_Q Q$, capital's revenue share $P_K K/P_Q Q$ and public capital's implicit revenue share $\Theta\frac{\partial F}{\partial G}\frac{G}{Q}$:

$$\gamma=\alpha_L+\alpha_K+\alpha_G, \tag{32}$$

where αs are revenue shares. Dividing (27) by $P_Q Q$ the profit rate can be expressed in terms of private revenue shares:

$$\Pi=(1-\alpha_L-\alpha_K)\frac{P_Q Q}{qK}, \tag{33}$$

which can be rewritten, using (32) as:

$$\Pi=(1-\gamma+\alpha_G)\frac{P_Q Q}{qK}. \tag{34}$$

Finally the real profit rate is given by:

$$\Pi^R=(1-\gamma+\alpha_G)\frac{Q}{K}. \tag{35}$$

If there are constant returns to scale in private and public inputs(ie, $\gamma=1$), (35) reduces to:

$$\Pi^R=\frac{\partial F}{\partial G}\frac{G}{K}. \tag{36}$$

In Chapter 2 it will be shown that the ratio *G/K* has fallen in the U.S. since the mid-1960s. This implies that the profit rate has fallen unless there have been compensating increases in infrastructure's marginal productivity.

Lynde (1992) derives the relationship between the profit rate and a production function and shows that the profit rate depends on the amount of private capital, the ratios of labour to private capital and public to private capital and returns to scale.

Public capital owned by states and local governments is found to contribute to output and profits. The marginal productivity of public capital has fallen significantly since the 1970s.

Lynde and Richmond (1993a) estimate profit share equations using aggregate time series data for the United States. They control for nonstationarity in the variables and analyse the effect of intermediate input price changes on value-added.[22] Productivity changes are divided into four components, one of which is changes in the ratio of public capital to labour. An average estimate of 0.20 for public capital's output elasticity is obtained (ie, approximately half that obtained in production function studies that use national-level data) and approximately 40 per cent of the slowdown in labour productivity growth is attributed to the decline in the public capital/labour ratio.

6. Avenues for New Research

6.1 Introduction

The previous sections reveal that production functions attribute to infrastructure an implausible role or are not robust. The cost function method has produced what are arguably more realistic results. There are opportunities for further research within this framework. Other opportunities for new research are discussed in the following subsections.

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[22] Lynde and Richmond point out that the effect on productivity growth of changes in the prices of intermediate goods, especially energy prices, is a subject of some debate in the productivity literature. The authors find that these changes, along with the effects of returns to scale and technology, account for 59 per cent of the decline in labour productivity growth.

6.2 Disaggregated Infrastructure Data

One aspect of the debate researchers have largely ignored is the importance to the private business sector of the various components of the infrastructure stock. Exceptions include Deno (1988), Munnell (1990b, 1993), and Hulten and Schwab (1991b). The reason this information is valuable is intuitively obvious. The finding that infrastructure investment on the whole has a high rate of return does not inform policymakers how much spending is required on the different types: schools, highways, water treatment facilities, fire stations, passenger terminals, *etc.*

The results obtained by Deno (1988) and Munnell (1990b, 1993) reveal that the contributions of the different types of public capital to productivity and their relationships with private inputs tend to vary. Deno estimates a translog profit function using regional manufacturing data and three infrastructure stocks: highways, water systems and sewer systems. Input demand and output supply elasticities are calculated using the resulting parameter estimates. These reveal that all three types of public capital have a positive effect on the supply of manufacturing output. A 10 per cent increase in highway and sewer capital leads to an increase in output of approximately 3 per cent. A similar increase in water capital generates an increase in output of 0.07 per cent. All three complement private labour and private capital. This finding suggests that, from a regional policy point of view, policymakers can use public capital to promote employment growth in this sector as well as expansion of the private capital stock. The derived elasticity estimates indicate that highway capital is the most effective policy tool for achieving this goal and water capital is the least effective. The results obtained by Deno using aggregate infrastructure data are of an unreasonable magnitude, however. The estimated output elasticity is 0.68, higher than that obtained in any of the aggregate production function studies.[23] Deno puts this down to the fact that the total measure includes a wide range of public capital inputs all of which may be employed by manufacturing firms either directly or indirectly. However, it is worth noting that "apportioned" infrastructure data is used in this study – the public capital stock is multiplied by the percentage of a region's population that is employed in manufacturing. This apportionment is designed to account for the collective nature of public capital and the fact that it is subject to congestion. This adjustment ignores the non-rivalrous nature of much of the public capital stock and possible spillover benefits from one region to another. Most studies in the infrastructure literature do not adjust the public capital stock in this way.[24]

Munnell (1990b, 1993) estimates Cobb-Douglas and translog production functions using state-level manufacturing data and data for the state highway stock, water and sewer systems capital and "other public capital".[25] The results are different in many respects to those obtained by Deno (1988). In both of Munnell's studies water and sewer systems were found to have the largest output elasticity (0.12 and 0.15 respectively), followed by highways (0.06 and 0.04 respectively). The coefficient estimate on other public capital[26] was found to be statistically insignificant. Together, the components of this stock make up a large fraction of the total non-military

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[23] Because spillovers between states and regions are not captured using geographically disaggregated data one would expect the output elasticity of infrastructure to be lower than that obtained in aggregate studies.

[24] Use of unapportioned data generates counterintuitive results, eg, negative output elasticities.

[25] It should be noted that no comprehensive measures of state public or private capital are available. In the case of public capital, state capital series were created using annual state public investment data and Bureau of Economic Analysis depreciation and discard schedules. In the case of private capital the total stock was apportioned on the basis of each state's activity in agriculture, manufacturing and non-manufacturing.

[26] This stock consists of equipment, schools, hospitals, industrial buildings and other buildings (general office buildings, police and fire stations, courthouses, auditoriums, garages and passenger terminals), conservation and other structures (electric and gas facilities, transit systems and airfields).

infrastructure stock – on average 45.9 per cent of the total stock over the estimating period. Estimates of cross-product terms indicate that highways and streets are substitutes for private capital. In Munnell's opinion:

> "This seems quite reasonable in that smooth, well-maintained roads will reduce the wear and tear on commercial vehicles. Moreover, private employers or developers may sometimes be required to build their own access roads." (p. 20)

Water and sewer systems are strong complements to private capital. Munnell argues that this finding can be explained by the fact that these inputs are generally publicly provided "and clearly augment private production."

Using a growth accounting framework, Hulten and Schwab (1991b) find that none of the public capital stocks is productive. Earlier it was pointed out that the specification in (2) may have important implications for standard calculations of the Solow residual. To obtain an accurate measure of TFP requires removing the contribution of public capital. The standard equation for the growth rate of the Solow residual is

$$\frac{\dot{\Theta}}{\Theta}=\frac{\dot{Q}}{Q}-\Theta\frac{\partial F}{\partial L}\frac{L}{Q}\frac{\dot{L}}{L}-\Theta\frac{\partial F}{\partial K}\frac{K}{Q}\frac{\dot{K}}{K}, \tag{37}$$

where $\Theta\partial F/\partial L$ is the marginal product of labour and $\Theta\partial F/\partial K$ is the marginal product of capital.[27] If (2) is the correct specification of the production function (37) should have an extra term appended on the right-hand side:

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[27] Chapter 4 contains a full derivation of the Solow residual.

$$\frac{\dot{\Theta}}{\Theta}=\frac{\dot{Q}}{Q}-\Theta\frac{\partial F}{\partial L}\frac{L}{Q}\frac{\dot{L}}{L}-\Theta\frac{\partial F}{\partial K}\frac{K}{Q}\frac{\dot{K}}{K}-\Theta\frac{\partial F}{\partial G}\frac{G}{Q}\frac{\dot{G}}{G}, \tag{38}$$

where $\Theta\frac{\partial F}{\partial G}\frac{G}{Q}\frac{\dot{G}}{G}$ is the public capital output elasticity, multiplied by the growth rate of public capital. If this term is omitted, the standard Solow residual attributes G's contribution to output growth to the Hicksian efficiency term. Thus the following adjustment has to be made to obtain the "true" Hicksian efficiency term:

$$\frac{\dot{\Theta}}{\Theta}=\frac{\dot{\Theta}^S}{\Theta^S}-\beta_G\frac{\dot{G}}{G}, \tag{39}$$

where $\dot{\Theta}^S/\Theta^S$ is the Solow residual and β_G is public capital's output elasticity. To obtain an estimate of β_G, Hulten and Schwab (1991b) regress the Solow residual on the growth rate of public capital as well as disaggregated public capital (highways, water and sewers and other public capital). All output elasticities are found to be insignificant. Some of the earlier criticisms apply to the empirical implementation of this approach. It is likely that $\dot{\Theta}^S/\Theta^S$ and $\dot{G}/G$ are integrated to different orders and below it will be argued that the Solow residual is arguably not an accurate measure of "true" TFP. However, from (39) it is also clear that the estimating equation should contain $\dot{\Theta}/\Theta$, the "true" Hicksian efficiency term. This is a difficult problem to overcome as a measure of this variable is not directly available. The authors use a constant and time dummies as a proxy for $\dot{\Theta}/\Theta$. Thus the estimating equation suffers from specification error and this may explain the insignificance of the public capital measures.

In summary, studies carried out thus far with disaggregated infrastructure data, in particular those by Deno and Munnell, reveal that determining the contribution of different types of capital provides important additional information to policymakers. In the next two subsections some of the uses to which disaggregated data can be put are described.

6.3 The Calculation of Optimal Infrastructure Stocks

One of the advantages of the cost function framework is that it can be used to calculate optimal infrastructure stocks. However, in only two studies in the literature have optimal stocks been estimated: Berndt and Hansson (1992) using data for the Swedish private business sector and Morrison and Schwartz (1996) using data for New England manufacturing. Optimal stocks have not been calculated using U.S. data at a more aggregated level, nor have optimal quantities of the individual types of infrastructure been estimated. Most cost function studies seek to establish the shadow value of infrastructure and the relationship between this input and private factor inputs.

The methodology used to construct these measures is outlined in detail in Chapter 3. The basic principle involves balancing the cost savings enjoyed by the private business sector against the costs to society of providing the additional capital. In equilibrium, the infrastructure stock is optimal if the marginal benefit and marginal cost of public capital are equal:

$$-\frac{\partial C}{\partial G} = P_G, \tag{40}$$

where P_G is the one-period user cost of public capital. Much of the recent cost function research also focuses on the importance of infrastructure to the manufacturing sector, either in the U.S. or other countries.[28] This is justifiable in the sense that a more complete set of input data is available for this sector. However, there are other sectors

[28] Exceptions include Berndt and Hansson (1992) and Lynde and Richmond (1992).

that benefit from infrastructure investment. These are some of the issues addressed in Chapter 3.

6.4 Focusing on the Other Variable in the Analysis

It is also clear that studies that make use of a direct measure of total factor productivity rely on standard constructions of TFP based on Solow (1957).[29] However, as Malley *et al.* (1998) point out, the standard Solow residual ignores considerations pertaining to market power, returns to scale and variable factor utilisation over the business cycle. If the Solow residual does not measure "true" productivity growth, it is possible that conclusions drawn about the relationship between productivity and infrastructure based on this residual are invalid. In Chapter 4 the focus moves from infrastructure to issues relating to productivity measurement. A measure of TFP is derived that takes account of non-constant returns to scale and unobserved changes in labour and capital utilisation. There are a number of uses to which such a measure can be put, one of which would be a re-examination of the role of different types of public capital. In Section 3.3.3 the possibility of "reverse causality" between infrastructure and productivity was discussed. An adjusted measure of TFP can be used to re-examine the direction of causation between the variables.

[29] These include production function studies, studies that use a growth accounting framework and studies in which causality tests are carried out. An exception is Lynde and Richmond (1993b) who adjust their measure of labour productivity to account for increasing returns to scale.

7. Conclusion

The two most popular empirical approaches in the infrastructure literature are the production function and the duality approach. The results of the various studies are often difficult to compare due to the use of datasets that differ by sector or by country or in the level of geographical aggregation, and due to differences in econometric technique. Although they rekindled interest in infrastructure's role in private production in the late 1980s, there is some evidence that the results of production function studies are not robust and that the methodology suffers from a number of weaknesses that are overcome by the duality approach. There has been a significant amount of infrastructure research using a variety of cost and profit function specifications and datasets. These studies generally attribute to infrastructure a significant role in the private production process. For example, shadow values and elasticity values indicate that increases in infrastructure reduce private costs. Unanswered questions remain, however, in particular concerning optimality. The finding that public capital reduces private costs is not the only information in which policymakers are interested. It is also important to weigh these cost savings against the cost of infrastructure. This exercise is performed in Chapter 3.

Turning to the other variable of focus, the growth rate of factor productivity, it is clear that many studies that directly calculate TFP base their measure on Solow (1957). However, use of this measure may cause the wrong conclusion to be drawn about infrastructure's effect on the private sector. The residual fails to take account of varying returns to scale and variable labour and capital utilisation over the cycle. The latest developments in the productivity literature are used in Chapter 4 to estimate an adjusted measure of TFP growth and uncover the relationship between infrastructure investment and the "true" productivity growth rate.

Regardless of the approach adopted, it is useful to compare the roles of the different types of infrastructure in the production process. Public capital ranges from short-lived equipment to long-lived roads and other networks. It is likely that the roles of the various stocks differ significantly. In the next chapter a closer look is taken at the different types of public capital.

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Chapter 2

An Analysis of the Severity and Causes of the Infrastructure Slowdown

1. Introduction

The state and local governments in the United States own over \$2.2 trillion of equipment, buildings and other structures, accumulated over more than a century. A significant portion of this wealth was acquired in the two decades following the Second World War: in 1946 state and local governments possessed \$424 billion of capital, by the end of the 1960s this figure had risen to \$1.2 trillion.[1] In the postwar years the U.S. was in what Seely (1993) describes as the "golden age of infrastructure development", with massive amounts being spent on roads, schools and public utilities. However, at the end of the 1960s the golden age came to an end. Public investment fell year after year for more than a decade. By 1982 investment expenditures were 30 per cent lower than in 1968. The situation improved thereafter but by the end of the 1980s there was little more investment than there had been in the Sixties. Books with titles such as *America in Ruins* and *Fragile Foundations*[2] argued that the U.S. was now in

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[1] The latter two figures and all other figures are expressed in 1987 dollars for comparative purposes, unless otherwise stated.
[2] National Council on Public Works Improvement, (1988).

an era of "crumbling" infrastructure. Dissection of the public investment data reveals that some categories were worse affected than others. Roads and schools were the main victims of the cutbacks. Eventually spending was insufficient to offset the depreciation of these stocks and so the "infrastructure slowdown" turned into an "infrastructure decline". Spending on other types of public capital fell but neither as severely nor for such a prolonged time. However, the cutbacks were severe enough to see the growth rates of all the different types of infrastructure fall well below levels seen in the 1950s and 1960s.

A crucial issue that the infrastructure literature seeks to resolve is whether the infrastructure slowdown contributed to the productivity growth slowdown that also reared its head in the early 1970s. At this time, public investment was falling relative to most measures of private economic activity (GDP, private investment and the growth of the workforce). However, productivity growth was not necessarily lower for this reason. First, it might be argued that falling public investment in the 1970s was a logical consequence of the high levels seen in the 1950s and 1960s. Secondly, it is unlikely that all types of public capital influence private productivity directly. Reduced spending on educational buildings, for example, may have had very little effect on educational attainment and to the extent that it did, the effect on labour productivity would possibly only have been felt with a very long lag. With streets and highways the story is possibly different. As the principle component of the core (productive) infrastructure stock, it is possible that the decline in road spending contributed to some extent to the productivity slowdown.

In this chapter a closer look is taken at the various types of public capital to determine which were most severely affected during the infrastructure slowdown and why the slowdown occurred. The main purpose of this chapter is to provide background information for the empirical work in the remaining chapters. The structure is similar to that of Gramlich (1994) and Tatom (1993). This chapter contributes to the existing body of knowledge by focusing on the role of economic depreciation and certain components of the core infrastructure stock.

In Section 2 a close look is taken at the changing roles of the federal and state governments in the provision of infrastructure. The individual components of the nonmilitary public capital stock are then examined in order to judge their relative importance. In Section 3 the infrastructure slowdown is illustrated using a wide variety of measures. Public investment is compared with GDP, private investment and growth in the U.S. population and labour force. The infrastructure data is dissected in order to determine which types of public capital experienced the most serious cutbacks. In Section 4 a number of causes of the infrastructure slowdown are analysed. Particular attention is paid to the effect of economic depreciation on the growth of the public capital stock. In Section 5 the link between the productivity slowdown and the infrastructure slowdown is analysed, with particular reference to spending on roads.

2. The Composition of U.S. Capital

2.1 Private versus Public

Although the private sector owns most of the tangible wealth in the U.S., the public sector accounts for one third of the total stock of nonresidential capital

Table 1. *Private and Public Net Nonresidential Capital Stocks, 1994*

Capital Stock	Billions of 1987 dollars	% of Total
Total	7.755.8	100
Total Private	5.144.4	66.3
Non-farm	5,009.2	64.6
Farm	135.2	1.7
Total Public	2,611.4	33.7
Military	468.8	6.0
Non-military	2,142.6	27.6
Federal	278.7	3.6
State & Local	1,863.8	24.0

Table 2. *Federal & State and Military and Non-military Capital, % Shares, 1944-94*

	1944	1954	1964	1974	1984	1994
Share of states in total *G*	33	51	60	70	72	71
Share of states in nonmilitary *G*	66	75	81	85	86	87
Share of nonmilitary *G* in total *G*	50	68	74	82	84	82
Share of nonmilitary *G* in Federal *G*	26	35	35	41	43	37

(Table 1). In 1994 there was $2.6 trillion of public capital, seven times more than in 1925. The public capital stock can be divided into two major categories: federal and state capital and military and nonmilitary capital. The Federal Government owns all the military capital (which accounts for 18 per cent of the total) and the state governments own most of the rest.[3] The states' share of total and total nonmilitary public capital

[3] Seely (1993) explains that the U.S. Congress severely limited the Federal Government's role in the provision of non-military capital from the outset. The first major debate involved the Gallatin Plan. a proposal for federal road development which was proposed in 1808 and ultimately rejected by Congress.

Table 3. *Composition of Public Capital*

	1944	1954	1964	1974	1984	1994
Equipment	15.0	8.1	6.8	7.2	6.9	9.7
Industrial buildings	9.4	7.2	3.5	1.5	1.3	1.0
Schools	10.7	13.1	16.3	18.2	15.7	13.9
Hospitals	2.8	3.9	3.1	2.8	3.0	2.6
Other buildings [a]	6.3	6.1	6.8	8.3	10.1	11.7
Highways & streets	32.2	34.8	38.0	36.7	34.3	32.3
Conservation	8.5	10.1	9.1	8.3	8.5	7.3
Other structures [b]	4.6	5.2	5.1	6.0	7.2	7.6
Sewers [c]	5.5	6.2	6.5	6.5	8.2	8.6
Water supply [d]	5.0	5.3	4.7	4.5	4.7	5.3
	100	100	100	100	100	100

Note: [a] Includes general office buildings, police & fire stations, courthouses, auditoriums, garages, passenger terminals. [b] Includes electric & gas facilities, transit systems, airfields. [c] Includes treatment plants. [d] Largely water mains and distribution lines.

increased considerably after the Second World War, levelling off in the 1970s (Table 2). This trend occurred mainly because the relative magnitude of the nonmilitary capital stock increased considerably after the War, rising from 50 per cent in 1944 to 82 per cent in 1974. From this point on, all references to the public capital stock are confined to nonmilitary capital. Furthermore, although the states own most of the nonmilitary capital, it is clear from Table 2 that a significant portion of federal capital is nonmilitary in nature. Therefore all references to the public capital stock are to nonmilitary federal and state capital.[4]

2.2 The Different Types of Public Capital

Table 3 shows the relative importance of the different components of the total infrastructure stock at various points in time from 1944-1994. Roads, schools, hospitals and water systems have all shrunk as a percentage of total infrastructure; the rest have all grown in importance. However, there has been considerable variation

[4] It also excludes investment in residential buildings, as does the private investment series which appears later.

along the way, as a cursory examination of the table makes clear. Equipment is a relatively small component of public capital, accounting for only 9.7 per cent of the total in 1994. This compares with private capital, where equipment makes up 48 per cent of the total capital stock. The bulk of the public capital stock is comprised of structures. Roads are by far the largest component, despite their relative decline in importance since the mid-1960s. By 1994 roads accounted for 32 per cent of the public capital stock. Educational buildings are another important category, although their importance has also declined since the mid-1970s.

3. The Infrastructure Slowdown

3.1 The Public Investment Slowdown, 1968-82

From 1959 to 1994 total government purchases of goods and services in the U.S. almost doubled, rising from \$475 billion to \$923 billion. Infrastructure spending also almost doubled over this period, rising from \$65 billion to \$125 billion. However, as Figure 1 makes clear, investment was far more volatile than other types of spending. Over the ten-year period from 1959 to 1968, investment grew by 5.3 per cent per year. There was then a sharp reversal, with spending declining by 2 per cent a year so that by 1982 investment in infrastructure was close to levels last seen in the early 1960s. In fact, at no time since the 1850s has public investment experienced such a prolonged period of decline.

Figure 1. *Total Government Purchases (excluding investment) and Non-military Government Investment (log scales, investment L.H.S)*

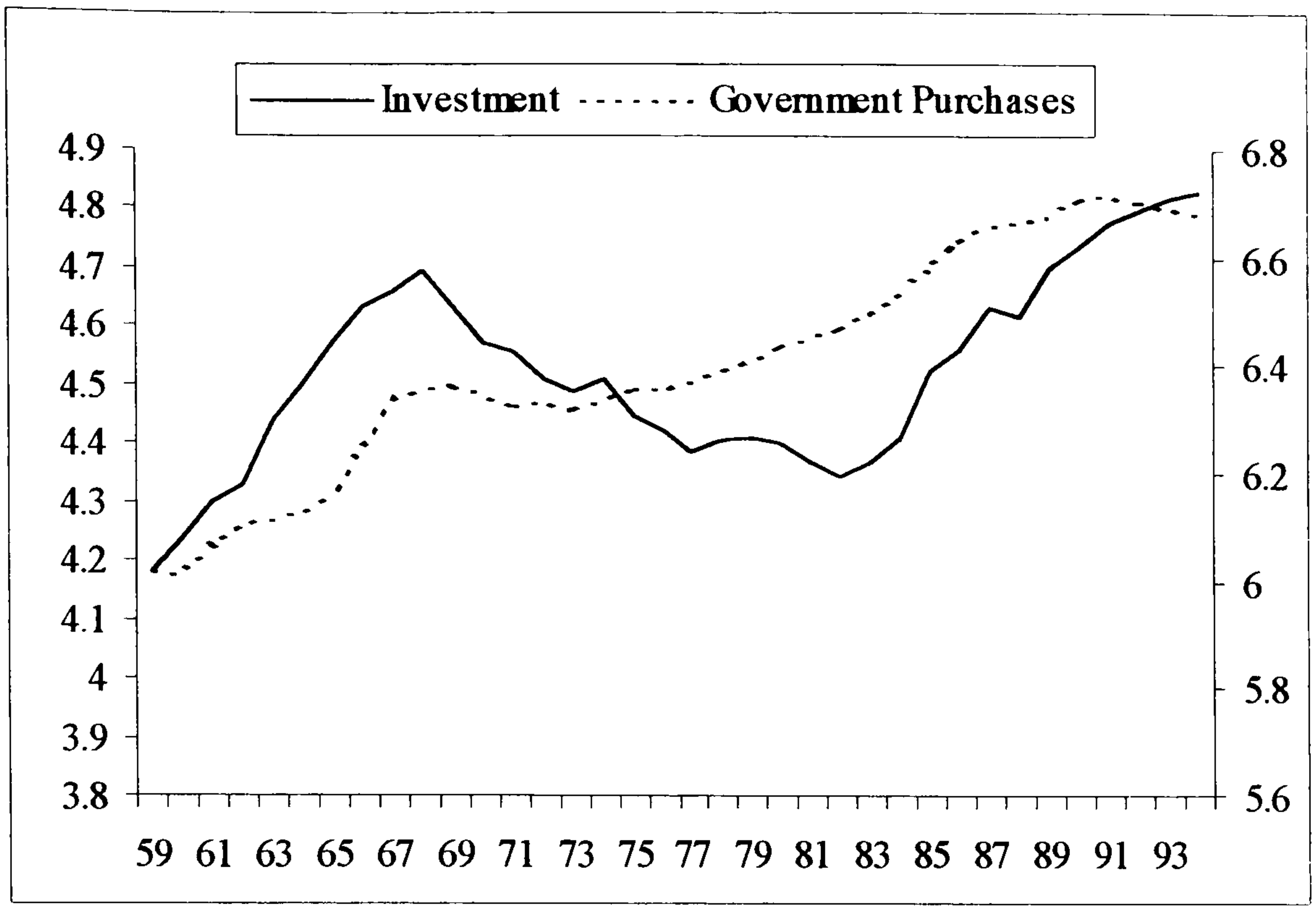
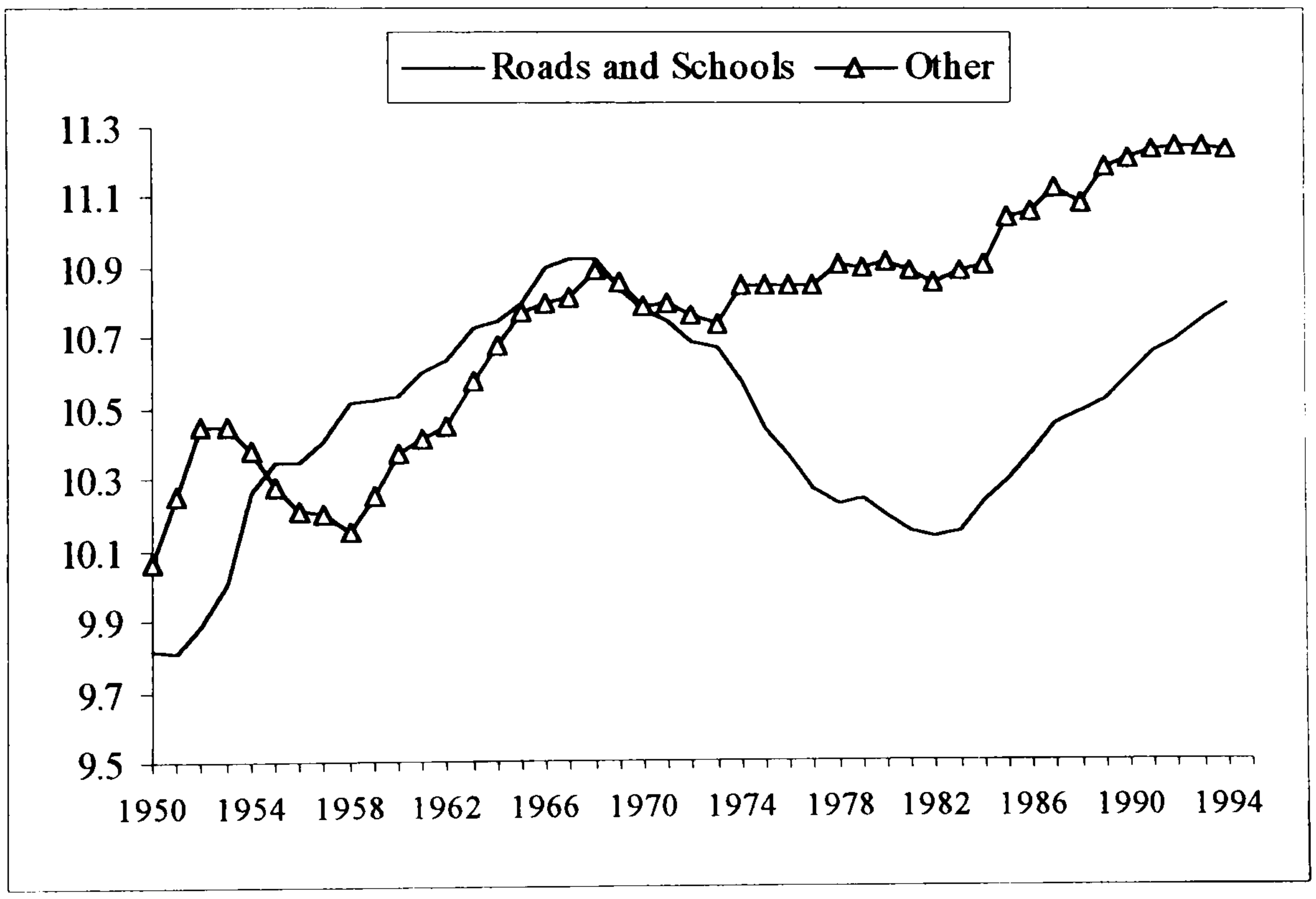
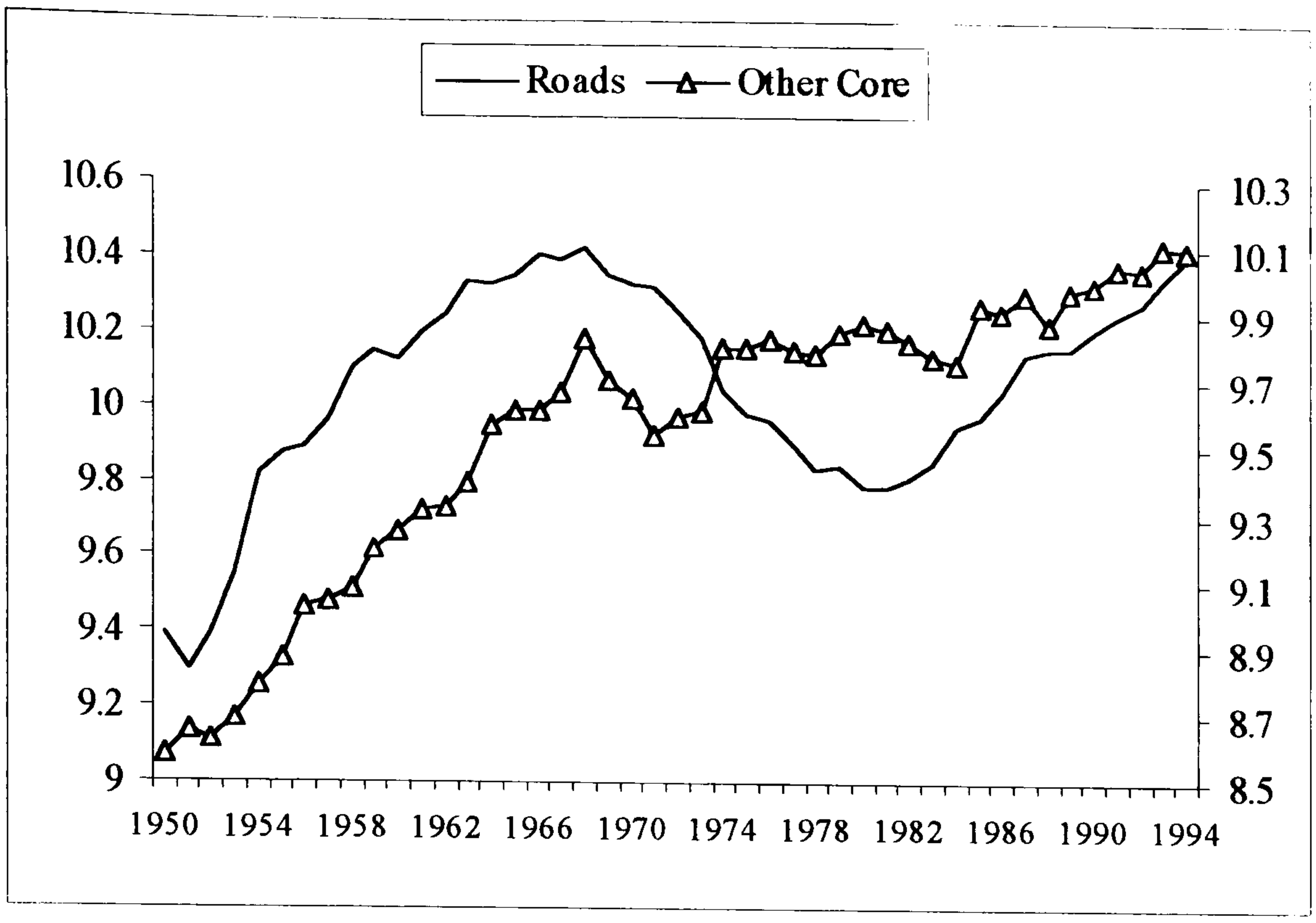


Figure 2. *Investment in Roads and Educational Buildings versus Other Public Investment (log scales)*



An important question is whether there was a decline in all types of public investment or just a few categories. Figure 2 divides the public capital stock into two components: roads and schools and the rest. It appears that the large decline in investment in streets

Figure 3. *Roads versus Other Core Investment (log scale, roads L.H.S)*

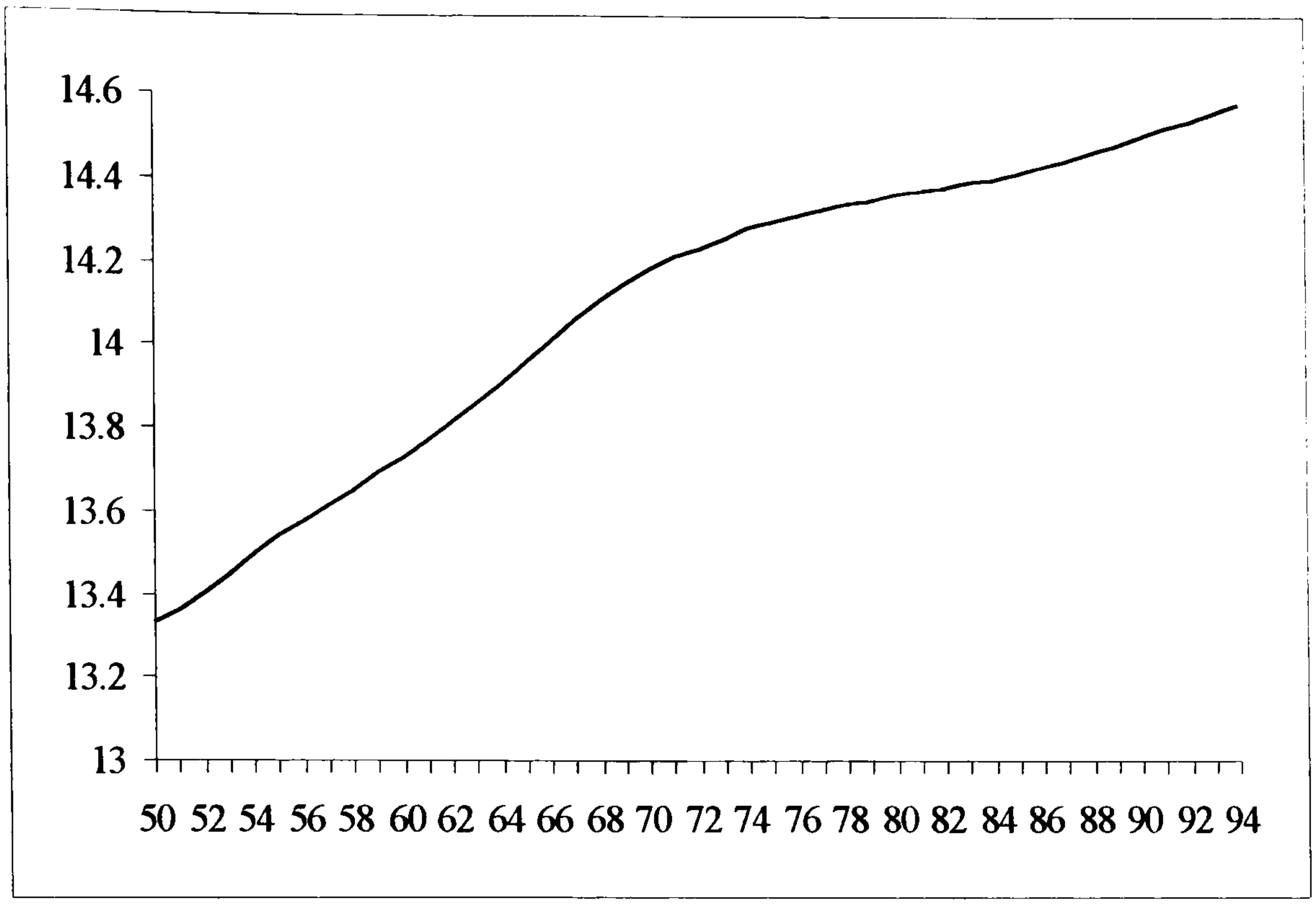


and highways and educational buildings contributed most to the decline in public investment from the late 1960s. The slowdown in other investment was not insignificant, however, declining for several years after 1968 and only starting to grow significantly from 1984.

In Chapter 1 it was mentioned that public capital can be placed into two groups: the productive core, consisting of highways and streets, sewer systems, water supply facilities, utilities, transit systems and airports; and the rest which does not contribute directly to private production, consisting of buildings (schools, hospitals, courthouses *etc.*) and conservation structures (water resource projects aimed at flood and erosion control).[5] In Figure 3 core investment is divided into its two major

[5] Although some public capital is arguably more productive than others, almost all creates an environment in which private production can take place. A healthy workforce is a productive workforce, so hospitals and conservation are important. An educated worker contributes more to GDP than his unskilled colleague so investment in schools affects productivity, even if only with a considerable lag. Infrastructure doesn't only facilitate private production. As Gramlich (1994) points out, a large share of the benefits of increased infrastructure investment involve improved security, personal time saving, a cleaner environment, and improved outdoor recreation – benefits that are difficult to measure and not included in official measures of national output.

Figure 4. *Non-military Government Capital Stock 1950-94 (log scale)*



components: roads and the rest. Clearly there was a significant decline in roads investment from the late 1960s. Although the decline in other core investment was not as prolonged, it took more than a decade for investment in these types of infrastructure to exceed levels last seen in the late 1960s. From 1950 to 1968 other investment grew by 6.8 per cent per year but then declined until 1973. From 1974 growth resumed but at a much slower rate than in earlier decades. Between 1974 and 1994 average annual growth in "other core" investment was only 1.4 per cent per year.

The infrastructure slowdown can also be pictured using stock measures. The evolution of the total infrastructure stock since 1950 is illustrated in Figure 4. The fall in investment spending from the late 1960s to the early 1980s is apparent from the "hump" in the graph, which represents a fall in the growth rate of the infrastructure stock. In Table 4 the growth rates of the individual infrastructure stocks are illustrated over two different periods: 1950-72, a period of rapid growth and 1973-94, a period of slow growth. Clearly most types of capital can be blamed for the "infrastructure crisis".

Table 4. *Growth Rates of Individual Infrastructure Stocks, 1950-94*

	1950-72	**1973-94**
Core infrastructure:		
Highways & streets	4.1	0.8
Sewer systems	3.9	3.1
Water supply	3.1	2.3
Utilities, transit systems & airports	3.8	2.7
Buildings:		
Educational	5.9	0.2
Hospitals	2.8	1.1
Other	4.7	3.2
Conservation & development	3.0	0.8
Equipment	4.7	2.8

Every type of capital experienced slower growth after 1972. However, some contributed to the decline more than others. For example, the stock of roads grew by only 0.8 per cent per year in the second period, compared with 4.1 per cent in the first period. In comparison the growth rate of sewers systems (also a component of core infrastructure) slowed from 3.9 per cent to 3.1 per cent. The reason both stock and flow measures are analysed is because the latter do not take account of economic depreciation. Depreciation has played a role in the infrastructure slowdown. Its role will be discussed further in Section 4.3.

3.2. Public Investment vs. Private Investment

Another way of illustrating the infrastructure slowdown is to compare infrastructure spending with various private sector variables. For example, the ratio of public to private investment has more than halved over the last 30 years, falling from a peak of

Figure 5. *Ratio of Public to Private Investment, 1959-94*

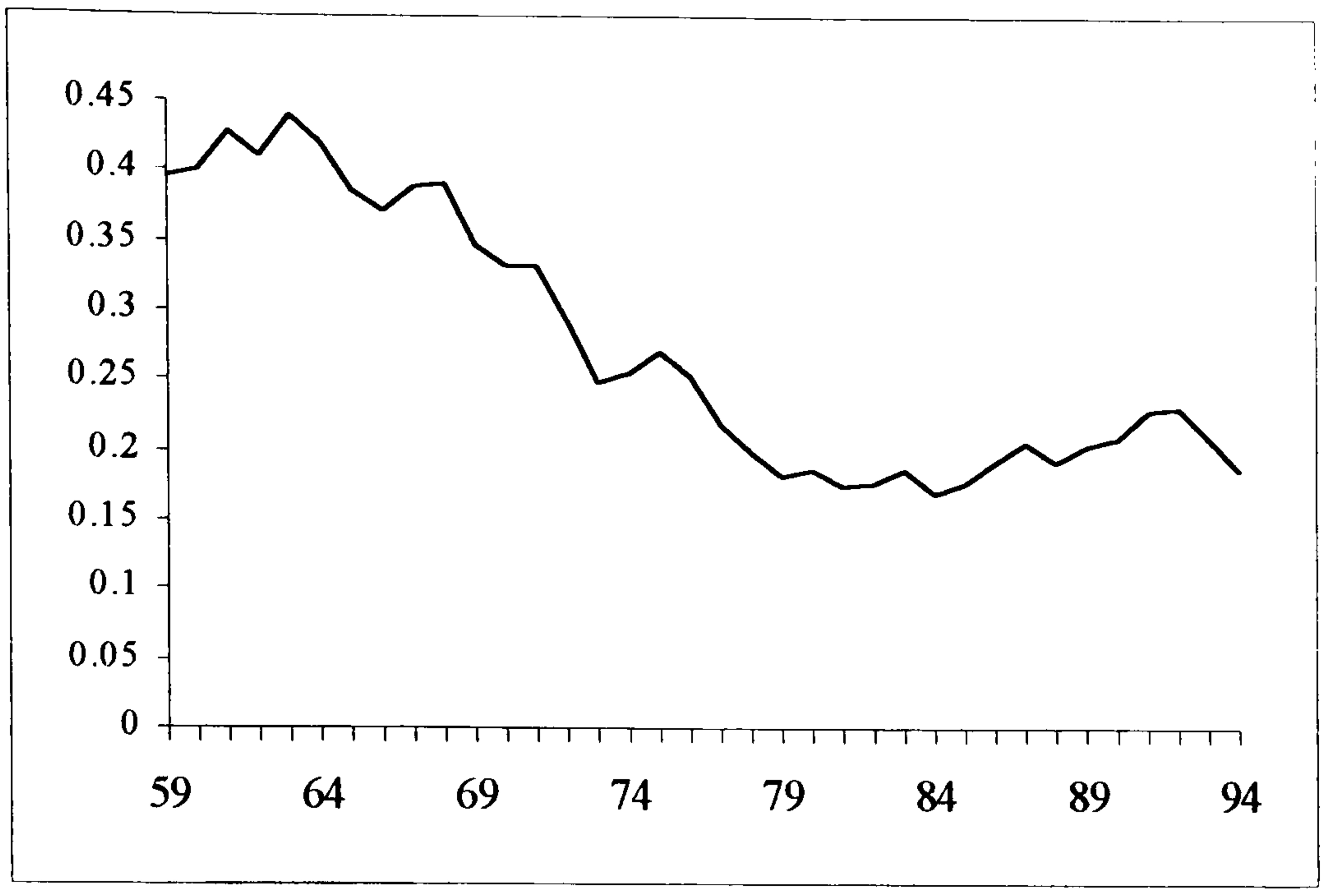
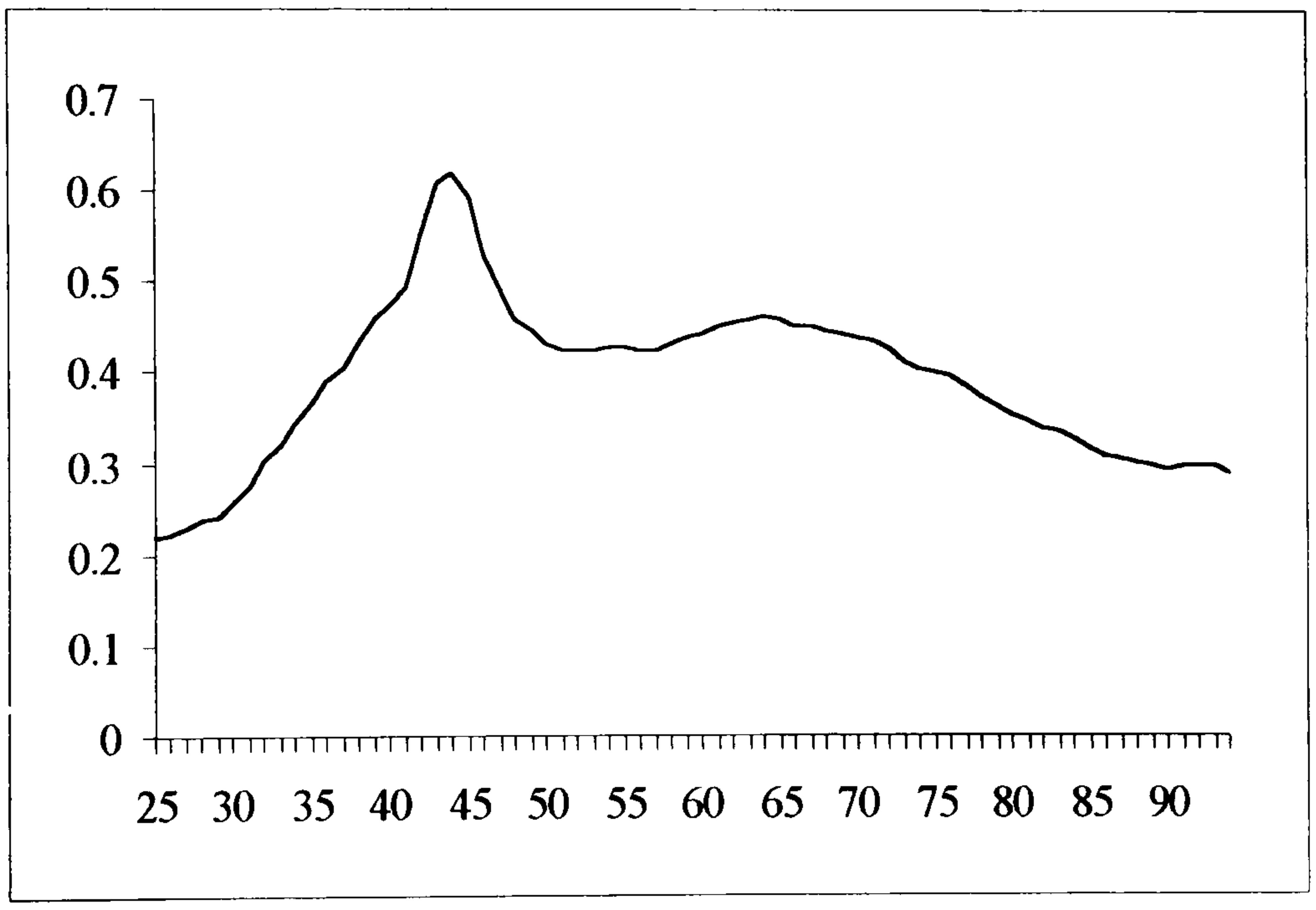
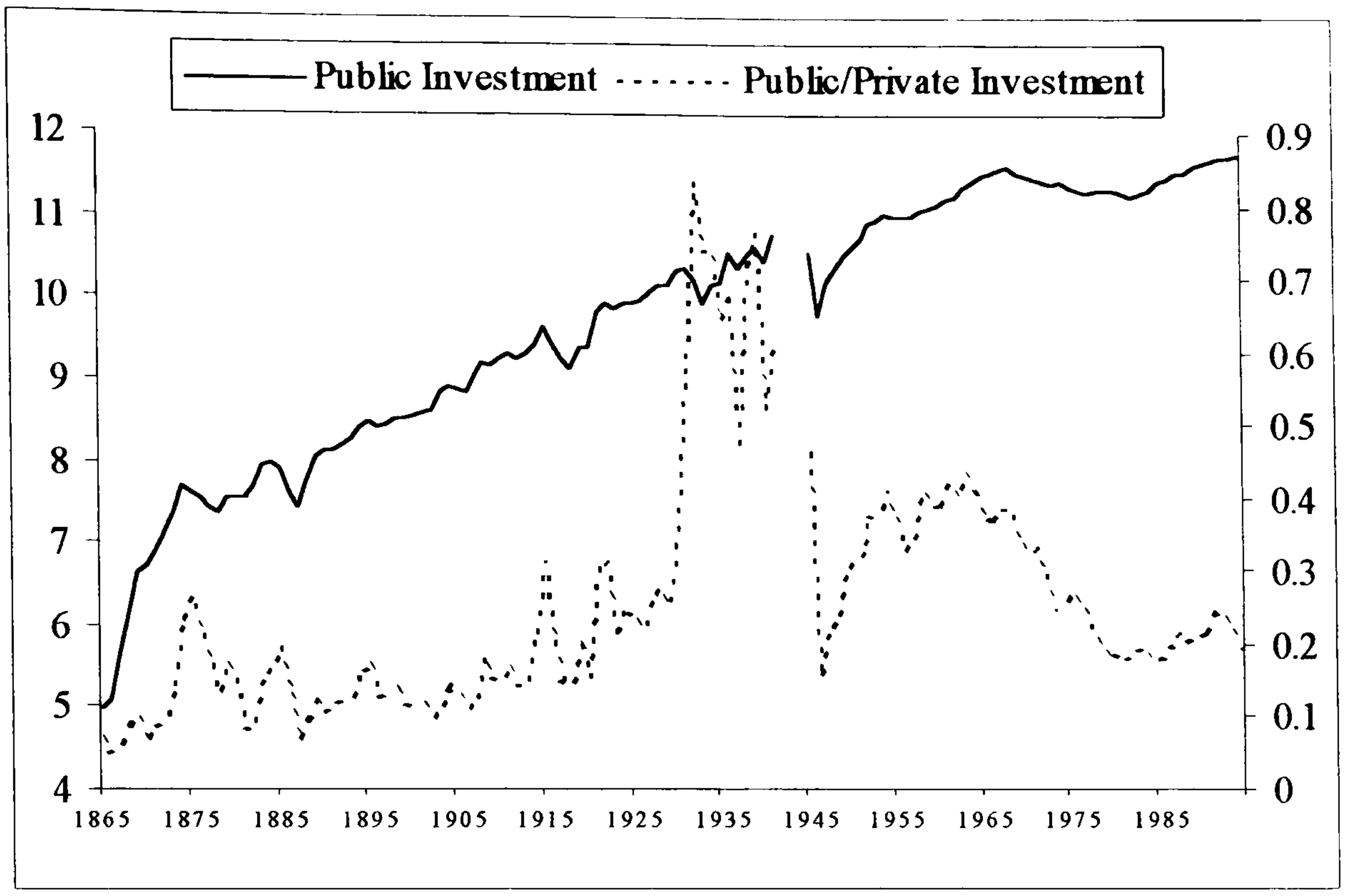


Figure 6. *Ratio of Public to Private Capital Stock, 1925-94*



0.44 in 1963 to 0.19 in 1994 (Figure 5). However, it did increase slightly from the mid-1980s when the level of public investment took off again. The G/K ratio is illustrated in Figure 6. The ratio peaked in 1944 when, for every $1.00 of private capital, there was $0.62 of public capital. This trend is not surprising given that the public sector had an abnormally large share of economic activity in the U.S. during the Great Depression and the Second World War. Further perspective on the fall in investment in

Figure 7. *Public Investment (log scale, L.H.S) and the Ratio of Public to Private Investment, 1865-1994*

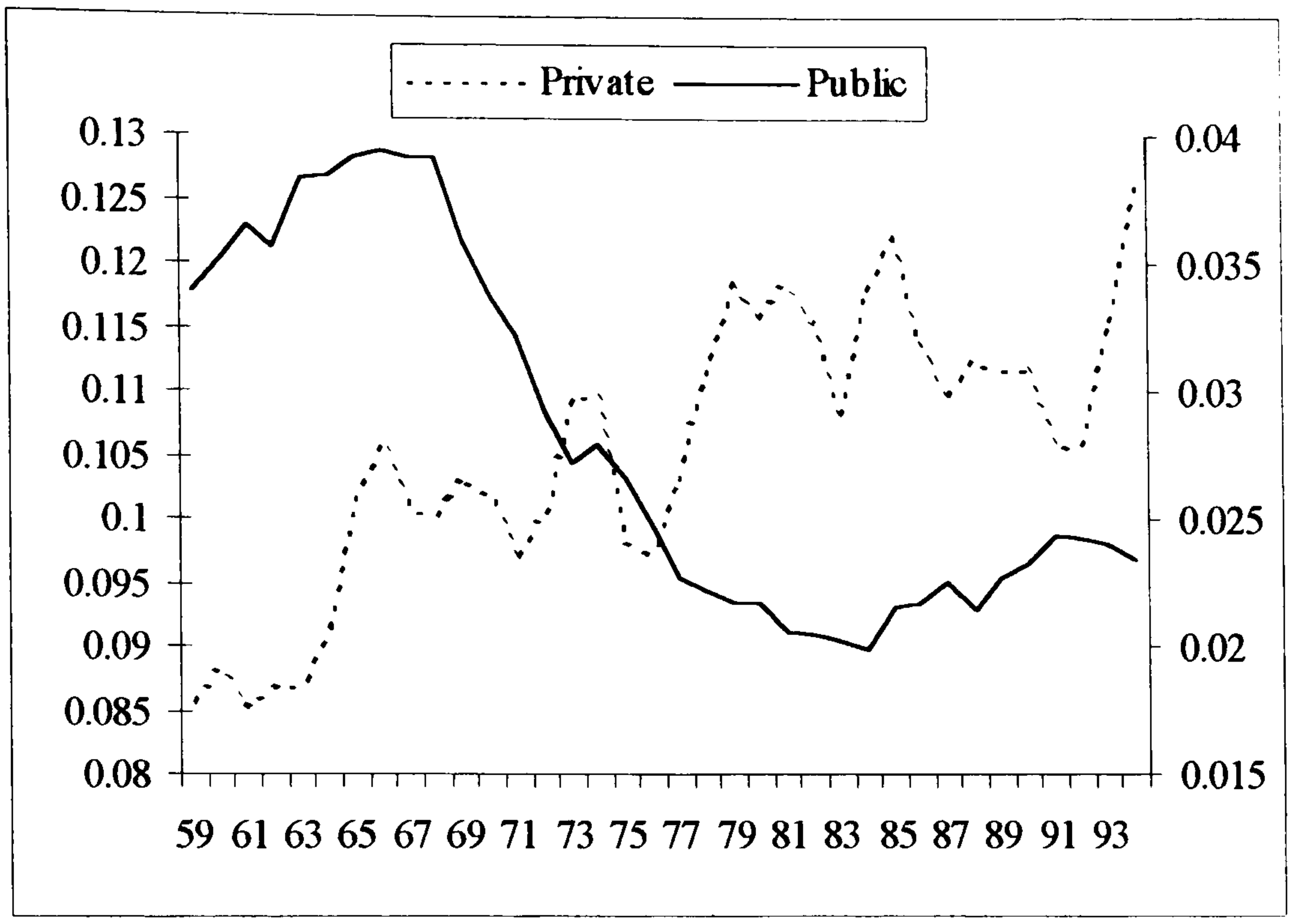


Note: War years omitted

the 1970s and the relative roles of the public and private sector is obtained by examining even longer data series. This way investment during the slowdown can be compared not just with the high levels of the 1950s and 1960s but with other times during the 20th Century. In fact, the U.S. Bureau of Economic Analysis provides investment data going right back to the 19th Century. It is clear from Figure 7 that the growth rate of public investment in the 1950s and 1960s was not abnormally high.[6] Although levels of investment in the 1970s were higher than at most other times in the history of the U.S., the growth rate was very low after 1968. It is also interesting to look at the public/private investment ratio over a longer period. Ignoring the period of the Great Depression and the Second World War when the ratio was abnormally high, it is apparent that public investment grew faster than private investment in the years leading up to the infrastructure slowdown. Although the ratio fell thereafter, it did not

[6] Note that the years of the Second World War have been omitted because they distort the picture.

Figure 8. *Private (L.H.S) and Public Investment as a Share of GDP*



fall below levels seen at most other times in the United States' history.

3.3. Public Investment and GDP

Another way of examining the infrastructure slowdown is to compare public investment with GDP. Over the period 1959-94 infrastructure investment has averaged 2.8 per cent of GDP (other spending 18 per cent). Investment peaked at 3.9 per cent in 1966 and bottomed out at 2.0 per cent in 1984 (Figure 11). Comparing *private* investment with GDP a different picture is obtained. The share of private fixed nonresidential investment in GDP has steadily increased over the years, from 8.6 per cent in 1959 to 12.6 per cent in 1994.

After increasing significantly in the 1950s and 1960s, most types of infrastructure declined relative to GDP between 1974 and 1994 (Table 5). Some categories have increased as a percentage of GDP, however. Investment in water and sewer systems grew as a result of federal grants in terms of the 1972 Clean Water Act. An increase in spending on public utilities, transit systems and airports saw

Table 5. *Total Public Capital in the United States by Type 1954-94*

Capital Stock	1994 stock (1987 dollars)	Percentage of GDP 1964	1974	1984	1994
Core infrastructure:	1,154.7	30.9	31.4	27.6	25.0
Highways & streets	692.9	21.6	21.5	17.3	15.0
Sewer systems	184.5	3.7	3.8	4.2	4.0
Water supply	113.7	2.7	2.6	2.4	2.5
Utilities, transit systems & airports	163.6	2.9	3.5	3.7	3.5
Buildings:	624.8	17.0	18.1	15.2	13.5
Educational	297.2	9.3	10.7	7.9	6.4
Hospitals	56.7	1.8	1.7	1.5	1.2
Other	270.9	5.9	5.7	5.8	5.9
Conservation & development	156.2	5.2	4.9	4.3	3.4
Equipment	206.8	3.8	4.2	3.5	4.5
Total	2,142.5	56.8	58.5	50.5	46.5

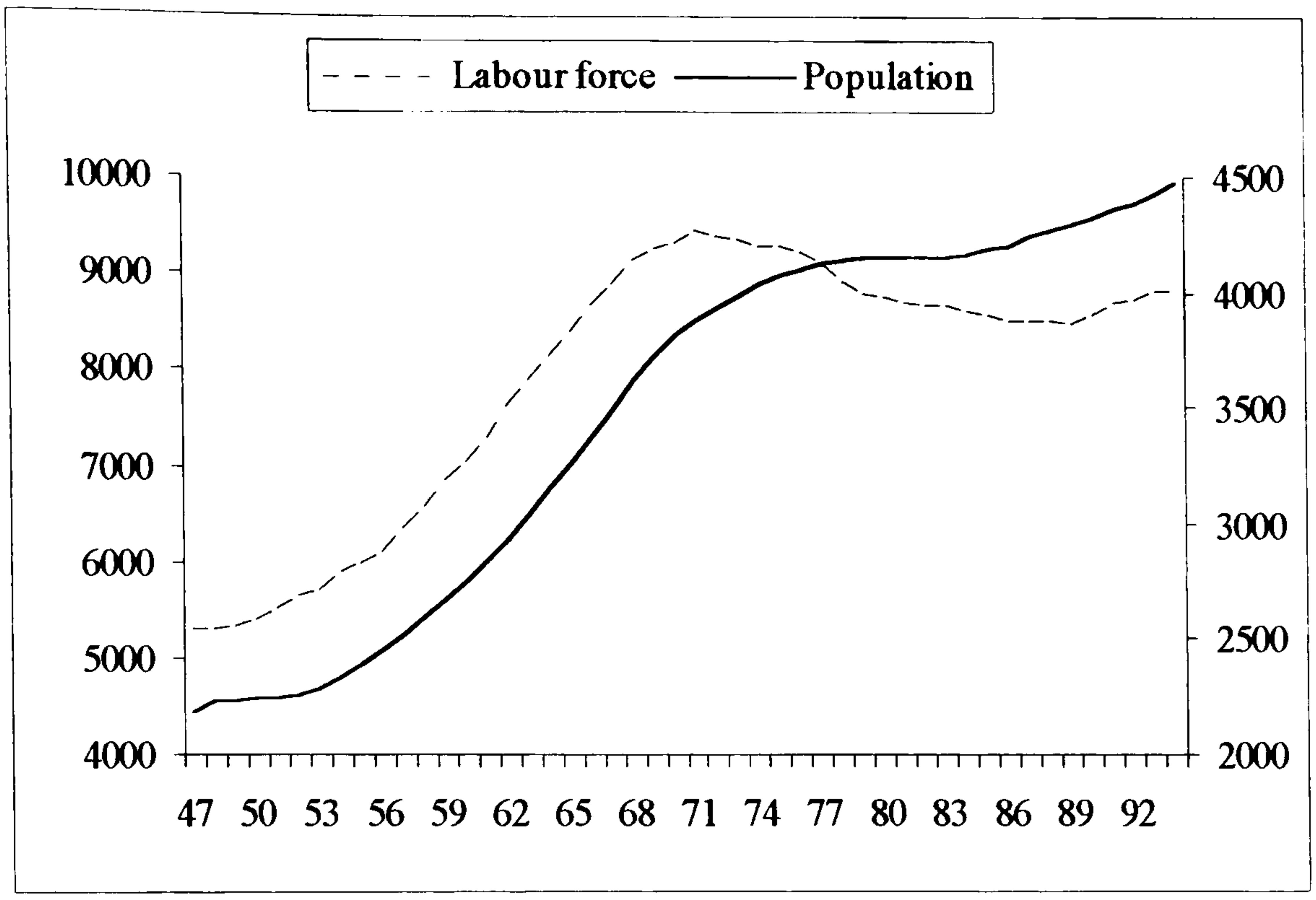
Note: GDP is for the private business sector.

the share of "other structures" in GDP rise from 2.9 per cent of GDP to 3.5 per cent of GDP. Thus most of the different *core* infrastructure stocks grew relative to GDP during the "infrastructure slowdown". An exception was the stock of roads which shrank from 21.6 per cent to 15 per cent of GDP. The fact that roads are such a large component of the core infrastructure stock had the effect that the core's share of GDP fell from 31 per cent in 1964 to 25 per cent in 1994.

3.4 Per Capita Measures of Public Capital

Finally, the infrastructure slowdown can be illustrated by taking a look at what has happened to public capital measured in per capita terms. The population of the U.S. has more than doubled over the last 70 years, rising from 122 million in 1925 to 260 million in 1994. This translates into growth of 1.1 per cent per year. The overall stock

Figure 9. *Core G per Person (R.H.S) and per Labour Force Member, 1947-1994*



of capital grew by 3.1 per cent per year during this period and thus the per capita stock of government capital has risen by approximately 2 per cent per year. There was \$8,220 of infrastructure capital per person in 1994, almost four times as much as in 1925. By the time the infrastructure slowdown started in the late 1960s, the population was growing at a much slower rate than it had been in the 1950s and early 1960s and so there was never a decline in the quantity of *G* per capita. The quantity of infrastructure per labour force member did, however, decline during the slow growth years. Infrastructure per labour force member is a more suitable measure to use if the focus is on labour productivity.[7] Figure 9 shows that this stock grew considerably until 1972. After that, as the "baby boom" generation started entering the work force, the variable declined at the rate of 0.3 per cent per year until 1994.

[7] The capital stock is measured relative to the labour force, not employment, to remove variations caused by the business cycle.

Table 6. *Public Investment: an International Comparison*

Public Investment as a Percentage of Private Investment

Period	U.S.	Canada	Germany	U.K.	Japan
1960-64	18.7	23.4	17.9	13.2	41.4
1965-69	19.3	21.6	19.6	7.4	45.8
1970-74	14.8	19.2	19.7	9.1	45.5
1975-79	11.1	15.3	19.1	6.1	59.8
1980-84	9.3	14.0	15.4	5.0	55.6
1985-89	10.0	13.1	13.2	4.5	38.9

Public Investment's Share in GDP

Period	U.S.	Canada	Germany	U.K.	Japan
1960-64	2.6	4.1	3.9	2.0	7.8
1965-69	2.8	4.1	3.9	1.3	8.0
1970-74	2.3	3.6	4.0	1.6	8.5
1975-79	1.8	3.1	3.3	1.1	8.8
1980-84	1.5	2.7	2.8	0.8	8.5
1985-89	1.5	2.4	2.3	0.8	6.5

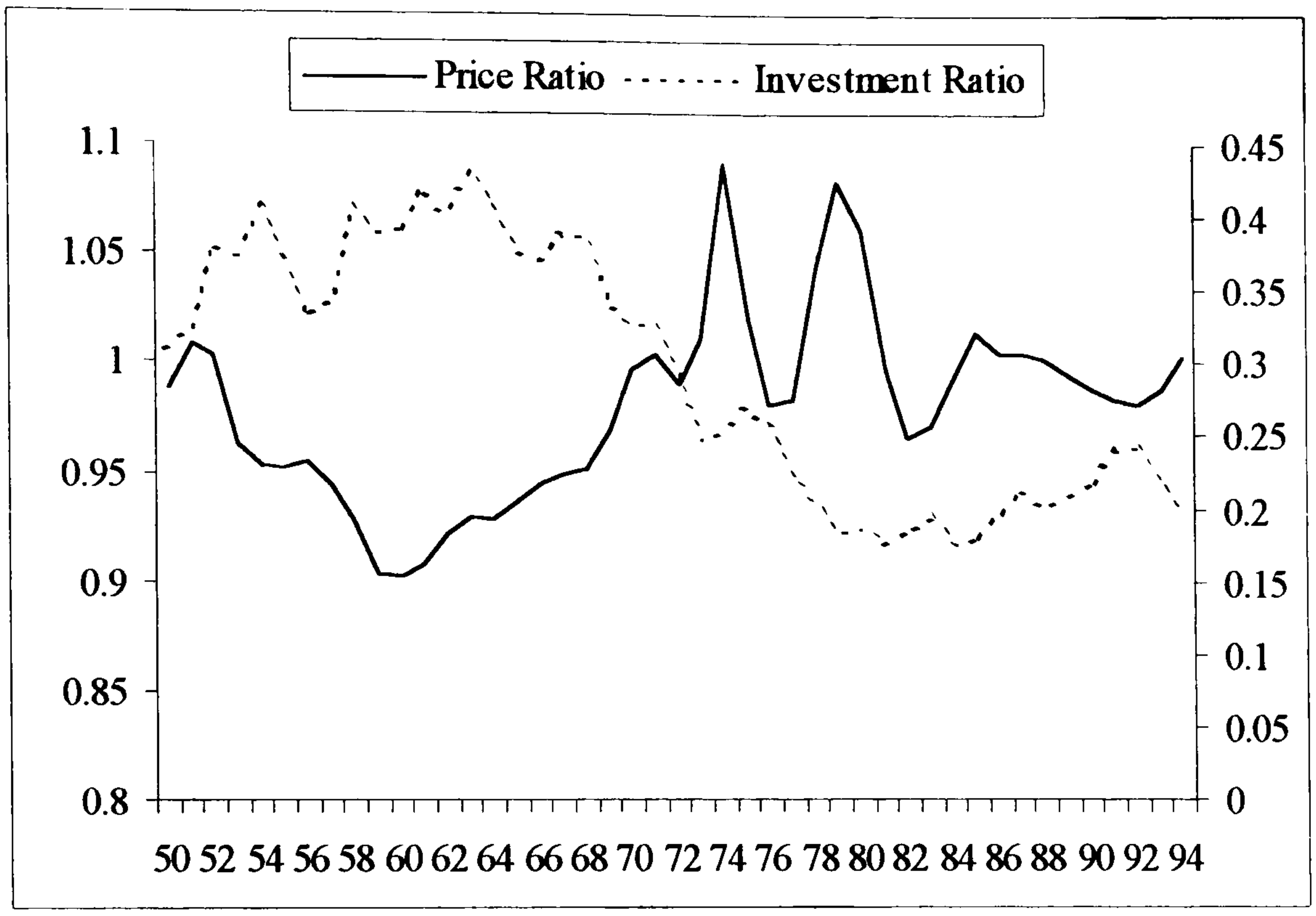
Source: Tatom (1993).

3.5 An International Comparison

As Tatom (1993) and Ford and Poret (1991) point out, it is difficult to compare the evolution of public capital in different countries because, for example, relatively large holdings of capital that in other countries would be held by the public sector are owned by the private sector in the United States. This is especially the case in transportation, communications and electric and gas utilities. Thus it is difficult to compare the absolute level of the public/private investment ratio in the U.S. and Japan.

Nevertheless a comparison of trends in public investment ratios provides an interesting story. With the exception of Japan, both the public/private investment ratio and public investment's share in GDP have declined in all the countries illustrated in Table 6. Thus the decline in public capital formation in the U.S. was not unique.

Figure 10. *Relative Price of Public Capital (L.H.S) and the Public/Private Investment Ratio, 1950-1994*



4. Reasons for the Slowdown

There are several possible explanations as to why the infrastructure slowdown occurred, including the rise in the relative price of public capital, the change in the composition of the public capital stock and pressure on state governments' finances.

4.1. The Rising Price of Public Capital

If the relative price of new public capital is defined as the price of new public capital divided by the price of new private capital, then it is possible to determine whether changes in relative price have had an effect on the accumulation of public capital relative to private capital in the post-war period.[8] It appears from Figure 10 that there

[8] The cost of public capital is measured as the public capital deflator, obtained by dividing the current stock of public capital by the constant dollar stock. The price of private capital is derived in a similar fashion. These measures are different to the *one-period* prices or user costs of private and public capital that are calculated in Chapter 3

is some evidence of a negative relationship between the relative price and the public/private investment ratio: when the relative price of public capital rises (falls) the investment ratio falls (rises). The correlation coefficient for the two series is -0.71. While increases in the price of private capital (relative to either public capital or labour) are likely to have a significant effect upon the private sector's decisionmaking process, public investment is also driven by political priorities, for example demands from state electorates that funds be spent on welfare programmes or that taxes be reduced.

4.2 The Pressure on State Finances

The reasons for the slow growth in U.S. infrastructure are many and varied. Dalenberg and Eberts (1988) argue that for certain cities much of the problem can be traced to an ageing industrial base which acts like a double-edged sword, reducing the tax base and increasing the need for welfare programmes. Furthermore, as time passes the location of economic activities changes but local governments are obliged in many cases to maintain a large portion of the existing infrastructure even when it is used below capacity. States may have placed a brake on their spending because much of it was financed by petrol taxes and the effective tax rate has fallen more at this level than at the federal level. Local governments whose role it has been to build schools, hospitals and police stations and local streets have also suffered funding pressures as a result of caps being placed on property taxes. Policymakers faced with tough budget decisions have often found it easier to cut back on public investment rather than consumption spending. Furthermore, according to Mudge (1996), there was a significant change in government's role in the economy in the late 1960s with the Great Society Programs leading to increased involvement at all levels of government in social programmes.

It was shown in Section 1 that the Federal Government plays only a minor role in the direct acquisition of public capital. However, it has played a significant role in financing state and local capital formation. It has been argued that reduced federal financing is to blame for the infrastructure slowdown. For example, Dalenberg and Eberts (1988) note that federal grants-in-aid dropped to 20 per cent of local government receipts in 1985 from a high of 30 per cent in the late 1970s.[9] However, there are reasons why it can be argued that the federal government is not to blame for the infrastructure slowdown. First, the Congressional Budget Office (1986) has shown that there is a considerable degree of substitutability between federal and state and local financing of state and local public spending. Tatom (1993) shows that federal grants aimed specifically at state and local capital formation grew at a far faster rate than GDP from 1989 to 1993. However, there was little change in the overall public investment percentage of GDP. The boost from the federal budget was offset by reduced funding at the state and local levels. New federal funding for state and local government capital spending may well finance projects that would have in any case been carried out. The savings generated by federal grants are then used to fund more pressing current expenditure.

Second, the decline in federal grants-in-aid to state and local governments relative to overall spending only occurred over a decade after the decline in public sector investment. Figure 11 makes it clear that federal grants peaked in importance in 1978, 12 years after investment's share of GDP started falling. Also, investment started to pick up from 1985 although the share of federal grants continued falling for several years. Third, while states and localities undertake almost all spending on nonmilitary

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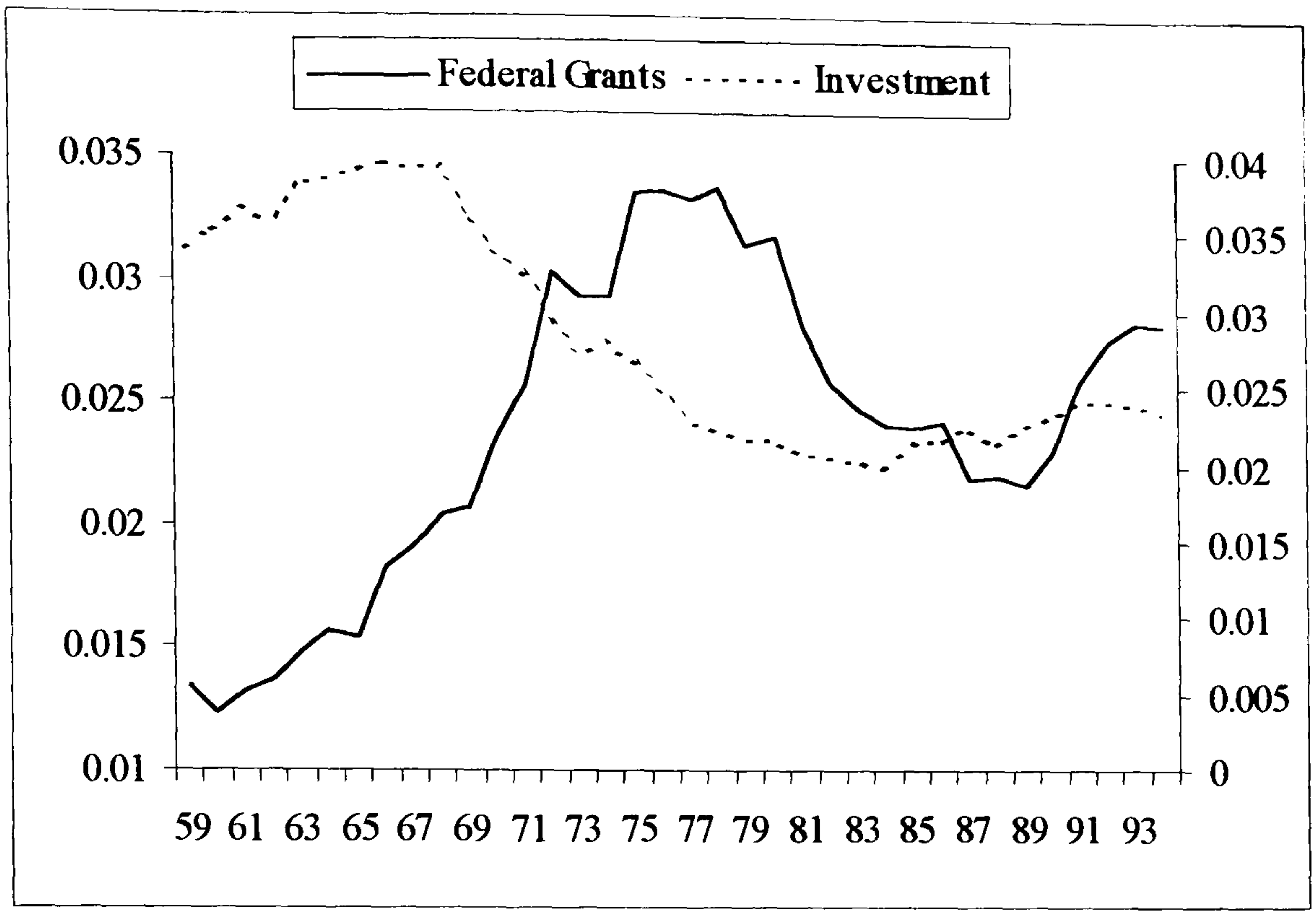
[9] Federal grants to state and local governments include funding for other programs besides capital outlays

Figure 11. *Grants-in-Aid (L.H.S) versus Public Investment (relative to GDP)*

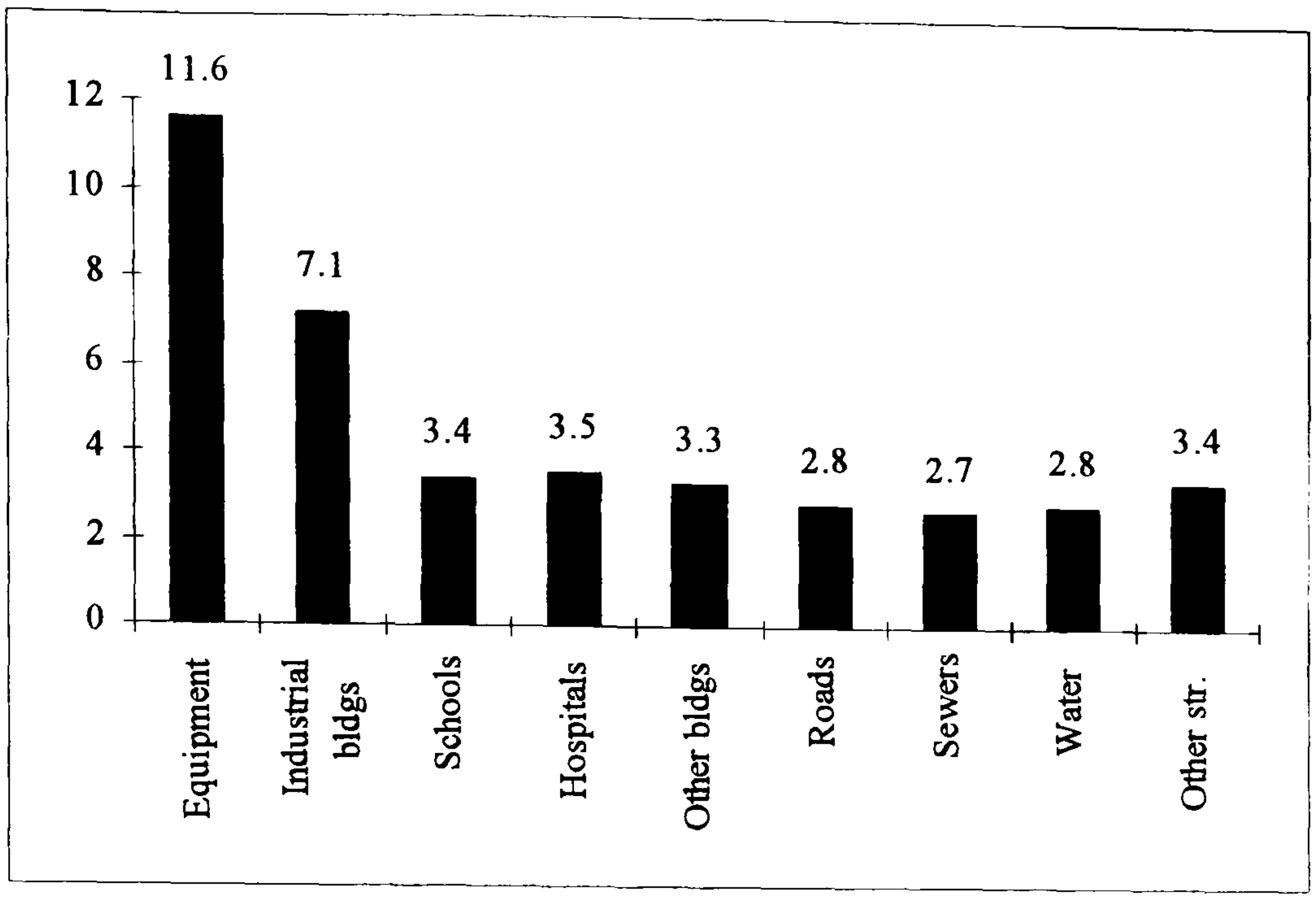


public capital, the federal government provides matching contributions for transportation and, more recently environmental projects. Thus the decision to invest in federally assisted spending depends on the willingness of state and/or local governments to meet federal matching requirements.

4.3 The Role of Economic Depreciation

The effect of economic depreciation on the public capital stock has received no attention in the infrastructure literature. However, an increase in economic depreciation accelerated the infrastructure slowdown to a small extent. In Section 3 it was pointed out that the change in the stock of infrastructure from year to year is determined not only by investment spending but by economic depreciation too.

Figure 12. *Average Economic Depreciation Rates, 1959-94.*



This is because the infrastructure stock in any year t is defined as:

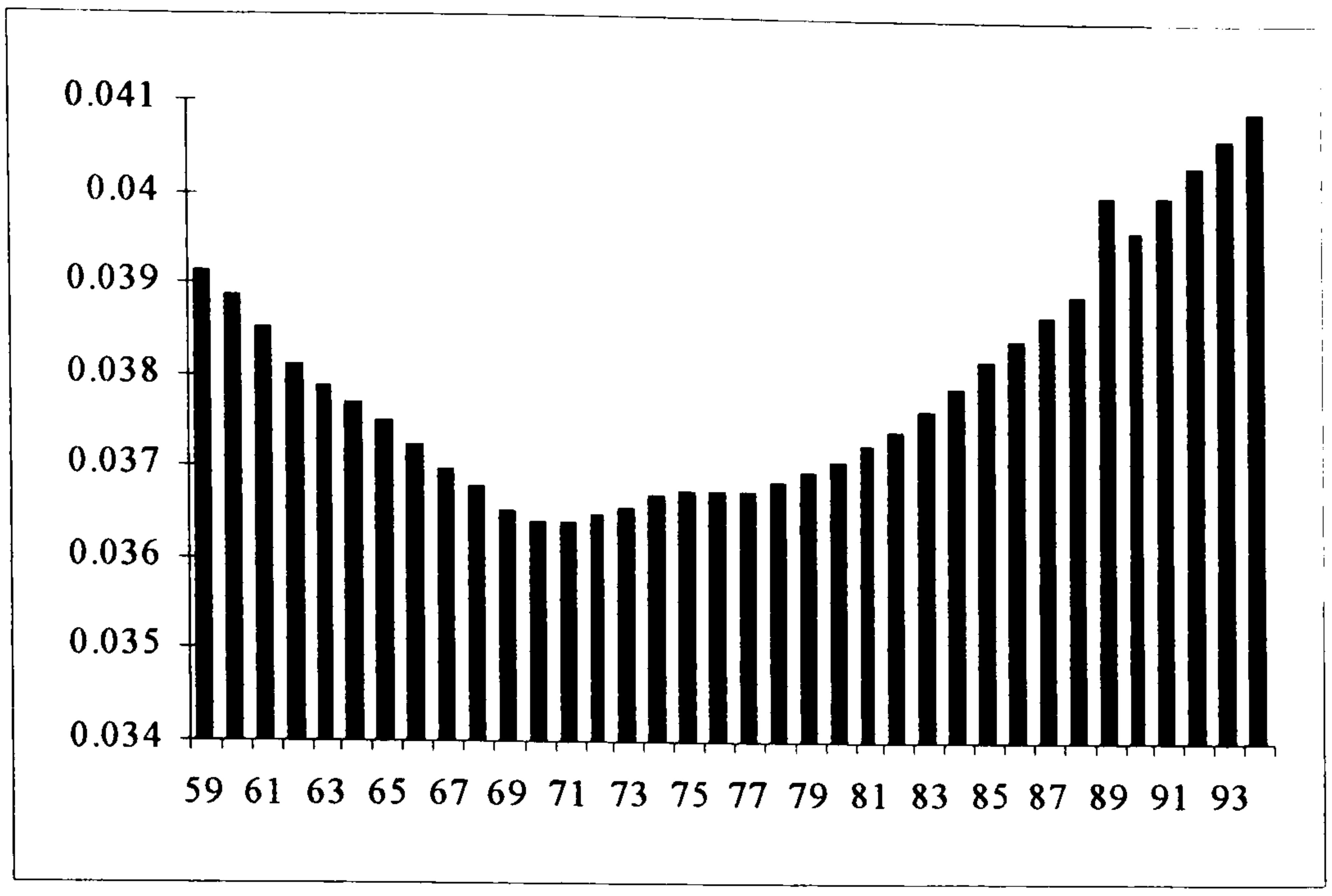
$$G_t = G_{t-1} + I_t - D_t, \tag{1}$$

where G_t is the stock of public capital in year t, I_t is public investment and D_t is economic depreciation. The depreciation rate is equal to

$$\frac{D_t}{G_{t-1}} = \delta_t. \tag{2}$$

The important point is that the annual depreciation rate of the public capital stock does not remain constant. As the composition of the public capital stock changes so too does the depreciation rate. This is because assets with longer lives have lower depreciation rates than assets with shorter lives. Figure 12 shows the average depreciation rates of the various types of infrastructure over the period 1959-94. As is to be expected, equipment has the highest depreciation rate because assets like cars and computers have shorter lives than buildings and other structures. However, there is also a significant difference between the depreciation rates of the different types of structures owned by the public sector. For example, hospitals depreciate by almost one percentage point per year more than sewers.

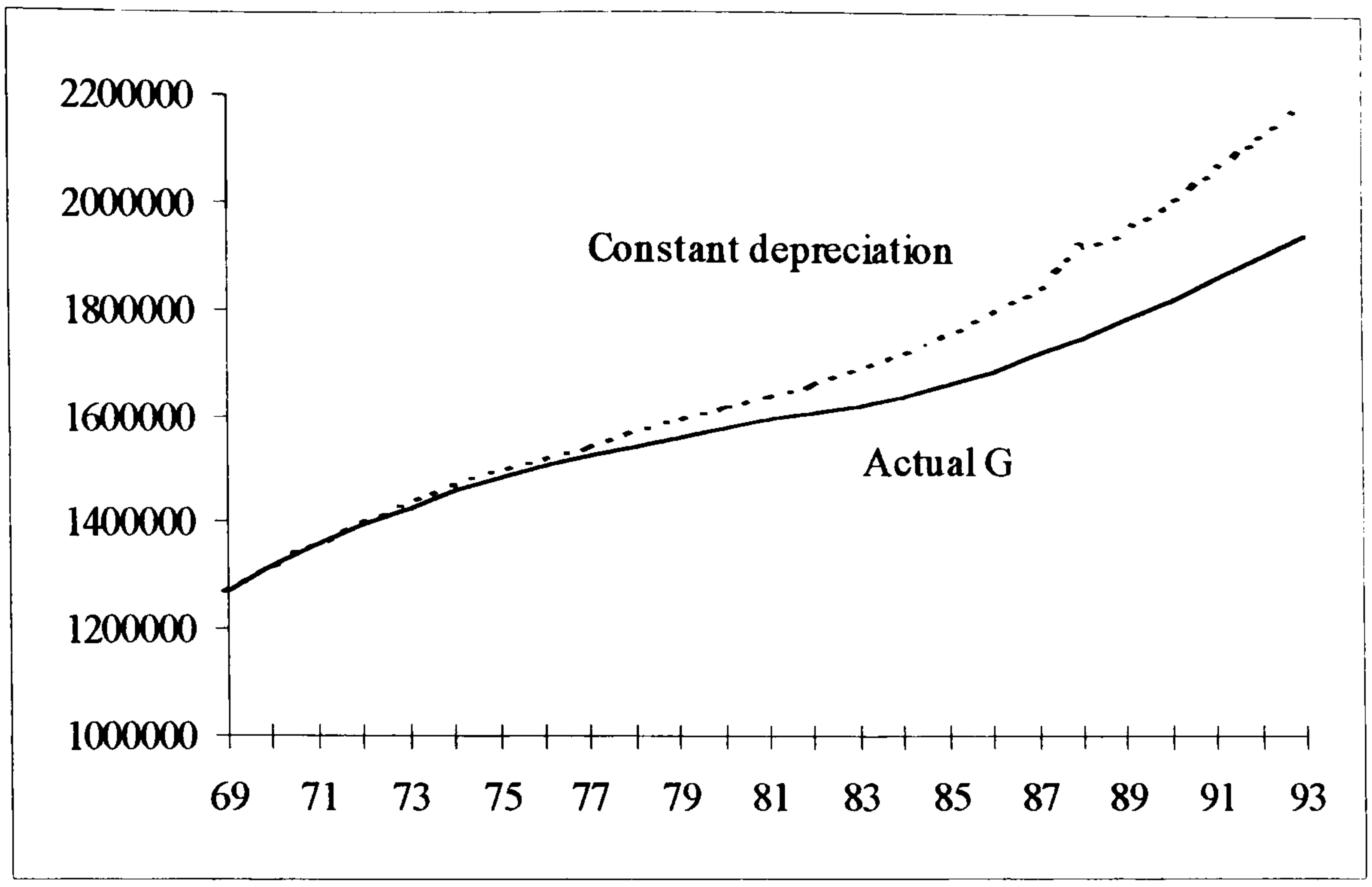
Figure 13. *Average Depreciation Rate, Total Infrastructure, 1959-94*



Since the late 1960s, the average depreciation rate of the total infrastructure stock has gradually increased, representing a fall in the life of assets owned by the public sector (Figure 13). This implies that the slowdown in the growth of public capital caused by the fall in investment spending from the late 1960s to the early 1980s was exacerbated by the change in asset mix. In order to estimate the contribution of the increased depreciation rate to the infrastructure slowdown, the infrastructure stock from 1969 (one year after infrastructure investment turned down and the year when the depreciation rate started to rise) was recalculated using (1) but keeping the depreciation rate fixed at its 1969 level of 3.5 per cent. It is clear from Figure 14 that if the composition of the infrastructure stock had remained the same as in 1969, the infrastructure stock would have been significantly higher, despite the fall in investment. In fact, there would have been 12.6 per cent ($245 billion) more public capital.[10] This simple exercise reveals two important points. Firstly, the way economic depreciation is calculated is crucial to infrastructure researchers or anyone using capital stock data.

[10] Of course this simple calculation makes the unrealistic assumption that the changing depreciation rate has no effect on the public sector's investment decisions.

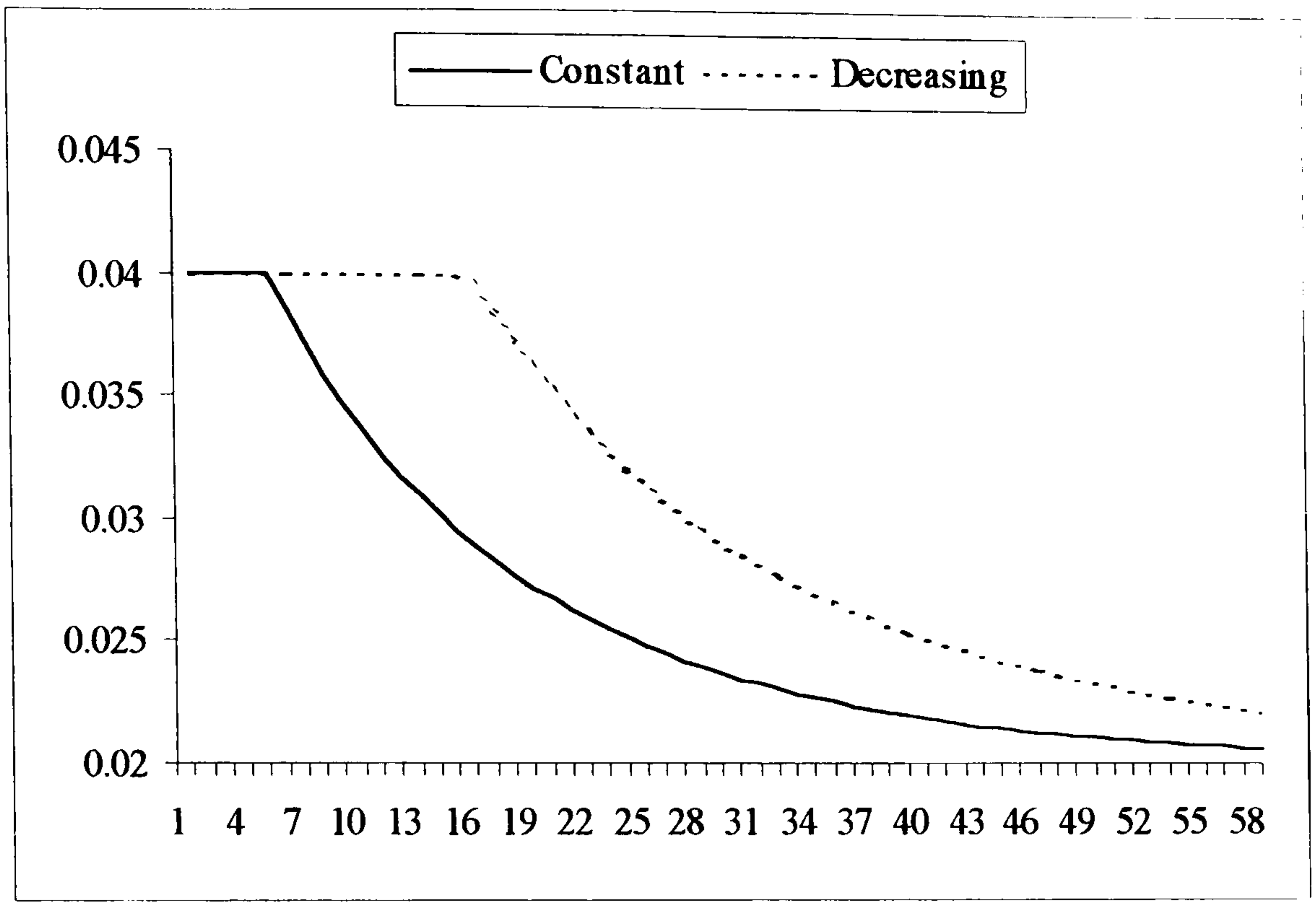
Figure 14. *Public Capital Stocks: Actual and Constant Depreciation Rates*



The difference between a depreciation rate of 3.6 per cent and 4.0 per cent makes itself felt over a long period, such as 20 years. This issue will be raised again in Chapter 3 when economic depreciation rates are used again to calculate the price of capital and to construct measures of capital input. Second, the infrastructure stock should not be viewed as just one measure. It is made up of numerous different types of buildings, machinery and structures. Spending \$1 billion in any year on roads rather than on equipment has important implications for the level of the overall public capital stock. In five years' time there will be considerably more road capital remaining, resulting in a higher overall capital stock. The question is, how much investment is required to keep the capital stock growing at a constant rate? In the presence of depreciation the growth rate of public capital can be calculated from (1):

$$\%\Delta G_t = \frac{G_t - G_{t-1}}{G_{t-1}} = \frac{I_t}{G_{t-1}} - \frac{D_t}{G_{t-1}} = \iota_t - \delta_t, \tag{3}$$

Figure 15. *Capital Stock Growth Rate: Constant vs. Decreasing Depreciation Rate, 58 Periods*



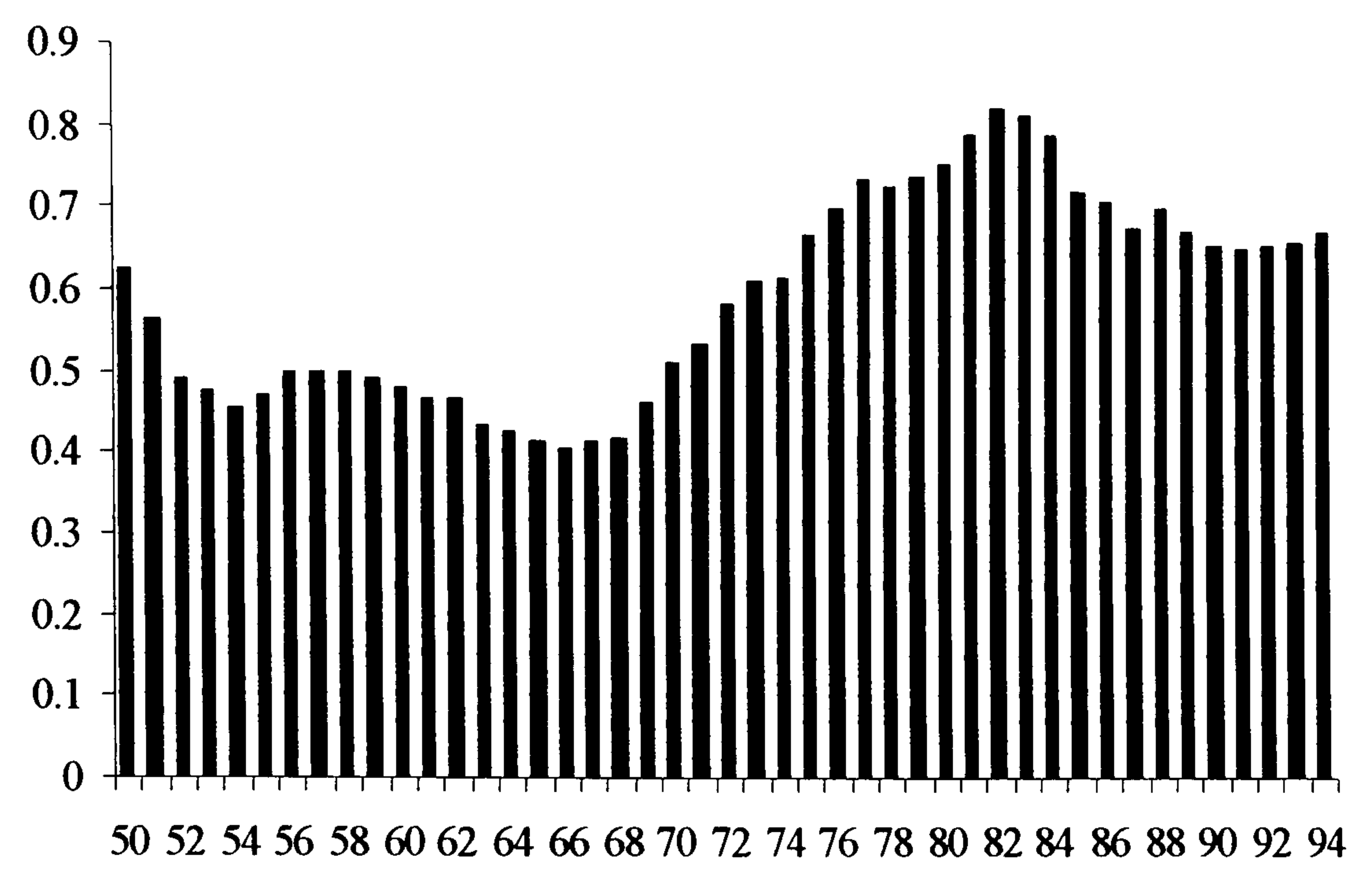
where $\%\Delta G_t$ is the target growth rate of public capital and ι_t (I_t/G_{t-1}) can be defined as the public capital investment rate. For the public capital stock to keep growing at $\%\Delta G_t$, the investment rate must be

$$\iota_t = \%\Delta G_t + \delta_t . \tag{4}$$

From (3) it can be seen that if the depreciation rate is 4 per cent the capital stock's growth rate will only fall from, say, 4 to 2 per cent if the investment rate falls from 8 to 6 per cent. For this to occur in a single period, the *level* of investment would have to fall. The effect of a fall in the investment *growth rate* is illustrated by the "Constant" line in Figure 15.[11] For the first five periods investment and the capital stock grow by 4 per cent a year. There is then a slowdown in investment growth from 4 to 2 per cent with the result that the capital stock's growth rate starts decreasing, eventually settling at 2 per cent.

[11] "Constant" refers to the fact that, in this example, the economic depreciation rate remains constant

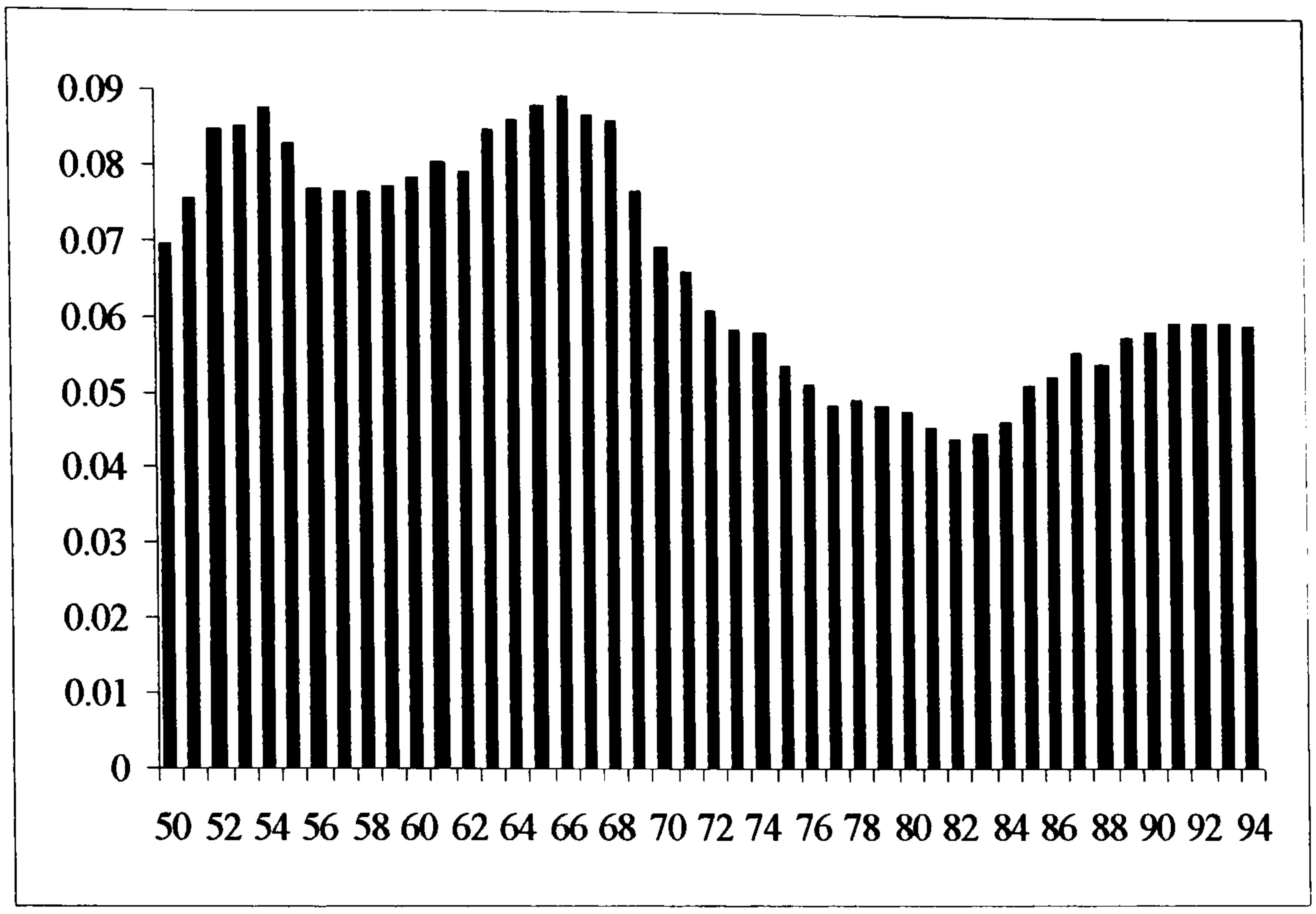
Figure 16. *Depreciation's Share of Total Public Investment, 1950-94*



The importance of changes in the composition of the capital stock (and hence its depreciation rate) coupled with a fall in the investment growth rate can also be illustrated using simple simulation techniques. The "Decreasing" line in Figure 15 also illustrates the effect of a slowdown in investment growth after period five. However, it is assumed that the depreciation rate falls each year for 10 years from 4 per cent to 2.5 per cent. This is analagous to a swing towards core infrastructure structures like roads and water and sewer systems. The depreciation rate then remains fixed at 2.5 per cent.[12] Despite the slowdown in investment growth, the capital stock continues growing at 4 per cent a year for a further ten periods because of the lower depreciation rate. Eventually, as the depreciation rate settles at 2.5 per cent, the effect of slower investment growth becomes apparent and the growth rate of the infrastructure stock falls gradually to 2 per cent.

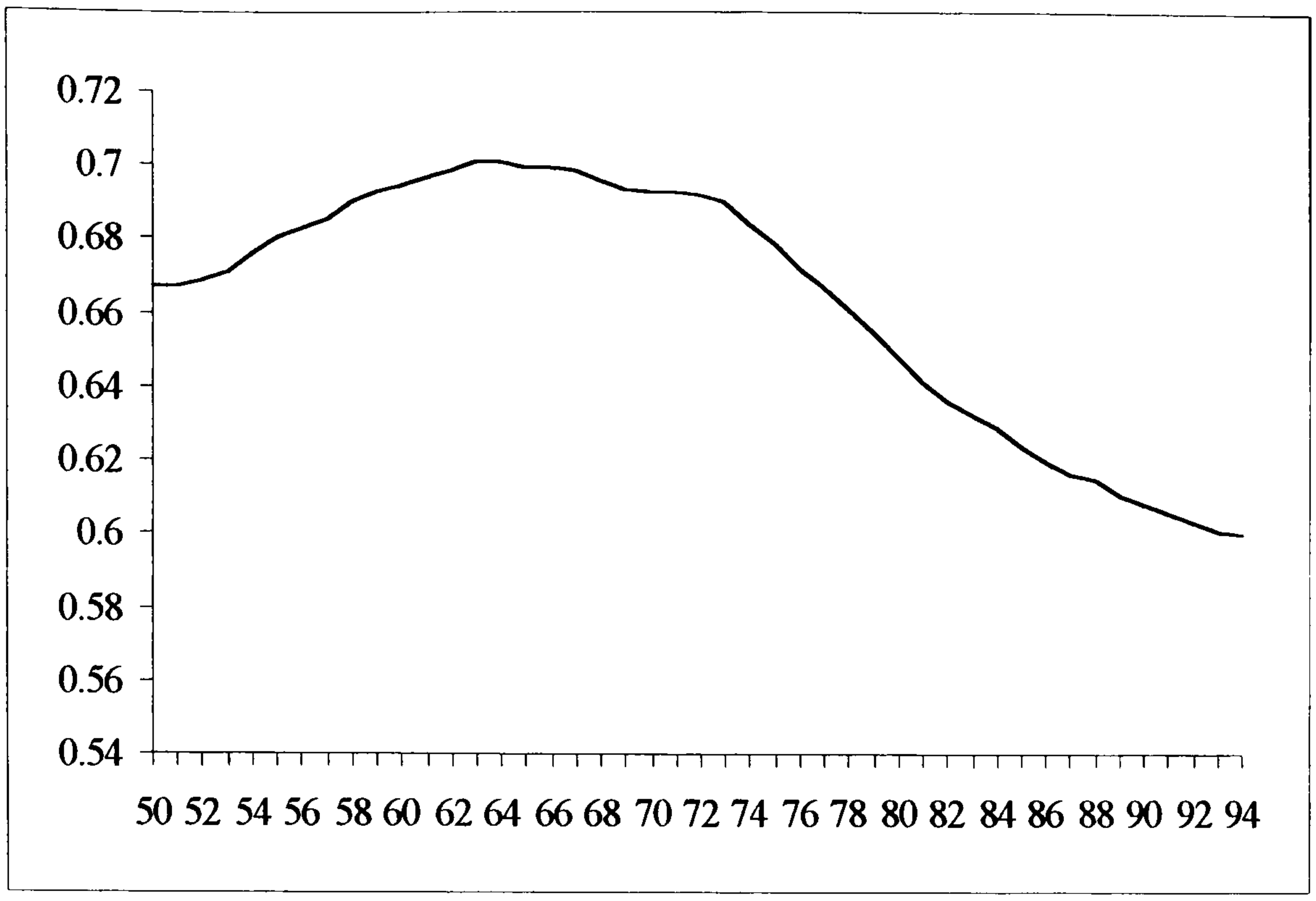
[12] The depreciation rates in each of the ten periods after period five are: 3.85, 3.70, 3.55, 3.40, 3.26, 3.12, 2.98, 2.85, 2.72, and 2.59 per cent respectively

Figure 17. *The Public Capital Investment Rate, 1950-94*



What this simple exercise illustrates is that changes in the composition of the public capital stock could alleviate any investment slowdown. Of course the opposite is also true. If the average depreciation rate were to rise (as it did from 1969) any investment slowdown would be exacerbated. It was mentioned above that part of every dollar invested represents replacement of worn out infrastructure and part represents increases in the capital stock. Whereas depreciation consumed 47 cents of every dollar invested from 1950 until 1968, it consumed on average 68 cents from 1969-94 (Figure 16). Interestingly, although investment was growing by 3.9 per cent per year between 1983 and 1994, depreciation claimed \$0.70 of every dollar invested, compared with just \$0.66 during the investment decline. This can explained by the fact that although investment fell from 1968, the investment rate, $\iota_t = I_t/G_{t-1}$ remained relatively high for a number of years. Similarly, although investment was growing rapidly in the 1980s and 1990s the investment rate was very low following many years of low investment. How fast investment is growing does not necessarily indicate how fast the capital stock is growing. The investment rate is also important (Figure 17).

Figure 18. *Share of Roads in Core Infrastructure Stock, 1950-94*



4.4 Highways and Streets

It is worth paying particular attention to what has happened to the stock of roads because this is by far the largest component of the public capital stock and, along with educational buildings, contributed most to the public capital slowdown. More importantly, roads account for the majority of the core (directly productive) infrastructure stock, despite their relative decline in importance over the years (Figure 18). Several authors (for example, Tatom, 1993) argue that the slowdown in highway growth was a logical consequence of the completion of the interstate highway system. As Cain (1997) points out, the prosperity of the postwar years and the automobile-based suburbanisation of the U.S. population increased the demand for new roads. Furthermore, the 1956 Interstate Highway Act, with a preamble citing national defence concerns, authorised a 42,500 mile system of limited access, high-speed roadways. The work was to be done by the states with 90 per cent of the funding coming from the federal government.

Table 7. *Average Annual Per Capita State and Local Government Highway Spending and Revenue (Constant 1982 dollars)*

	------ Expenditure ------		
	Current	Capital	Highway user taxes
1965-69	71	146	117
1970-74	71	125	116
1975-79	73	94	96
1980-84	72	84	75
1985-89	77	95	85

Source: Netzer (1992)

The stock of highways and streets rose sharply from the early 1960s until the mid 1970s but the growth rate declined thereafter as interstate construction slowed and the previously built highways depreciated. The stock of roads grew by 4.28 per cent from 1960-69, by 1.23 per cent between 1970-79 and by only 0.89 per cent between 1980-94. Netzer (1992) blames the decline in capital spending for highways not on the completion of the interstate system but on the way the highway system is financed. About 70 per cent of all funding comes from highway-user sources, directly and indirectly. The decline in highway capital spending reflects a decline in highway-user revenue. Average annual per capita highway user tax receipts declined by more than one third from the 1965-74 period to the early 1980s (Table 7). With current spending (for traffic operations etc.) remaining relatively constant, capital spending also declined sharply. Netzer (1992) notes that there is an obvious explanation as to why highway tax revenues declined. With very few exceptions motor fuel taxes are based on the physical volume of fuel sold and because of increased vehicle fuel efficiency less taxes have been collected.[13] While states are free to change the basis of taxation or increase

[13] The average amount of fuel consumed per vehicle fell by 20 per cent from 1970-89.

fuel tax rates, many electorates have voted not to raise adequate funds to support highway spending needs. Netzer also argues that state and local governments should have adequate replacement strategies in which they, like private firms, weigh replacement costs against ongoing repair costs. He argues that financing systems should not encourage the substitution of capital for operating expenditures. For example, the Federal Government should not offer financial inducements only to build new plant and equipment at new sites rather than repair and replace components of the existing capital stock.

5. Public Capital and Productivity

In Section 3 the fall in infrastructure investment was compared with trends in various private sector variables, namely GDP, private investment and the size of the labour force. The core infrastructure stock declined relative to all three from the 1960s. It is interesting to compare the historical pattern of infrastructure growth with that of direct measures of productivity. Table 8 compares the growth rates of three infrastructure variables (total, core and disaggregated core) with that of productivity over three time periods.[14] It is clear that the two sets of measures have a similar pattern: the growth rates for both fell from the 1970s. Whether the infrastructure slowdown contributed to the productivity growth slowdown or not cannot be ascertained from a simple comparison of growth rates, however. More convincing arguments are derived from a formal analysis of the variables, for example by conducting Granger causality tests

[14] The TFP growth rate is the standard Solow residual which, though not the most accurate measure of productivity, will suffice for the purposes of this discussion.

Table 8. *Comparison of Public Capital and Productivity Growth Rates, 1960-89*

	1960-69	1970-79	1980-89
Growth in public capital (% p.a.)			
Total public capital	4.31	2.00	1.38
Core infrastructure	3.99	2.06	1.30
Highways & streets	4.28	1.23	0.59
Other core	4.33	3.00	2.19
Growth in productivity (% p.a.)			
Labour productivity	2.90	1.31	1.28
Total factor productivity	1.82	0.60	0.87

Source: Aschauer (1993) and Bureau of Economic Analysis

within a multivariate framework and subjecting the results to rigorous diagnostic testing. Nevertheless there is a certain amount of intuitive evidence indicating that the decline in certain types of investment had a negative effect on productivity. For example, there is some evidence that roads were more congested in the years following the massive cutbacks in investment than in previous years. The Federal Highway Administration forecast that urban highway congestion would increase by 436 per cent by 2005 unless the interstate highway system was improved (U.S. Department of Transportation, 1987). Increased congestion on roads networks increases business costs and therefore affects productivity. However, roads were not the only type of investment subject to cutbacks. If the other components of the core (water and sewer systems capital and other structures) are productive, then it is possible that the halving in the growth rate of these types of capital has had an effect on TFP. New light is shed on these issues in Chapter 4.

6. Conclusion

The analysis in this chapter serves a number of purposes. The first aim is to illustrate the infrastructure slowdown that took place from the late 1960s to the early 1980s and place it in the context of developments in the private economy. There has been a substantial increase in the quantity of public capital since the Second World War. However, public investment has not kept up with growth of the private economy, falling relative to private investment, GDP and the labour force. More importantly, due to the emphasis in this thesis on the importance of the different infrastructure stocks to the private production process, the aim has been to illustrate the growth paths of the different types of infrastructure, especially the components of the core that are analysed in greater detail in the remaining chapters. It is clear that growth in all the components of the core infrastructure stock slowed between 1973 and 1994. At one extreme the growth rate of the roads stock (accounting for more than 60 per cent of the core in the post-war period) fell from 4.1 per cent in the 1950-72 period to 0.8 per cent in the 1973-94 period. At the other extreme, the stock of sewer capital fell from 3.9 per cent to 3.1 per cent. Relative to GDP, only roads fell significantly. To the extent that core infrastructure is productive, it is possible that slow growth in each of these types of capital contributed, in varying degrees, to the productivity slowdown.

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Data Appendix

All private and public capital stock data (including investment and economic depreciation) were obtained from the U.S. Bureau of Economic Analysis *Fixed Reproducible Tangible Wealth* diskettes. All measures are in constant 1987 dollars unless otherwise stated. Net stocks of nonresidential capital were used to construct the various ratios and other measures.

All of the remaining data was obtained from the *Economic Report of the President* (various years). This includes data for GDP, government purchases, the population, the labour force and grants in aid. Where applicable all measures were in constant 1987 dollars.

Chapter 3

Are the Public Capital Stocks Optimal? Results for the Private Business Sector, 1959-94

1. Introduction

One of the advantages of the cost function approach is that it can be used to determine the optimal stock of public capital. This is useful because the finding that public capital has a positive and significant output or cost elasticity does not necessarily mean that there should be extra spending on infrastructure (ie, that the public capital stock is suboptimal). The benefits of increased investment – measured as increased business output or lower business costs – have to be weighed against the cost of providing the additional capital. In the absence of user charges, the direct cost of most infrastructure services is zero. Thus firms could be expected to demand more public investment as long as the additional capital lowers their costs. Of course, this is not the whole story. New public projects impose a cost on society in the form of higher taxes. Thus, in the absence of infrastructure user charges, the optimal public capital stock is derived by balancing the cost savings enjoyed by the private business sector against the costs to society of providing the extra capital.

Optimal public capital stocks have been derived in only two cost function studies in the infrastructure literature: Berndt and Hansson (1992) using data for the Swedish private business sector and Morrison and Schwartz (1996) using data for manufacturing in New England. Most cost function studies examine other important and related issues concerning infrastructure's effect on the private production process. For example, Lynde and Richmond (1992), estimating a translog cost function using data for the non-financial corporate business sector, find that public capital has a positive marginal product, that the hypothesis of constant returns to scale is accepted when public capital is included with private capital and labour, and establish that public and private capital are complements. Nadiri and Mamuneas (1994), estimating a translog cost function using data for the manufacturing sector, find that the effect of public capital on costs varies significantly across industries.

Another relatively unexplored avenue in the infrastructure literature is the importance of the individual infrastructure stocks to the private business sector. None of the cost function studies and very few production function studies use disaggregated infrastructure data. Instead, focus has fallen on the effects of two aggregate public capital measures: the total public capital stock and the narrower core infrastructure stock, which contains only those types of capital that are expected to have a direct effect upon private sector production. The type of disaggregation that has received most attention in the literature is that in which all variables are disaggregated by *geographic* region (Costa *et al.*, 1987; Mera, 1973; Eberts, 1986; Garcia-Mila and McGuire, 1992; and Hulten and Schwab, 1991a). Just as these studies provide useful information about the productivity of public capital in different regions of the United States, a study that divides the infrastructure stock into its various components provides useful information about the role of the different types of capital in private production. The reason this information is valuable is intuitively obvious. The finding that infrastructure investment on the whole has a high rate of return does not inform policymakers how much spending is required on the different types: schools, highways, sewer systems, police stations, passenger terminals *etc.*

In this chapter the optimal core infrastructure stocks for the period 1959-94 are calculated using data for the U.S. private business sector. The stock of core is then disaggregated so that the optimal amount of each type of infrastructure (roads, water and sewer systems, and "other structures") can be calculated. The output elasticities of the different types of public capital are also estimated and compared with the results of the production function studies reported in Chapter 1. Following Berndt and Hansson (1992) and Morrison and Schwartz (1997) the analysis is based on cost-side marginal products (shadow values). Shadow values are computed as the potential cost savings arising from a decline in the variable inputs required to produce a given amount of output, when infrastructure investment is increased. The optimal infrastructure stocks are calculated by equating cost savings to the price of public capital.[1] The output elasticity and optimal quantity of private capital are also calculated for comparative purposes.

Apart from estimating the optimal quantities of the different types of public capital, this study includes a number of other innovations. For the estimations using aggregate public capital data, the public capital input is computed by Divisia quantity aggregation. As Jorgenson and Griliches (1967) point out, simple aggregation overlooks the fact that some assets are more productive than others – assets with high user costs are more productive in

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[1] As has already been mentioned in the literature review in Chapter 1, public infrastructure also provides benefits to consumers, the analysis of which is beyond the scope of this thesis.

equilibrium than assets with lower rental prices. Divisia aggregation has not been applied in any infrastructure study using U.S. data. I also expand the core infrastructure stock to incorporate the "other structures" component, which includes the stocks of electric and gas facilities, mass transit facilities and airfields.[2] Several infrastructure studies (for example, Morrison and Schwartz, 1997) include only roads and water and sewer systems in their definition of core infrastructure. Those studies that use disaggregated infrastructure data (Munnell 1990a and Hulten and Schwab 1991b) use a rather broad measure of "other" public capital that includes largely unproductive types of public capital such as the stocks of publicly owned buildings and equipment.

To estimate the cost function and calculate the optimal capital stocks, data is required on the prices of labour, private capital and public capital. The studies in the infrastructure literature differ considerably in their treatment of these variables for tax purposes. For example, Berndt and Hansson (1992) do not adjust any of their variables for taxation, Nadiri and Mamuneas (1994) adjust the price of labour and private capital but do not adjust the price of public capital, and Morrison and Schwartz (1997) adjust the prices of private and public capital but not the wage rate. The optimal capital stock calculations are compared under a number of different taxation scenarios.

Use is also made of the wealth of private and public capital data available from the Bureau of Economic Analysis. For example, to construct accurate rental price measures I use economic depreciation rates that are sector-specific (to calculate the user cost of private capital in each industry) or asset-specific (to calculate the user cost

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[2] The term "other structures" is used by the U.S. Bureau of Economic Analysis. Other structures include electric and gas facilities, transit systems and airfields. This data is not available in a more disaggregated form.

of the different types of public capital). Many infrastructure studies do not make full use of the available depreciation data. For example, Morrison and Schwartz (1997) use the same economic depreciation rate for their private and public capital rental price measures. To calculate the rental price of private capital in different *sectors* of the Swedish economy, Berndt and Hansson (1992) use *asset* specific depreciation rates calculated by Hulten and Wykoff (1981) using U.S. data. Great care has to be taken in constructing rental price measures because of their importance in calculating the Divisia indices and optimal capital stock measures.

The chapter is divided into nine sections. In Section 2 the theoretical framework is provided. The concept of the shadow value of infrastructure and the determinants of the optimal public capital stock are discussed. Infrastructure's output elasticity is derived as well as a number of optimal infrastructure elasticities, which show the direction and extent of factor input price changes on the optimal infrastructure stock. In Section 3 the proposed functional form for the cost function is outlined and the two estimating models (one using aggregate infrastructure, the other using disaggregated data) are derived. The optimal capital stock equations are also derived in this section. In Section 4 the construction of the private and public capital Divisia indices and the rental prices of the capital measures is discussed. In Section 5 the SUR estimation procedure is outlined and results from tests for contemporaneous error covariance are reported. In Section 6 the empirical results for the aggregate infrastructure model are reported and discussed. Next the optimal stock of public capital is calculated and compared with the actual stock to determine whether there was an infrastructure shortage in the U.S. during any of the years of the sample period. In Section 7 the disaggregated infrastructure model is estimated and the resulting optimal stocks of roads, water and sewer systems and other structures are calculated.

Comparing optimal and actual capital stocks allows one to establish whether increased spending is required on any of the different components. In both models use is made of pre-tax and tax-adjusted measures of the price of labour and private and public capital. In Section 8 the optimal quantity of private capital is calculated and there is some brief discussion as to why this measure is at times greater than or less than the actual stock of private capital. An overall summary of the findings is provided in the conclusion in Section 9 and further information is provided in the appendices.

2. Theoretical Framework

The importance of public capital to the U.S. private business sector is gauged by estimating a variable cost function, with infrastructure included as a fixed unpaid factor of production. Following Berndt and Hansson (1992) and Morrison and Schwartz (1997), the analysis is based on cost-side marginal products (shadow values). Shadow values are computed as the potential cost savings arising from a decline in the variable inputs required to produce a given amount of output, when the public capital stock is increased. The optimal infrastructure stocks are calculated by equating cost savings to the price of public capital. Given standard continuity and regularity conditions on the production function,[3] there exists a cost function dual to the production function, having the general form:

$$C = F(\boldsymbol{p}, Q, t, G), \tag{1}$$

[3] The dual cost function is assumed to be increasing in output and prices, and homogeneous of degree 1 in prices. It is assumed that the purchase prices of inputs are given.

where C is the cost of buying inputs, $\boldsymbol{p}$ is a vector of input prices, Q is output, t is a time trend representing technology and G is the stock of public capital. Some inputs, such as private capital, are typically fixed in the short run, while others (labour, energy and other intermediates) are variable. In the short run, firms choose quantities of variable inputs to minimise total variable costs, C_V, given $\boldsymbol{p}_V$, Q, G, t and K, where K is capital belonging to the private sector, $\boldsymbol{p}_V$ is a vector of variable input prices and C_V is the sum of short-run costs. Following Samuelson (1953), a short-run or variable private cost function can be specified as

$$C_V = F(\boldsymbol{p}_V, Q, t, K, G). \tag{2}$$

For the total cost function (1), the shadow value or marginal benefit of an exogenous increase in G is defined as

$$Z_G \equiv -\frac{\partial C}{\partial G}, \tag{3}$$

and the shadow value for the variable private cost function is defined as

$$Z_{VG} \equiv -\frac{\partial C_V}{\partial G}. \tag{4}$$

For the firm minimising *short-run* variable costs, there is also a shadow value relationship involving its private capital stock. The shadow value of private capital is defined as

$$Z_{IK} \equiv -\frac{\partial C_V}{\partial K}. \tag{5}$$

The partial derivatives will be negative as long as K or G provide variable input savings due to substitution possibilities. If the firm were in long-run equilibrium with respect to its private inputs, then the marginal benefits of K would just equal the marginal cost of private capital. Calling the *ex ante* one-period price of private capital P_K, then at this long-run equilibrium point the optimal amount of private sector capital, K^*, is that amount at which the marginal benefit equals the marginal cost, ie:

$$K = K^* \Leftrightarrow Z_{VK} = P_K. \tag{6}$$

Similarly, the optimal amount of infrastructure capital is that amount at which the marginal benefit equals the marginal cost:

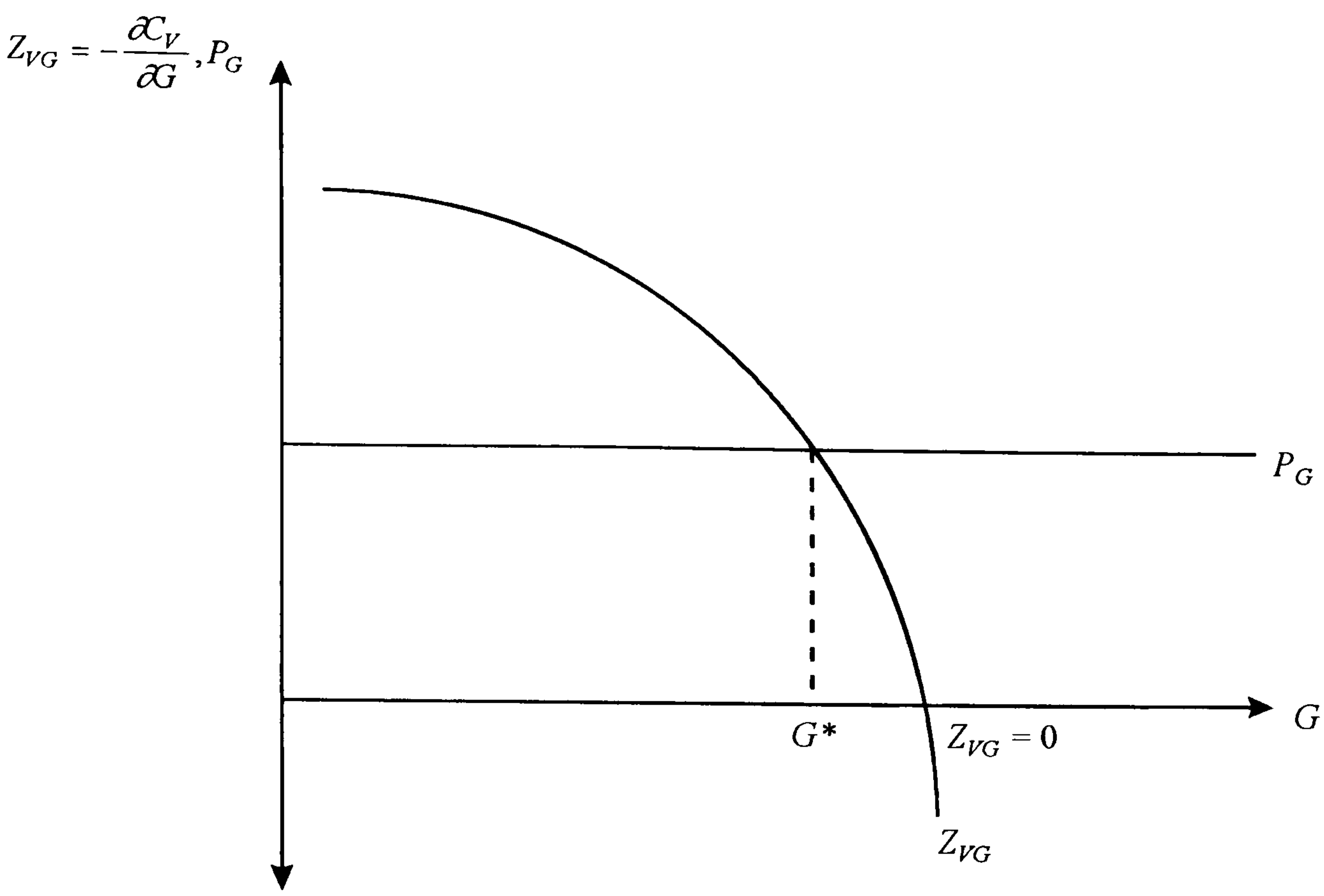
$$G = G^* \Leftrightarrow Z_{VG} = P_G. \tag{7}$$

As Morrison (1988) points out, this is a standard result that is conceptually obvious. The market and implicit values of a capital stock must be equal in full equilibrium or further adjustments would be desirable.[4] Because of the assumption that there are no private costs associated with infrastructure capital, firms benefit from having extra G as long as they enjoy further cost savings from substituting G for other inputs. However, although there are no private costs associated with the infrastructure stock, there are social costs. If the social cost of investing in one more unit of infrastructure capital is less than the cost savings enjoyed by the private business sector, the expenditure is justified because there is a net benefit.

These concepts are illustrated graphically in Figure 1. The curve labelled Z_{VG} is the shadow value of infrastructure. Its slope (given by $\partial Z_{VG}/\partial G = -\partial^2 C/\partial G^2$) is negative, reflecting diminishing marginal returns (in the form of input cost savings) to public investment. The business sector would ideally like infrastructure investment to take place up to the point where the marginal benefit is zero (ie, $Z_{VG} = 0$). From society's viewpoint, however, infrastructure investment should only take

[4] This result can be illustrated analytically. In full equilibrium it must be the case that the short-run average cost curve and long-run average cost curve are tangent. This tangency condition is $\partial C/\partial K = 0$, where $C = C_V + P_K K$. Differentiation implies that $-\partial C_V/\partial K = P_K$, where $-\partial C_V/\partial K$ is by definition the shadow value Z_{VK}. In the short run, inputs may not be instantaneously adjustable, resulting in a divergence between the market price and shadow values of G or K.

Figure 1. *Deriving the Optimal Infrastructure Stock*



place up to the point where marginal benefit and marginal cost are equal (G^* in the diagram). At points to the left of G^* marginal benefit exceeds marginal cost and the optimal strategy is to invest more. At points to the right of G^* the cost of additional capital is not covered by business sector cost savings and the optimal strategy is to let the infrastructure stock depreciate. A problem lies in measuring the one-period social price of government capital. In this chapter it is assumed that the two main differences between P_K and P_G are the differential cost of funds to each sector and the effects of the taxation system. This issue is discussed in greater detail in Section 4.

The optimal capital stock equations, K^* and G^*, are obtained by setting the shadow value expressions equal to the respective rental price measures, ie:

$$-\frac{\partial C_V}{\partial K} = P_K \text{, and} \tag{8}$$

$$-\frac{\partial C_V}{\partial G} = P_G . \tag{9}$$

Equations (8) and (9) can then be solved simultaneously with respect to K and G. It is easily seen from (2), (8) and (9) that the optimal private and public capital stocks can be expressed as

$$K^* = G(\boldsymbol{p}_V, t, Q, P_K, P_G)\text{, and} \tag{10}$$

$$G^* = G(\boldsymbol{p}_V, t, Q, P_K, P_G). \tag{11}$$

Focusing on (11), it is clear that the optimal quantity of infrastructure depends on variable input prices (for example, the wage rate of labour), quasi-fixed input prices (the rental price of private capital), private business output and the price of public capital.

Several points are worth making about the factors that influence G^*, especially in the context of the infrastructure slowdown discussed in Chapter 2. From 1968 to 1982 public investment fell by 2.3 per cent per year and this event alone prompted U.S. policymakers and several academic researchers to question the adequacy of the nation's infrastructure. However, it is clear from (11) that whether the infrastructure slowdown translated into an infrastructure shortage (ie, whether $G < G^*$) was dependent on factors other than the growth rate of public investment. For example, the level of unionisation, the introduction of investment tax incentives, increases in interest rates and the level of exports are all factors that could influence the variables in (11) and thus the optimal quantity of public capital. It may be that the infrastructure slowdown did not result in a suboptimal infrastructure stock. Similarly, the large-scale public investment of the 1950s and 1960s may have been followed by an infrastructure shortage, depending on the magnitude and direction of changes in the variables in (11).

Equation (11) also provides an indication of the appropriate public sector response to the discovery of an infrastructure shortage of surplus. The wedge between the optimal and actual infrastructure stock in any year t can be defined as

$$\varphi_t = G_t - G_t^* . \tag{12}$$

Both positive and negative values of φ_t would invoke a policy response if the policy goal is to set $G = G^*$.[5] However, it is clear from a cursory examination of the factors influencing G^* in (11) that even if $\varphi_t \neq 0$, a higher or lower level of investment is not necessarily warranted. For example, it could be that the infrastructure surplus or shortage is caused by a change in the rental price of private capital which in turn is caused by, for example, a change in interest rates. A reversal in the public investment policy on the basis of this change would be proved unwarranted if interest rates reverted to their previous level after a short period of time.[6] On the other hand, a permanent increase in the level of output may warrant a change in the public investment policy. It is also necessary to establish the *direction* of the effect of changes in input prices on the optimal infrastructure stock. For example, if public capital and private capital are complements then

$$\frac{\partial G^*}{\partial P_K} < 0 . \tag{13}$$

In other words, if a rise in the rental price of private capital leads to a fall in the optimal stock of infrastructure, the two types of capital are complements. Similarly, if

---

[5] The appropriate policy response where $\varphi_t < 0$, *ceteris paribus*, is an increase in public investment; and the appropriate policy response where $\varphi_t > 0$, *ceteris paribus*, is to curtail investment and let the public capital stock depreciate.

[6] For example, Moody's Aaa rate rose from 8.02 per cent in 1977 to 14.17 per cent in 1981, resulting in a significant increase in the user cost of private capital. However, by 1986 the rate had fallen to 9.02 per cent.

$$\frac{\partial G^*}{\partial P_K} > 0, \tag{14}$$

private and public capital are substitutes. It is possible that some types of public capital are complements while others are substitutes. For example, in Chapter 1 Munnell's (1993) results on substitutability and complementarity were discussed. Munnell found that highways and streets are substitutes for private capital, and water and sewer systems are complements. She justified these findings on the grounds that well-maintained roads reduce the depreciation rate of commercial vehicles whereas water and sewer systems are generally only publicly provided. It is also possible to establish whether public capital complements or substitutes for labour, ie, whether

$$\frac{\partial G^*}{\partial P_L} < 0 \text{ or } \frac{\partial G^*}{\partial P_L} > 0. \tag{15}$$

These optimal infrastructure changes can be converted into unitless optimal infrastructure elasticities:

$$\varepsilon_{G^*P_K} = \frac{\partial G^*}{\partial P_K}\frac{P_K}{G^*}, \text{ and} \tag{16}$$

$$\varepsilon_{G^*P_L} = \frac{\partial G^*}{\partial P_L}\frac{P_L}{G^*}. \tag{17}$$

It is likely that the optimal infrastructure stock is inelastic with respect to factor price changes, ie:

$$0 < \left|\varepsilon_{G^*i}\right| < 1 \quad i = P_L, P_K. \tag{18}$$

Thus if G and K are complements, a 25 per cent fall in P_K due to, for example, a drop in interest rates is not likely to lead to an increase in G^* of 25 per cent or more.[7]

It is also possible to use the cost function framework to derive infrastructure's output elasticity, and thus make direct comparisons with the results of the large body of production function research. From the cost minimisation problem the shadow value of infrastructure can be expressed as

$$-\frac{\partial C_V}{\partial G} = \lambda \frac{\partial F}{\partial G}, \tag{19}$$

where $\lambda = \frac{\partial C_V}{\partial Q}$, ie, marginal cost. If the infrastructure stock is in long-run equilibrium (ie, $G = G^*$):

$$\lambda \frac{\partial F}{\partial G} = P_G, \tag{20}$$

and the output elasticity of infrastructure (optimally provided) can be expressed as

$$\varepsilon_{QG*} = \frac{\partial F}{\partial G}\frac{G^*}{Q} = \frac{P_G G^*}{\lambda Q}. \tag{21}$$

The output elasticity of private capital can also be derived along similar lines:[8]

$$\varepsilon_{QK*} = \frac{\partial F}{\partial K}\frac{K^*}{Q} = \frac{2P_K K^*}{\lambda Q}. \tag{22}$$

All of the above measures can also be derived for the individual infrastructure stocks.

---

[7] One would expect a *flow* measure such as public investment to be more elastic, however.

[8] The asymmetry between the two output elasticities results from the fact that infrastructure enters the cost minimisation problem as an unpaid factor input.

3. The Estimating Models

To calculate the optimal capital stocks in (6) and (7) a functional form for the cost function has to be specified. Most empirical studies based on flexible functional forms have used the translog functional form developed by Christensen *et al* (1973). Its logarithmic form facilitates empirical imposition of homogeneity constraints, regularity conditions, and the calculation of elasticities.[9] However, Morrison (1988) points out that a problem with using the translog function for short-run studies is that, due to its nonlinear logarithmic form, it is not possible to analytically compute the full equilibrium level of the fixed inputs. Instead one must rely on iterative numerical techniques. Some researchers, she points out, have encountered problems in obtaining numerical convergence with the translog variable cost function and thus with computing estimates of long-run elasticities.[10]

As an alternative, Morrison (1988) developed a Generalised Leontief (GL) cost function that permits the steady-state levels of quasi-fixed inputs to be derived. The traditional GL cost function is a functional form in the square root of prices.[11] A variety of generalisations have been appended to account for, for example, technical change and returns to scale (Parks, 1971; Woodland, 1975; Berndt and Khalad, 1979; and Diewert and Wales, 1987) and for fixed inputs (Mork, 1978 and Mahmud *et al.*, 1986). These extensions vary in their emphases and therefore in their methods used for "generalising" the cost function.

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[9] Lynde and Richmond (1992) and Nadiri and Mamuneas (1994) are two of the most widely quoted infrastructure studies that make use of a translog functional form.

[10] See, for example, Berndt and Hesse (1986).

[11] See Berndt (1990) for information on this functional form.

Morrison (1988) extends the standard GL to allow for fixed inputs in a manner comparable to Parks (1971), Woodland (1975) and Diewert and Wales (1987). She kept the additive structure used by Parks and Woodland and the interaction and price-sum terms of Diewert and Wales. However, the interaction and intercept terms in the Diewert and Wales studies are simplified to allow for a symmetric representation of additional arguments of the cost function, thereby facilitating incorporation of multiple quasi-fixed inputs (for example, the disaggregated public capital stocks). The GL restricted (or variable) cost function can be written as

$$
\begin{aligned}
C_V(\boldsymbol{x},\boldsymbol{P},t,Q) = {} & Q\cdot\left[\sum_i\sum_j \alpha_{ij}P_i^{0.5}P_j^{0.5} + \sum_i\sum_m \delta_{im}P_i s_m^{0.5} + \sum_i P_i \sum_m\sum_n \gamma_{mn} s_m^{0.5} s_n^{0.5}\right] \\
& + Q^{0.5}\cdot\left[\sum_i\sum_k \delta_{ik}P_i x_k^{0.5} + \sum_i P_i \sum_m\sum_k \gamma_{mk} s_m^{0.5} x_k^{0.5}\right] + \sum_i P_i \sum_k\sum_l \gamma_{lk} x_k^{0.5} x_l^{0.5},
\end{aligned}
\tag{23}
$$

where P_i is the price of variable input i, x_k and x_l are the stocks of quasi-fixed inputs,[12] and s_m and s_n depict the remaining arguments. Demand equations can be derived from (23) based on Shephard's lemma.[13] As an alternative, to reduce possible heteroskedasticity, input-output equations can be derived as follows:

$$
\begin{aligned}
\frac{\partial C_V}{\partial P_i}\frac{1}{Q} = {} & \sum_j \alpha_{ij}\left(\frac{P_j}{P_i}\right)^{0.5} + \sum_m \delta_{im} s_m^{0.5} + \sum_m\sum_n \gamma_{mn} s_m^{0.5} s_n^{0.5} \\
& + Q^{-0.5}\cdot\left[\sum_k \delta_{ik} x_k^{0.5} + \sum_m\sum_k \gamma_{mk} s_m^{0.5} x_k^{0.5}\right] + \sum_k\sum_l \gamma_{lk} x_k^{0.5} x_l^{0.5}.
\end{aligned}
\tag{24}
$$

From (23) it is clear that if variable input prices increase by some proportion λ, C_V will also increase by λ, thereby satisfying linear homogeneity in prices. Similarly, from (24)

---

[12] These inputs are subject to homogeneity conditions in the sense that scale effects are dependent on them. By contrast, McFadden's "environmental variables" discussed in Morrison (1988) and Berndt and Hansson (1992) may have impacts on a firm's costs but do not affect scale properties.

[13] Shephard's lemma states that the optimal (cost-minimising) demand for input i can simply be derived by differentiating the cost function with respect to P_i.

it is apparent that if input prices increase equiproportionally, factor demands remain constant.[14]

Morrison and Schwartz (1997) and Seitz (1994) are two studies in the infrastructure literature that make use of this functional form. Morrison and Schwartz considered five inputs: private and public capital (the quasi-fixed inputs), production and nonproduction labour and energy (the variable inputs).[15] Q was gross state manufacturing output net of non-energy materials. Because the focus in this study is on the effect of infrastructure on the costs of the total private business sector, value-added output, rather than gross output, is the appropriate measure. The only variable input is labour and the cost function includes three inputs: private capital and public capital (aggregate or disaggregate data) and production workers' hours. Seitz used value-added data in his study of West German manufacturing. However, he estimated a long-run rather than a short-run cost function to determine the relationship between G, L and K.

3.1 Aggregate Infrastructure Model

The measure of public capital used by Morrison and Schwartz (1997) includes highways, water and sewer capital. Together these accounted for 46.2 per cent of the total infrastructure stock in 1994.[16]

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[14] Curvature is easily tested at each sample point by determining whether $\partial^2 C_V/\partial x_k^2 > 0$ and $\partial^2 C_V/\partial P_i^2 < 0$.

[15] Non-energy materials are not included in the specification due to difficulties in constructing the appropriate state-level price data and for conceptual reasons. Attempts to include non-energy materials, which represent a very large fraction of total costs, caused the estimates to be more sensitive to specification and parameterisation.

[16] The authors state that the estimated impact of infrastructure on costs is smaller when "other" public capital is included in the analysis. This, they say, is due to the composition of other capital, "...apparently largely containing government buildings which do not augment efficiency".

This measure of productive public capital is expanded to include the "other structures" component (electric and gas facilities, transit systems and airfields, etc.), while excluding nonproductive infrastructure such as hospitals, schools, industrial buildings and other buildings.[17] The addition of other structures adds a further 7.6 per cent of the total infrastructure stock into the measure of G. Incorporating the various variables, the cost function (23) becomes:

$$\begin{aligned} C_V(P_L,K,G,Q,t) = Q\cdot\big[&\alpha_{LL}P_L + \delta_{Lt}P_L t^{0.5} + \delta_{LQ}P_L Q^{0.5} + P_L\gamma_{tQ}t^{0.5}Q^{0.5} \\ &+ P_L\gamma_{tt}t + P_L\gamma_{QQ}Q\big] \\ &+ Q^{0.5}\cdot\big[\delta_{LK}P_L K^{0.5} + \delta_{LG}P_L G^{0.5} + P_L\gamma_{tK}t^{0.5}K^{0.5} + \\ &P_L\gamma_{QK}Q^{0.5}K^{0.5} + P_L\gamma_{tG}t^{0.5}G^{0.5} + P_L\gamma_{QG}Q^{0.5}G^{0.5}\big] \\ &+ P_L\gamma_{KK}K + P_L\gamma_{GG}G + P_L\gamma_{GK}G^{0.5}K^{0.5}, \end{aligned} \tag{25}$$

where P_L is the price of labour, Q is value-added output, t is a time trend denoting technology, K is private capital and G is infrastructure. Using Shephard's lemma the optimal demand for labour is obtained:

$$\begin{aligned} L = \frac{\partial C_V}{\partial P_L} = Q\cdot\big[&\alpha_{LL} + \delta_{Lt}t^{0.5} + \delta_{LQ}Q^{0.5} + \gamma_{tQ}t^{0.5}Q^{0.5} + \gamma_{tt}t + \gamma_{QQ}Q\big] \\ &+ Q^{0.5}\cdot\big[\delta_{LK}K^{0.5} + \delta_{LG}G^{0.5} + \gamma_{tK}t^{0.5}K^{0.5} + \\ &\gamma_{QK}Q^{0.5}K^{0.5} + \gamma_{tG}t^{0.5}G^{0.5} + \gamma_{QG}Q^{0.5}G^{0.5}\big] \\ &+ \gamma_{KK}K + \gamma_{GG}G + \gamma_{GK}G^{0.5}K^{0.5}, \end{aligned} \tag{26}$$

where L is hours worked. Following Berndt (1990) and Morrison and Schwartz (1997) this equation is transformed into an optimal input-output equation to accommodate heteroskedasticity:

---

[17] The "other buildings" component includes general office buildings, police and fire stations, courthouses, auditoriums, garages and passenger terminals.

$$\frac{L}{Q}=\frac{\partial C_V}{\partial P_L}\frac{1}{Q}=\alpha_{LL}+\delta_{Lt}t^{0.5}+\delta_{LQ}Q^{0.5}+\gamma_{tQ}t^{0.5}Q^{0.5}+\gamma_{tt}t+\gamma_{QQ}Q$$
$$+Q^{-0.5}\cdot\left[\delta_{LK}K^{0.5}+\delta_{LG}G^{0.5}+\gamma_{tK}t^{0.5}K^{0.5}+\right.$$
$$\left.\gamma_{QK}Q^{0.5}K^{0.5}+\gamma_{tG}t^{0.5}G^{0.5}+\gamma_{QG}Q^{0.5}G^{0.5}\right] \tag{27}$$
$$+\gamma_{KK}\frac{K}{Q}+\gamma_{GG}\frac{G}{Q}+\gamma_{GK}\frac{G^{0.5}K^{0.5}}{Q}.$$

3.2 Disaggregated Infrastructure Model

When the infrastructure stock is disaggregated, the cost function (23) becomes

$$C_V(P_L,K,G_H,G_{WS},G_O,Q,t)=Q\cdot\left[\alpha_{LL}P_L+\delta_{Lt}P_Lt^{0.5}+\delta_{LQ}P_LQ^{0.5}+P_L\gamma_{tQ}t^{0.5}Q^{0.5}\right.$$
$$\left.+P_L\gamma_{tt}t+P_L\gamma_{QQ}Q\right]+$$
$$Q^{0.5}\cdot\left[\delta_{LK}P_LK^{0.5}+\delta_{LG_H}P_LG_H^{0.5}+\delta_{LG_{WS}}P_LG_{WS}^{0.5}+\delta_{LG_O}P_LG_O^{0.5}\right.$$
$$+P_L\gamma_{tK}t^{0.5}K^{0.5}+P_L\gamma_{QK}Q^{0.5}K^{0.5}+P_L\gamma_{tG_H}t^{0.5}G_H^{0.5}$$
$$+P_L\gamma_{QG_H}Q^{0.5}G_H^{0.5}+P_L\gamma_{tG_{WS}}t^{0.5}G_{WS}^{0.5}+P_L\gamma_{QG_{WS}}Q^{0.5}G_{WS}^{0.5} \tag{28}$$
$$\left.+P_L\gamma_{tG_O}t^{0.5}G_0^{0.5}+P_L\gamma_{QG_O}Q^{0.5}G_O^{0.5}\right]$$
$$+P_L\gamma_{KK}K+P_L\gamma_{G_HG_H}G_H+P_L\gamma_{G_{WS}G_{WS}}G_{WS}+P_L\gamma_{G_OG_O}G_O$$
$$+P_L\gamma_{G_HK}G_H^{0.5}K^{0.5}+P_L\gamma_{G_{WS}K}G_{WS}^{0.5}K^{0.5}+P_L\gamma_{G_OK}G_O^{0.5}K^{0.5}$$
$$+P_L\gamma_{G_HG_{WS}}G_H^{0.5}G_{WS}^{0.5}+P_L\gamma_{G_HG_O}G_H^{0.5}G_O^{0.5}+P_L\gamma_{G_{WS}G_O}G_{WS}^{0.5}G_O^{0.5},$$

where G_H is street and highway capital, G_{WS} is water and sewer systems capital and G_O is the stock of other structures. Again, using Shephard's lemma, and dividing through by Q the optimal labour input-output equation is obtained:

$$\frac{L}{Q}=\frac{\partial C_V}{\partial P_L}\frac{1}{Q}=\alpha_{LL}+\delta_{Lt}t^{0.5}+\delta_{LQ}Q^{0.5}+\gamma_{tQ}t^{0.5}Q^{0.5}+\gamma_{tt}t+\gamma_{QQ}Q$$
$$Q^{-0.5}\cdot\left[\delta_{LK}K^{0.5}+\delta_{LG_H}G_H^{0.5}+\delta_{LG_{WS}}G_{WS}^{0.5}+\delta_{LG_O}G_O^{0.5}\right.$$
$$+\gamma_{tK}t^{0.5}K^{0.5}+\gamma_{QK}Q^{0.5}K^{0.5}+\gamma_{tG_H}t^{0.5}G_H^{0.5} \tag{29}$$
$$+\gamma_{QG_H}Q^{0.5}G_H^{0.5}+\gamma_{tG_{WS}}t^{0.5}G_{WS}^{0.5}+\gamma_{QG_{WS}}Q^{0.5}G_{WS}^{0.5}$$
$$\left.+\gamma_{tG_O}t^{0.5}G_0^{0.5}+\gamma_{QG_O}Q^{0.5}G_O^{0.5}\right].$$

It is clear from (28) that inclusion of the extra infrastructure terms leads to a large increase in the number of parameters to be estimated due to the numerous cross-product terms. It is for this reason – to conserve degrees of freedom – that water and sewers structures were combined into a single capital stock measure.

3.3 The Optimal Capital Stock Equations

From (6) and (7) the optimal private and public capital stocks are obtained by differentiating the short-run cost function with respect to K and G, setting the negative values of the partial derivatives equal to P_K and P_G respectively and then solving simultaneously for K^* and G^*, the optimal quantities. Differentiating (25) with respect to K and G and setting the negative values of the partial derivatives equal to the marginal costs of the respective capital stocks:

$$-\frac{\partial C_V}{\partial K} = \frac{-0.5P_L\left(\delta_{LK}Q^{0.5} + \gamma_{tK}t^{0.5}Q^{0.5} + \gamma_{QK}Q + 2\gamma_{KK}K^{0.5} + \gamma_{GK}G^{0.5}\right)}{K^{0.5}} = P_K \text{, and} \tag{30}$$

$$-\frac{\partial C_V}{\partial G} = \frac{-0.5P_L\left(\delta_{LG}Q^{0.5} + \gamma_{tG}t^{0.5}Q^{0.5} + \gamma_{QG}Q + 2\gamma_{GG}G^{0.5} + \gamma_{GK}K^{0.5}\right)}{G^{0.5}} = P_G . \tag{31}$$

These expressions show that the shadow values of private capital and core infrastructure depend not just on the size of the capital stocks but are also dependent on the level of GDP and the price of labour. Solving (30) with respect to K gives

$$K = \left(\frac{-\frac{1}{2}P_L\left(\delta_{LK}Q^{1/2} + \gamma_{tK}t^{1/2}Q^{1/2} + \gamma_{QK}Q + \gamma_{GK}G^{1/2}\right)}{P_K + P_L\gamma_{KK}} \right)^2 . \tag{32}$$

Substituting (32) into (31) and solving for G generates the optimal infrastructure stock equation:

$$G^* = \left(-\frac{\delta_{LG}Q^{1/2} + \gamma_{tG}t^{1/2}Q^{1/2} + \gamma_{QG}Q - \frac{1}{2}P_L\gamma_{GK}\left(\frac{\delta_{LK}Q^{1/2} + \gamma_{tK}t^{1/2}Q^{1/2} + \gamma_{QK}Q + \gamma_{GK}G^{1/2}}{P_K + P_L\gamma_{KK}}\right)}{2\left(\frac{P_G}{P_L} + \gamma_{GG}\right)\left(1 - \frac{\gamma_{GK}^2}{4(P_G/P_L + \gamma_{GG})(P_K + P_L\gamma_{KK})}\right)} \right)^2 , \tag{33}$$

where G^* is the optimal quantity of public capital. In a similar fashion the equation for the optimal stock of private capital, K^*, is derived:

$$K^* = \left(-\frac{\delta_{LK}Q^{1/2} + \gamma_{tK}t^{1/2}Q^{1/2} + \gamma_{QK}Q - \frac{1}{2}P_L\gamma_{GK}\left(\dfrac{\delta_{LG}Q^{1/2} + \gamma_{tG}t^{1/2}Q^{1/2} + \gamma_{QG}Q + \gamma_{GK}K^{1/2}}{P_G + P_L\gamma_{GG}}\right)}{2\left(\dfrac{P_K}{P_L} + \gamma_{KK}\right)\left(1 - \dfrac{\gamma_{GK}^2}{4(P_K/P_L + \gamma_{KK})(P_G + P_L\gamma_{GG})}\right)} \right)^2 \quad (34)$$

Using equations (33) and (34) the optimal capital stocks can be calculated for each year of the sample period. The equations contain both parameters (estimates of which are obtained by estimating the system of equations (25) and (27)) and variables (the rental prices of the two types of capital, the price of labour and value-added output). Similarly, optimal capital equations can be calculated using the disaggregated infrastructure model. This time there are four partial derivatives similar to (30) and (31) that have to be solved simultaneously: one for private capital and three for public capital (roads, water and sewer systems, and other structures).

4. Construction of Private and Public Capital Inputs and Rental Price Measures

Before presenting the results from estimating the above systems of equations and calculating the optimal capital stocks, it is necessary to highlight several important issues concerning the construction of the aggregate measures of private and public capital and the formulation of capital rental prices.

4.1 Private and Public Capital Inputs

Both types of capital have to be aggregated by type and across sectors. For private capital the Bureau of Economic Analysis provides private capital data by type (equipment and structures) and by sector (manufacturing, mining, *etc.*). The obvious way of aggregating these stocks would be to perform a simple summation of the different types of capital. For example, the aggregate stock of private capital would be calculated by performing the following operation

$$\widetilde{K}_t = \sum_{i=1}^{n} K_{i,t} , \tag{35}$$

where $\widetilde{K}_t$ is the total stock of private capital in year t and $K_{i,t}$ is the total stock of capital (equipment and structures) in sector i. In a similar fashion the total stock of public capital could be calculated:

$$\widetilde{G}_t = \sum_{i=1}^{n} G_{i,t} , \tag{36}$$

where $\widetilde{G}_t$ is the total stock of public capital in year t and $G_{i,t}$ is the stock of capital of type i.[18] However, the problem with the simple aggregation method is that it overlooks the fact that some assets are more productive than others. If it is assumed that producers equate the marginal product of any type of capital to its marginal cost (or user cost), capital assets with high user costs are more productive in equilibrium than assets with low rental prices.

[18] Where each type of capital (roads, water and sewers *etc.*) is the sum of the federal and state and local capital stocks.

This important point has been emphasised by Jorgenson and Griliches (1967), who calculated an aggregate measure of private capital input for the U.S. by Divisia quantity aggregation. They call the ratio of this index to the unweighted sum of capital goods the average quality of capital. Quality rises if the stock of short-lived assets is growing faster than the stock of long-lived assets and falls if the amount of short-lived assets is growing at a slower rate than the amount of long-lived assets. This is because short-lived assets have higher depreciation rates than long-lived assets and hence higher user costs and thus higher marginal productivities.

Following Harper *et al* (1995), the Tornqvist discrete approximation to the continuous Divisia index was employed to calculate aggregate measures of capital input for both the private and public sectors. This index has a number of attractive properties. As has been shown by Diewert (1980), it can be viewed as an exact index corresponding to a second-order approximation in logarithms to an arbitrary production or cost function. In particular, the Tornqvist index places no prior restrictions on the substitution elasticities among the goods being aggregated. The index is defined in terms of the rates of growth of the different capital stocks. The change in aggregate capital input is a weighted sum of the changes in the individual capital stocks, where the weights are the arithmetic averages of the relative cost shares. For example, the index for private capital is[19]

$$\ln \widetilde{K}_t - \ln \widetilde{K}_{t-1} = \sum \bar{s}_{k,t}\left(\ln K_{k,t} - \ln K_{k,t-1}\right), \text{ where} \tag{37}$$

$$\bar{s}_{k,t} = \tfrac{1}{2} s_{k,t} + \tfrac{1}{2} s_{k,t-1}; \quad s_{k,t} = \frac{\left(P_{k,t} \cdot K_{k,t}\right)}{\left(\sum P_{k,t} \cdot K_{k,t}\right)},$$

[19] Note subscripts are now "k"s to denote further disaggregation, eg, manufacturing capital is now disaggregated into manufacturing equipment and manufacturing structures. Further disaggregation is not required with respect to G.

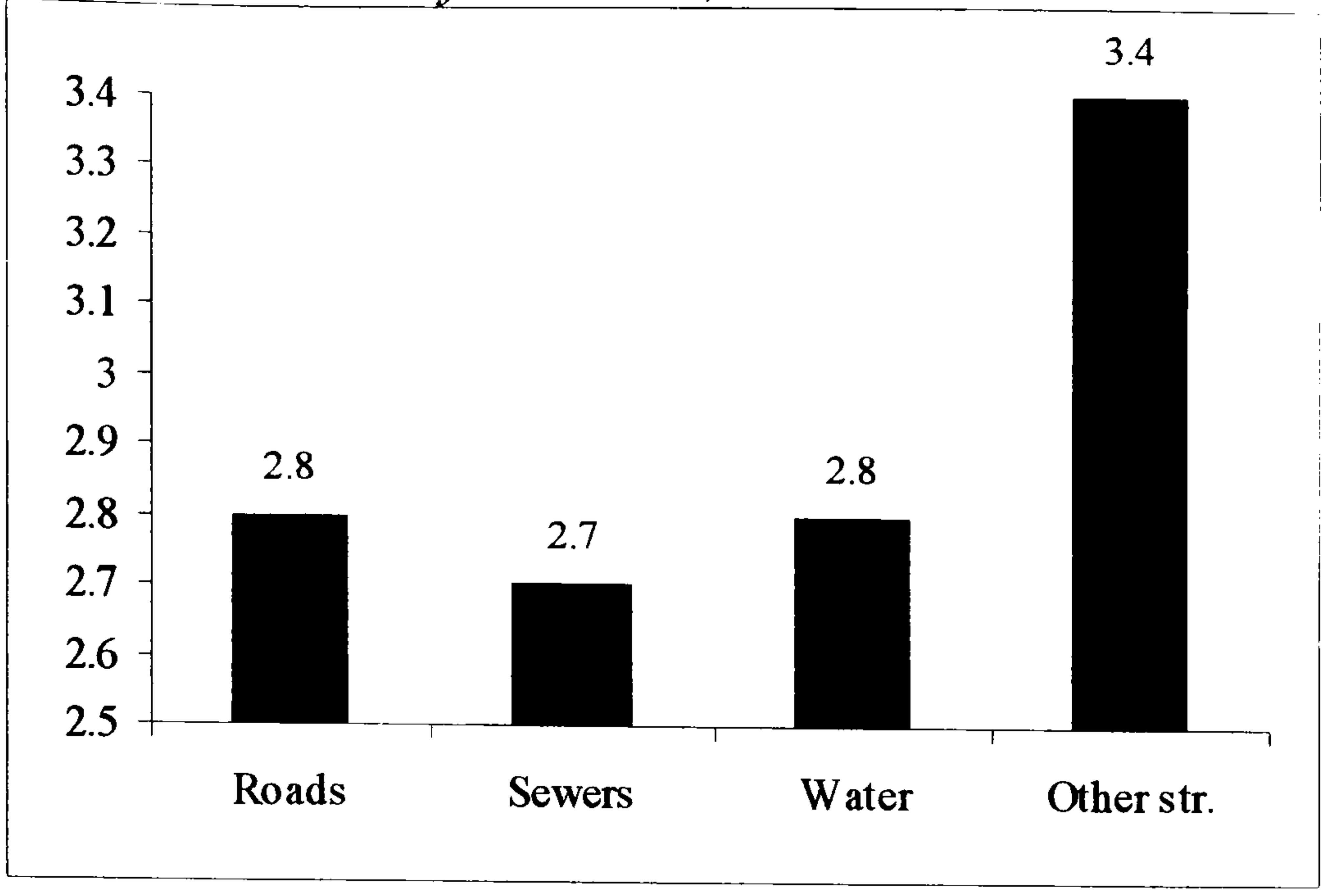
Table 1. *Sectors Contained in the Index of Private Capital*

Mining
Manufacturing:
Durable Goods
Nondurable Goods
Transportation & Public Utilities:
Railroad
Local and Interurban Passenger Transit
Trucking and Warehousing
Water Transportation
Transportation by Air
Pipelines except Natural Gas
Transportation Services
Communications
Electric, Gas and Sanitary Services
Wholesale Trade
Retail Trade
Finance, Insurance and Real Estate
Services

and $P_{k,t}$ is the *ex ante* rental price or user cost of equipment or structures capital in one of the sectors. It is clear that the higher the user cost of a particular capital stock, the greater the weight attached to that type of capital in the aggregate measure. The economic intuition behind this result is that, because equipment has a shorter life than buildings, a one dollar investment in equipment provides more services to a firm in any year than a dollar's investment in buildings. Thus equipment is given a greater weighting in the measure of $\widetilde{K}_t$. To obtain the quantity index itself (as opposed to its rate of growth) a base must be chosen for the index. In this study the base is made equal to the unweighted sum of the individual capital stocks in 1987. The aggregate rental price is found by dividing total capital cost by aggregate capital input. To construct the private capital index, net equipment and structures' stocks (measured in constant 1987 dollars) were obtained for each of the industries listed in Table 1. The index of core public capital was calculated in a similar fashion:

$\ln \widetilde{G}_t - \ln \widetilde{G}_{t-1} = \sum \bar{s}_{i,t}\left(\ln G_{i,t} - \ln G_{i,t-1}\right)$, where (38)

Figure 2. *Average Economic Depreciation Rates, Core Infrastructure, 1959-94.*



$$\bar{s}_{i,t} = \tfrac{1}{2}s_{i,t} + \tfrac{1}{2}s_{i,t-1}; \quad s_{i,t} = \frac{(P_{i,t} \cdot G_{i,t})}{\left(\sum P_{i,t} \cdot G_{i,t}\right)}.$$

For the second study, using disaggregated infrastructure data, an index of water and sewer systems structures was also obtained using (38). All the public capital stocks used in this chapter can be classified as structures so at first glance there is no need to perform Divisia aggregation.[20] However, the different structures depreciate at different rates. The length of life of a highway is bound to be different to the length of life of an electric facility which, in turn, is bound to be different to the length of life of a water pipeline. The fact that each type of structure depreciates at a different rate (and therefore has a different rental price) implies that the various infrastructure stocks should be given different weightings in the index of public capital. The average economic depreciation rates of the components of the core infrastructure stock are illustrated in Figure 2. The roads, sewers and water stocks have

[20] Of course, the public sector also owns a significant quantity of equipment (equipment accounted for 9.7 per cent of the non-military public capital stock in 1994). However, this capital (computers owned by the IRS *etc.*) does not have a direct effect upon private sector production (see Chapter 2).

Table 2. *Comparison of Different Private Capital Stock Aggregation Methods*

Time span	Growth Rates (1) Divisia aggregation	(2) Direct aggregation	Composition effect: (1)-(2)
1948-1984	3.4	2.6	0.8
1948-1973	3.6	2.6	1.0
1973-1981	3.4	2.8	0.6
1981-1984	2.3	2.1	0.2

Source: Bureau of Labour Statistics (1985), quoted in Harper *et al* (1995)

very similar average depreciation rates. The stock of other structures depreciated by over half a percentage point more per year than the other stocks. From these results one would expect some, but very little difference, between a measure of core public capital calculated using Divisia aggregation and one calculated from a straight summation of individual capital stocks. Divisia aggregation can, however, generate very different capital stock growth rates from the simple aggregation method. Harper *et al* (1995) calculate the difference between the growth rates of a rental price-weighted Divisia index for private capital and a simple aggregation private capital stock and refer to the difference as the *capital composition effect.* Since the Second World War this effect has been strongly positive in the U.S., due to the steady shift in the investment mix toward shorter-lived equipment assets and away from structures and land. As can be seen from Table 2, for the period 1948-1984 private capital input (using Divisia aggregation) grew by 3.4 per cent per year, while the capital stock (using direct aggregation) grew by only 2.6 per cent a year. Subtracting the one from the other, the composition effect of 0.8 per cent is obtained. According to Harper *et al* (1995), one underlying reason for the difference between the two measures is that equipment grew by 4.9 per cent per year while nonresidential structures grew by 2.8 per cent per year, inventories grew at 3.3 per cent and land at only 2.0 per cent. Because equipment is more productive than other capital, the index grew at a faster rate. The authors found that the importance of the capital composition effect has declined considerably over time; from 1948 to 1973 it averaged 1 per cent per year, while from 1973 to 1981 it fell slightly to 0.6 per cent per year, and over the most recent time period examined by the authors (1981-1984) it dropped to 0.2 per cent per year. The annual differences between the newly calculated indices of private and public capital and simple aggregation methods are compared in Table 12, Table 13 and Table 14 in Appendix B.

4.2 The Rental Prices of Private and Public Capital

The user cost or rental price of capital – the opportunity cost of owning an asset – is an important variable in the analysis and thus deserves special attention. The aim of this study is to compare *actual* capital stocks with *optimal* capital stocks (both private and public). From (33) and (34) it can be seen that the user costs of both types of capital appear in the optimal capital stock formulas.[21] Furthermore, the user cost of capital also plays an important role in the calculation of the indices of private and public capital. In fact, it is only this variable that distinguishes the Tornqvist indices from simple aggregation of capital in each sector. The user cost of capital derives from Jorgenson's (1963) model of investment behaviour. Two rental price measures were calculated for each type of capital: the first is a pre-tax measure, the second takes account of taxation effects.

[21] Similarly, when public capital is completely disaggregated, the rental prices for each type of capital appear in each of the optimal capital formulas.

4.2.1 The Rental Price of Private Capital

As far as private firms are concerned if the user cost of capital is relatively high, *ceteris paribus*, a less capital-intensive technology will be chosen, and vice-versa. In its simplest form the rental price of private capital, K, of type k is

$$P_{K,k} = q_k(r + \delta_k), \tag{39}$$

where q_k is the physical capital deflator obtained by dividing the current dollar capital stock by the constant dollar capital stock, reflecting inflation in investment prices, r is the discount rate represented by Moody's Aaa rate,[22] and δ_k is the rate of economic depreciation. If a firm purchases an asset for q_k dollars, the cost to the firm in any time period is the interest paid on the loan to purchase the asset (alternatively, the return the firm could have earned from lending q_k dollars) plus the depreciation on the asset. In the neoclassical model, firms desire to invest up to the point where the marginal return to capital assets just equals the opportunity cost of owning them. The pre-tax measure of private capital for the aggregate private business sector is derived from (37) and inserted into the optimal capital stock equations (33) and (34). Some infrastructure studies (eg, Berndt and Hansson, 1992; and Seitz, 1994) use only a pre-tax measure of private capital.[23] While this measure was used to calculate one set of optimal capital stocks for comparative purposes, it is not the most accurate measure of the cost of capital to private business. The fact that U.S. firms have in the past been able to claim investment tax credits and depreciation of their capital, has reduced the user cost of capital and increased the desired quantity of private capital. Similarly, the fact that

[22] Moody's Aaa rate probably reflects the private sector's cost of borrowing better than, for example, the rate on ten-year Treasuries (used by Nadiri and Mamuneas, 1994). On average Moody's Aaa rate is 9.1 per cent higher than the rate on Treasuries over the sample period.

[23] Berndt and Hansson (1992) did not include corporate taxes in their private rental price measure under the assumption that, in many cases, assuming the marginal corporate tax rate in Sweden is zero is reasonable.

corporate income tax reduces firms' earnings increases the cost of capital. Incorporating various elements of the U.S. corporate tax system into the analysis (investment tax credits, capital consumption allowances, and corporate income tax) leads overall to an increase in the user cost of private capital. The after-tax price of capital is on average 32 per cent higher than the pre-tax measure.

The rise in the price of private capital should lead to a fall in the optimal private capital stock. The reason for this can be found by referring back to (6). The private business sector equates the marginal benefit of increased investment with the cost of extra capital. If the marginal cost of capital rises in the presence of corporate tax provisions, marginal cost will be higher than marginal benefit in the short run. Firms stop investing, the capital stock declines due to depreciation, until costs and benefits are equated once again. Following Jorgenson and Sullivan (1981), the after-tax price of capital is defined as

$$P_{K,k} = q_k(r+\delta_k)\left(\frac{1-\iota-uz}{1-u}\right), \tag{40}$$

where ι is the investment tax credit, u is the corporate income tax rate and z is the present value of capital consumption allowances, defined as

$$z = \rho(1-\iota)/(r+\rho), \tag{41}$$

where ρ is the capital consumption allowance rate obtained by dividing capital consumption allowances by the total capital stock (see Bernstein and Nadiri, 1987, 1988, and 1991). Annual measures of the rental price of private capital are contained in Table 15 in Appendix C. The presence of $(1-u)$ in the denominator takes account of the fact that the corporation tax leaves the firm only $(1-u)$ of each dollar earned, in effect increasing the cost of capital by the reciprocal of that amount, $1/(1-u)$.[24]

Several authors make adjustments to the rental price to take account of the corporate tax system (eg, Nadiri and Mamuneas, 1994).[25] Since industry-specific tax data was not used, incorporating the corporate tax system into the rental price measure does not affect the calculation of the aggregate private capital input in (37). However, from (33) and (34) it is clear that including an after-tax measure of private capital affects the size of the optimal private and public capital stocks.

4.2.2 The Rental Price of Public Capital

Deriving the rental price of public capital is somewhat more controversial. Because individual firms do not directly pay for many of the infrastructure services they use (for example, the use of most highways and streets), it could be argued that the user cost of public capital is zero. Of course, firms pay a share of the cost of additional public infrastructure in taxes, suggesting that P_G is not zero. However, for many authors in the infrastructure literature the relationship between spending on G and the taxes firms

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[24] The presence of $(1 - u)$ in the denominator can be explained in a more rigorous fashion. Assuming competitive equilibrium and the absence of taxes, total revenue equals total costs, ie, $P_Q Q = P_K K + P_L L$. Introducing a corporate tax at rate u and assuming that the opportunity cost of capital is not deductible but wage costs are deductible, the firm's tax liability is $u(P_Q Q - P_L L)$. The zero profits condition becomes: $P_Q Q = P_K K + P_L L + u(P_Q Q - P_L L)$. Rearranging this equation yields $P_Q Q = [P_K /(1 - u)]K + P_L L$. Comparing this to the equilibrium condition without taxes, it can be seen that the effective cost of capital has risen from P_K to $P_K/(1-u)$.

[25] Contrary to the literature on the construction of rental price measures, the tax adjustment used by Nadiri and Mamuneas (1994) does not include the term $(1-u)$ in the denominator, resulting in a tax-adjusted measure which is *lower* than the pre-tax measure. The after-tax measures calculated by Nadiri and Mamuneas and those calculated in this study differ substantially in relative magnitude (by a factor of at least 50 per cent in most years). As a result there is a significant difference between optimal capital stocks calculated using the rental price of Nadiri and Mamuneas and the rental prices calculated in this chapter. There are other adjustments that can be made to the rental price measure. For example, Lynde and Richmond (1992) included the term Δq_k to reflect the change in the price of capital goods and Hall (1990) argues in favour of including the dividend yield on a portfolio of stocks such as the S & P 500 index as a proxy for the discount rate.

pay is sufficiently indirect for P_G to be left equal to zero. Of course, policymakers formulating public spending plans are not just interested in the cost of public capital to firms. They, it could be argued, are interested in investing in infrastructure up to the point where the cost savings enjoyed by private business equal the cost to the nation as a whole of providing the additional capital. Thus, whereas each firm equates the marginal cost of *private* capital and the marginal benefit of that capital, policymakers equate the marginal cost of *public* capital to society and the marginal benefits enjoyed by firms.[26] Following Berndt and Hansson (1992), the formula for the aggregate rental price of public capital is

$$P_G = q_G(r + \delta_G), \tag{42}$$

where q_G is the physical capital deflator for core infrastructure, r is the discount rate and δ_G is the economic depreciation rate for core infrastructure. Estimates of (42) are obtained from (38). A further three user cost measures are used to study the effects of disaggregated infrastructure capital:

$$\begin{aligned} &P_H = q_H(r + \delta_H), \\ &P_{WS} = q_{WS}(r + \delta_{WS}), \text{ and} \\ &P_O = q_O(r + \delta_O), \end{aligned} \tag{43}$$

where H denotes highways and streets, WS denotes water and sewer systems, and O denotes other structures. The discount rate, r, was approximated by the rate on ten-

[26] Of course, the public sector is also interested in the benefits consumers derive from infrastructure capital, ignored for the purposes of this analysis.

year Treasury Bills.[27] Of course, the public sector's investment decisions are not directly influenced by investment tax provisions. Nevertheless the *incidence* of taxation may still affect the user cost of public capital. The concept of excess burden should play an important role in any study of whether the benefits of infrastructure investment exceed the costs of raising tax revenue to finance it. The measures P_G, P_H, P_{WS}, and P_O do not account for the wedge that taxes insert between the demand and supply prices of privately produced goods. These tax wedges distort private decisions and lead to losses in efficiency. According to Jorgenson and Yun (1991) the excess burden imposed on the U.S. economy is very large. The authors estimate the marginal excess burden of the U.S. tax system (the efficiency loss per dollar for the last dollar of revenue raised) to be \$0.39. Ballard *et al.* (1985) also found that the marginal excess burden of taxes in the United States is large. The welfare loss from a one per cent increase in distortionary tax rates was estimated to be in the range of \$0.17 – \$0.56 per dollar of extra revenue. This leads the authors to conclude that:

> "A public project must produce marginal benefits of more than \$1.17 per dollar of cost if it is to be welfare improving. This suggests that many projects accepted by government agencies in recent years on the basis of cost benefit ratios exceeding unity might have been rejected if the additional effects of distortionary taxes had been take into account." (p. 128)

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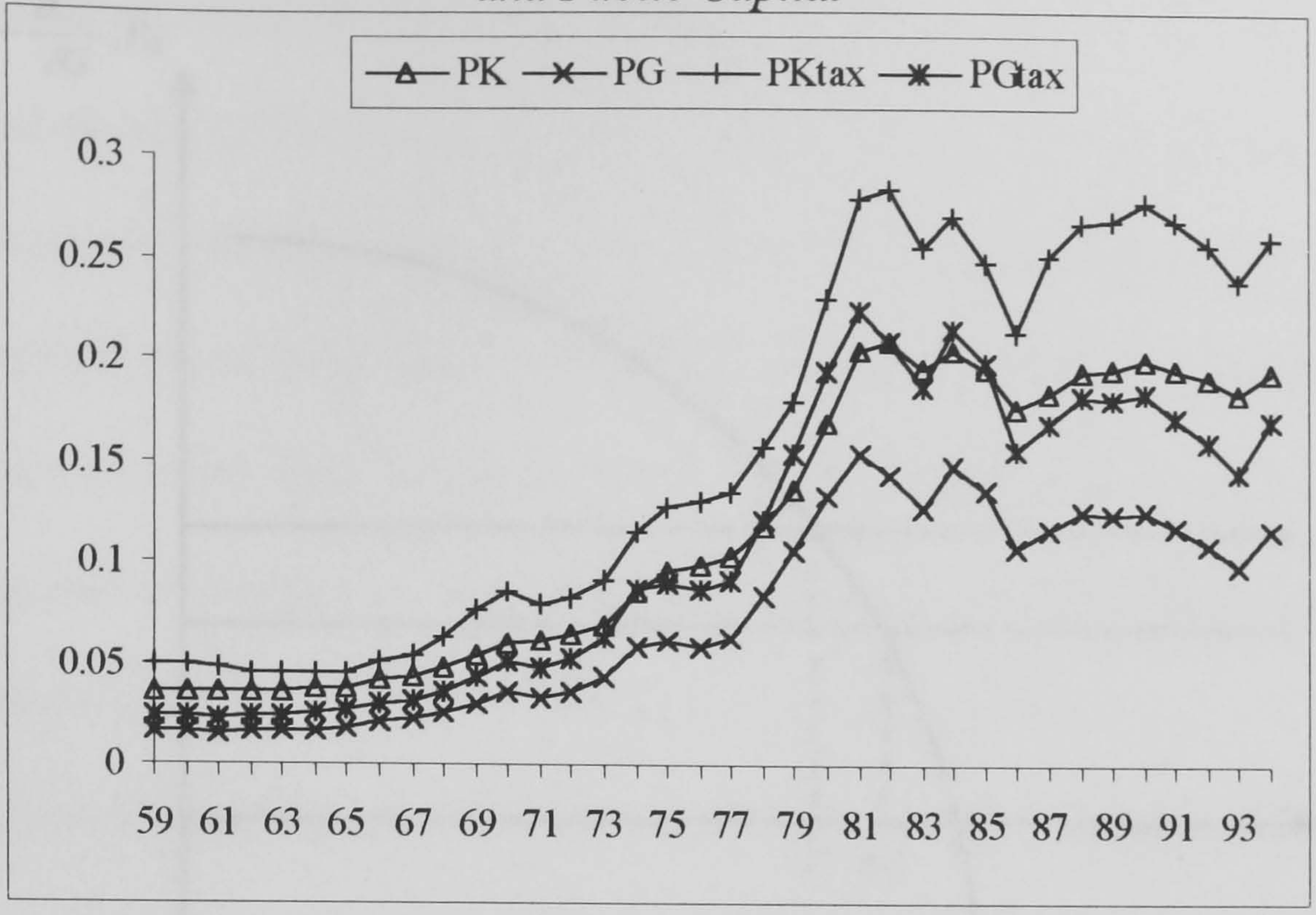
[27] Although such a market rate of interest is easily observed, it is questionable whether it is the appropriate discount factor for public investment decisions. Arrow and Kurz (1970) point out that if it is accepted that the public sector has an obligation to future generations, the social rate of time preference may be below the common value of the opportunity cost of capital and the individual rate of time preference. It is then socially advantageous to transfer resources for consumption to social investment because of the divergence between social and individual time preferences. The appropriate rate of discount on future benefits from social investment will be an average of the social rate of time preference and the opportunity cost of capital, with weights dependent on the extent to which resources are drawn from consumption to investment.

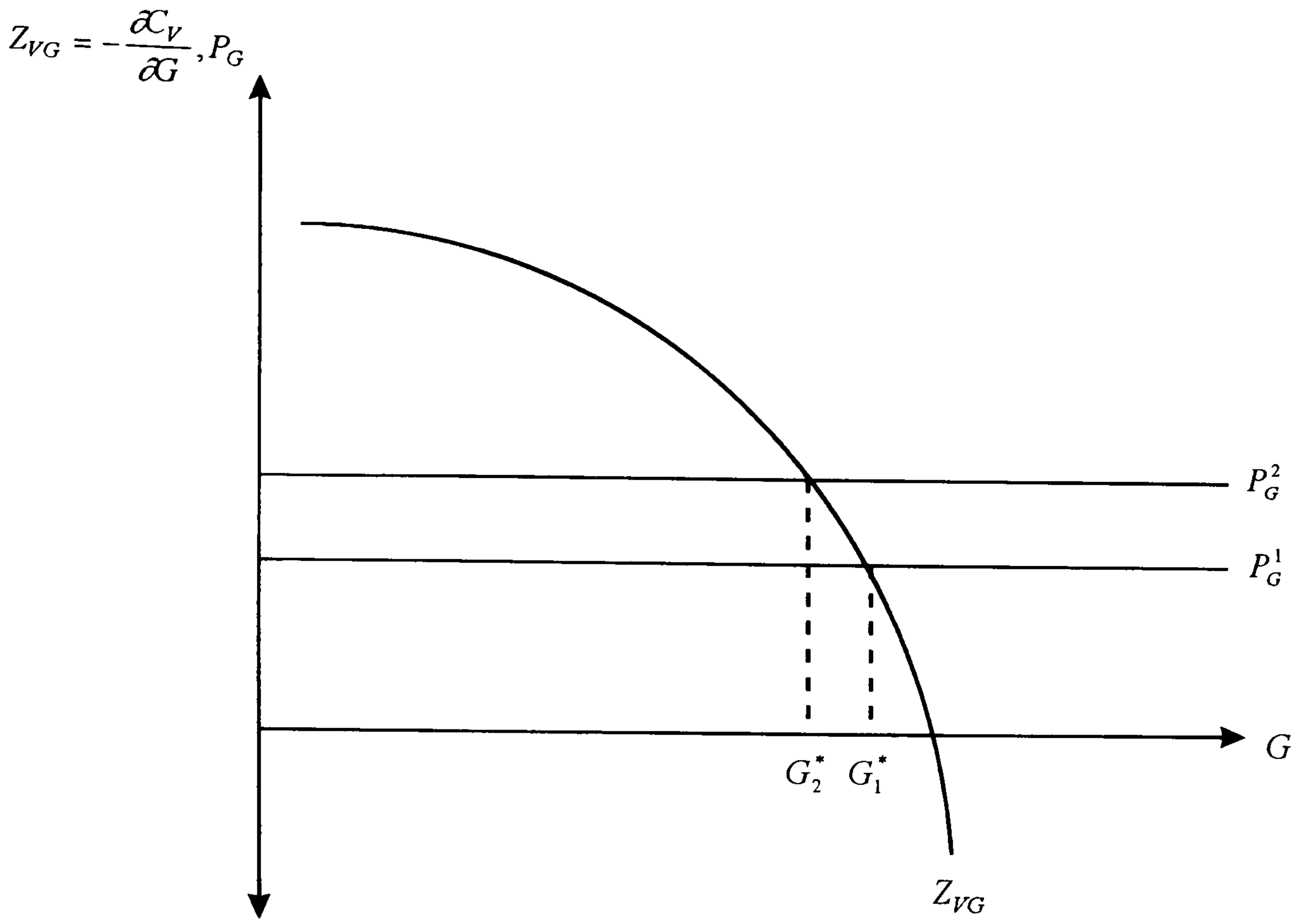
Figure 3. *Pre-tax and Tax-adjusted Rental Prices of Private and Public Capital*



Note: PK and PG are pre-tax prices; PKtax and PGtax are tax-adjusted prices.

The after-tax prices of public capital were adjusted in accordance with Jorgenson's and Yun's estimate of the marginal cost of public funds. Estimates of the rental prices of the different types of public capital are contained in Table 15 Appendix C. Figure 3 illustrates the different aggregate rental prices graphically. The fact that $P_G < P_K$ can be explained by the fact that the public sector's borrowing costs are less than those of the private sector and, more importantly, because most of the core infrastructure stock consists of long-lived structures that have low depreciation rates. The excess burden of taxation and the taxation of profits raise the respective prices of public and private capital. The effect of adjusting the price of public capital in this way is illustrated in Figure 4. An increase in the price of public capital from P_G^1 to P_G^2 leads to a fall in the optimal infrastructure stock from G_1^* to G_2^*. The magnitude of the fall depends not only on the size of the excess burden but also on the shape of the cost function from which the shadow value curve is derived. The greater the slope of

Figure 4. *The Effect of Excess Burden on the Optimal Stock of Infrastructure*



the curve, the greater the error in estimating G^* if the rental price of public capital is calculated incorrectly.

4.2.3 Economic Depreciation Rates

There are also a number of points worth making about economic depreciation rates, which are important components of the rental price measures. Following Berndt and Hansson (1992), economic depreciation rates were initially taken from Hulten and Wykoff (1981). Hulten and Wykoff show how depreciation can be estimated using an approach that relies on market price data. The change in an asset price over time has two components, one due to depreciation and one due to inflation. The most significant finding of their research is the approximately geometric form of the age-price profiles for assets.[28] This implies that each class of assets can be characterised by a single constant rate of depreciation. However, the depreciation rates calculated by Hulten and Wykoff (1981) are *asset* specific, not *sector* specific. For example, instead of calculating the individual economic depreciation rates for equipment and structures in the wholesale trade, retail trade, and finance, insurance and real estate trade, Berndt and Hansson (1992) used the Hulten and Wykoff depreciation rate for "office, computing and accounting" equipment for all three sectors and the Hulten and Wykoff depreciation rate for "commercial structures" for all three sectors.

Morrison and Schwartz (1997) assume that the private and public capital depreciation rates, δ_K and δ_G respectively, are identical. However, comparisons of the service lives of private and public assets in recent research by Katz and Herman (1997) reveal significant differences between δ_K and δ_G. Highways and streets, water systems, sewer systems and other structures have an average service life of 60 years; private equipment assets have an average service life of 14 years; private structures have an average service life of 36 years. Thus the assumption that $\delta_K = \delta_G$ biases upwards the estimate of P_G, leading to inaccurate estimation of G^*.

Using Bureau of Economic Analysis (BEA) data, private capital depreciation rates were calculated for each sector's equipment and structures stock using the formula:

$$\delta_{k,t} = \frac{D_{k,t}}{K_{k,t-1}}, \tag{44}$$

where $D_{k,t}$ is the economic depreciation of the kth capital good in year t, measured in

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[28] See Katz and Herman (1997) for a discussion of recent adjustments to the BEA's method of calculating economic depreciation. The authors also find that depreciation takes on a geometric pattern.

1987 dollars (see Hulten and Wykoff, 1981). The same formula was used to compute the economic depreciation rates of the different types of public capital. The average depreciation rates for the period 1959-94 are listed in Table 16 in Appendix D. The BEA depreciation rates are also compared with the Hulten and Wykoff rates (Table 17) used by Berndt and Hansson (1992). It is clear that there are significant differences between the two sets of measures.

In summary, considerable attention was paid to the construction of the rental prices of private and public capital because these measures are important for calculating aggregate capital inputs and, more importantly, the optimal capital stocks. Taken together, the wrong choice of interest rate, economic depreciation rate and tax adjustment could be sufficient to produce the result that there is, for example, a substantial shortage of capital when in fact the stock is close to optimal or in surplus.

5. The Estimation Procedure

Before the results from estimating the various models are presented, some comments about the estimation procedure are necessary. Equation by equation OLS is possible because the estimating equations (25), (27),(28) and (29) are linear in the parameters. However, it is also possible that the disturbances across the cost and labour input-output equations are contemporaneously correlated, implying that the disturbance covariance matrix is nondiagonal. In that case, it is best to estimate the equations as a system (for example, using Zellner's SUR estimator).[29] Estimating the cost and labour

[29] See Lynde and Richmond (1992) for a comparison of the two estimation procedures.

equations by OLS assumes the following specification for the error vectors of the two equations

$$e = \begin{bmatrix} e_C \\ e_L \end{bmatrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, E\begin{pmatrix} e_C e_C' & e_C e_L' \\ e_L e_C' & e_L e_L' \end{pmatrix} = \begin{pmatrix} \sigma_C^2 & 0 \\ 0 & \sigma_L^2 \end{pmatrix}\right], \tag{45}$$

where the errors of the cost equation [(25) or (28)], e_C, and the errors of the labour input-output equation [(27) or (29)], e_L, are uncorrelated and thus the off-diagonal blocks of the covariance matrix are zero. To take account of the fact that the errors for the two equations may be contemporaneously correlated, consider the off-diagonal block $E[e_C e_L']$, which can be expressed as

$$E[e_C e_L'] = E\begin{bmatrix} e_{C1}e_{L1} & e_{C1}e_{L2} & \cdots & e_{C1}e_{Ln} \\ e_{C2}e_{L1} & e_{C2}e_{L2} & \cdots & e_{C2}e_{Ln} \\ \vdots & \vdots & \ddots & \vdots \\ e_{Cn}e_{L1} & e_{Cn}e_{L2} & \cdots & e_{Cn}e_{Ln} \end{bmatrix} = \begin{bmatrix} \sigma_{CL} & 0 & \cdots & 0 \\ 0 & \sigma_{CL} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_{CL} \end{bmatrix} = \sigma_{CL} I_n, \tag{46}$$

where the elements on the diagonal are contemporaneous covariances, denoted σ_{CL} and the off-diagonal elements are covariances between the equations' errors in different time periods (taken to be zero). The joint error vector (45) can be re-specified as

$$e = \begin{bmatrix} e_C \\ e_L \end{bmatrix} \sim N\left[\begin{pmatrix} 0 \\ 0 \end{pmatrix}, E\begin{pmatrix} \sigma_C^2 I_n & \sigma_{CL} I_n \\ \sigma_{LC} I_n & \sigma_L^2 I_n \end{pmatrix} = W\right]. \tag{47}$$

A test for contemporaneous error covariance is based on the following Lagrange Multiplier test statistic (Breusch and Pagan, 1980):[30]

$$\chi_{LM} = nr^2, \tag{48}$$

[30] See Lynde and Richmond (1992) for an application of this test.

Table 3. *Lagrange Multiplier Tests for Contemporaneous Error Covariance*

	$\chi_{LM} = nr^2$
Aggregate Infrastructure Model	23.15***
Disaggregated Infrastructure Model	27.05***

*** Rejection of null hypothesis of zero contemporaneous correlation at the 1 per cent level at least.

where r^2 is the squared correlation coefficient between the OLS residuals of the two equations. Asymptotically, χ_{LM} is distributed as a $\chi^2(1)$ random variable. Table 3 contains the test statistics for each of the models. In each case the hypothesis of zero contemporaneous covariance is rejected. This implies that SUR estimation is not equivalent to OLS applied separately to the two equations. Because each equation contains the same coefficient vector the model to be estimated can be written in the form

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{C} \\ \boldsymbol{L} \end{bmatrix} = \begin{bmatrix} \boldsymbol{X}_C \\ \boldsymbol{X}_L \end{bmatrix} \gamma + \begin{bmatrix} \boldsymbol{e}_C \\ \boldsymbol{e}_L \end{bmatrix} = \boldsymbol{Z}\gamma + \boldsymbol{e}, \tag{49}$$

where $\boldsymbol{C}$ and $\boldsymbol{L}$ are vectors of dependent variables, the Xs are matrices of regressors and γ is the common parameter vector of the two equations. Using (47) and (49), the following generalised least squares estimator is obtained:

$$\hat{\gamma} = \left[\boldsymbol{Z}'\hat{\boldsymbol{W}}^{-1}\boldsymbol{Z}\right]^{-1}\boldsymbol{Z}'\hat{\boldsymbol{W}}^{-1}\boldsymbol{y}, \text{ where}$$

$$\boldsymbol{Z} = \begin{bmatrix} \boldsymbol{X}_C \\ \boldsymbol{X}_L \end{bmatrix}. \tag{50}$$

An estimate of $\boldsymbol{W}$ is obtained using

$$\hat{\boldsymbol{W}} = \begin{bmatrix} \hat{\sigma}_C^2 \boldsymbol{I}_n & \hat{\sigma}_{CL}^2 \boldsymbol{I}_n \\ \hat{\sigma}_{LC}^2 \boldsymbol{I}_n & \hat{\sigma}_{LL}^2 \boldsymbol{I}_n \end{bmatrix} = \frac{1}{36}\begin{bmatrix} \hat{\boldsymbol{e}}_C'\hat{\boldsymbol{e}}_C \boldsymbol{I}_{36} & \hat{\boldsymbol{e}}_C'\hat{\boldsymbol{e}}_L \boldsymbol{I}_{36} \\ \hat{\boldsymbol{e}}_L'\hat{\boldsymbol{e}}_C \boldsymbol{I}_{36} & \hat{\boldsymbol{e}}_L'\hat{\boldsymbol{e}}_L \boldsymbol{I}_{36} \end{bmatrix}, \tag{51}$$

where use is made of the least squares residuals $\hat{e}_C$ and $\hat{e}_L$ obtained from individually estimating the cost and labour equations and there are 36 observations in the sample. In summary, the SUR technique uses equation-by-equation OLS to obtain an estimate of the disturbance covariance matrix $\boldsymbol{W}$ and then does generalised least squares, given this initial estimate of $\boldsymbol{W}$. The estimates of $\boldsymbol{W}$ can be updated and the SUR procedure can be iterated until changes from one iteration to the next in the estimated parameters and the estimated $\boldsymbol{W}$ become arbitrarily small. Estimating the model as a system adds structure to it and leads to more efficient estimates. The additional structure and robustness, as well as the increased efficiency of the estimates (lower standard errors), support the systems estimation procedure.

6. Empirical Results – Aggregate Infrastructure Model

In Section 6.1 the results from estimating the aggregate infrastructure model [(25) and (27)] and performing a number of hypothesis tests are presented and discussed. In Section 6.2 the optimal infrastructure stock is calculated (under a number of scenarios regarding the tax treatment of factor prices).

6.1. Estimation Results

Results from estimating (25) and (27) by SUR are contained in Table 4. Two versions of the model were estimated: one using an after-tax measure of the price of labour (following Nadiri and Mamuneas, 1994), and the other using the wage rate with no tax adjustment (Morrison and Schwartz, 1997; Berndt and Hansson, 1992; and Seitz, 1994). Following Seitz (1994), no a priori restrictions were imposed on the parameters of the cost function. However, a Wald test of the restriction $\delta_{LQ} = \gamma_{tQ} = \gamma_{QQ} = \gamma_{QK} = \gamma_{QG} = 0$ strongly rejects against the assumption of constant returns to scale. Other restrictions to the model to test the appropriateness of the specification are also rejected. These include constraints on the "t" parameters and the fixed effects (both independently and grouped). Of most interest is the test to determine whether the public capital variables belong in the model. The model which includes infrastructure variables was tested against the model that incorporates the restriction: $\delta_{LG} = \gamma_{tG} = \gamma_{QG} = \gamma_{GG} = \gamma_{GK} = 0$. The Wald statistic that results from this test, W_G, is reported in Table 4. Clearly, the test rejects strongly in favour of including the infrastructure terms. Thus, as other cost function studies have found, infrastructure seems to have a significant effect on private sector costs. However, it is only when the reductions in business costs are weighed against the cost of additional infrastructure capital that it can be determined whether the core public capital stock is suboptimal or not.

Given the complexity of the functional form, the estimated parameters have no economic interpretation. As can be seen from (25) and (27) all the regressors are multiplicative combinations of two to four variables. Nevertheless, the adequacy of the model can be tested in the usual way. Most of the coefficients are statistically significant at the 1 per cent level at least. The high values for $\overline{R}^2$ show that the model fits the data very well but are not unusual in cost function models (Lynde and Richmond, 1992, and Nadiri and Mamuneas, 1994 report similar values for $\overline{R}^2$). The Durbin-Watson statistics lie in the inconclusive region so the Breusch-Godfrey Lagrange Multiplier test was conducted as an alternative. Test statistics of 0.45 and 0.06 respectively mean that the null hypothesis of

Table 4. *Estimation Results: Aggregate Infrastructure Model, 1959-94*

Parameter		Model 1 After-tax Wages	Model 2 Pre-tax Wages
α_{LL}		-10.40***	-10.37***
		(5.03)	(4.99)
δ_{Lt}		-0.7864***	-0.7942***
		(3.38)	(3.41)
δ_{LQ}		0.0065***	0.0065***
		(5.08)	(5.06)
γ_{tQ}		0.0003***	0.0003***
		(4.01)	(4.04)
γ_{tt}		-0.0174***	-0.0177***
		(2.86)	(2.92)
γ_{QQ}		-0.1113E-05***	-0.1112E-05***
		(5.49)	(5.46)
δ_{LK}		-2.32*	-2.22*
		(1.78)	(1.71)
δ_{LG}		27.97***	27.73***
		(6.11)	(6.03)
γ_{tK}		-0.1333	-0.1247
		(1.38)	(1.29)
γ_{QK}		0.0010**	0.0010***
		(2.48)	(2.41)
γ_{tG}		1.08***	1.08***
		(4.47)	(4.43)
γ_{QG}		-0.0090***	-0.0090***
		(6.19)	(6.12)
γ_{KK}		-0.1679	-0.1973
		(0.48)	(0.57)
γ_{GG}		-18.33***	-18.15***
		(7.28)	(7.19)
γ_{GK}		2.85***	2.81***
		(3.02)	(2.98)
Diagnostic Tests			
$\bar{R}^2$	C	0.999	0.999
	L/Q	0.998	0.998
DW	C	1.73	1.72
	L/Q	2.23	2.21
$LM\sim\chi^2(1)$	C	0.45	1.37
	L/Q	0.06	0.06
$JB\sim\chi^2(2)$	C	0.15	4.52
	L/Q	0.20	0.20
$W_G\sim\chi^2(5)$		267.79	261.74

Note: LM = Lagrange Multiplier test for first order serial correlation; JB = Jarque-Bera normality test statistic; W_G = Wald test statistic on infrastructure coefficients; t-stats in parentheses and are computed using White robust heteroskedastic-consistent standard errors.

*** Significant at the 1 % level at least.

** Significant at the 5 % level at least.

* Significant at the 10 % level at least.

serial independence cannot be rejected for either equation. The Jarque-Bera normality test also concludes that the errors of the two equations are normally distributed.

Lynde and Richmond (1993a,b) point out that many economic time series are non-stationary and that ordinary statistical inference techniques are rendered invalid if applied to such data. Following Vijverberg *et al.* (1997), to address concerns of possible spurious regression results the residuals of the two equations in each of the models were tested for the presence of unit roots. In each case application of the augmented Dickey-Fuller (ADF) test leads to rejection of the null hypothesis of a unit root. For example, for the cost equation in Model 1 the ADF test statistic of -5.69 exceeds the MacKinnon (1991) critical value of -4.25 leading to rejection of the null hypothesis of a unit root at the 1 per cent level. The ADF test statistic for the labour input-output equation is -5.90. The parameter estimates obtained using the wage rate without any tax adjustment are almost identical to those obtained using the after-tax price of labour. However, this does not mean that the optimal capital stocks calculated using the two sets of parameters will be of a similar magnitude. Because the wage rate itself appears in the optimal public and private capital stock equations, different measures of the wage rate may have a substantial effect on the size of the optimal capital stocks. It will be shown below that whether P_L is adjusted for tax purposes determines in certain years whether some types of capital are oversupplied or in shortage.

The question of endogeneity is an issue of some concern in the infrastructure literature.[31] For example, it may be argued that the private business sector is large enough that output should be considered endogenous. To address the problem of

[31] See Morrison and Schwartz (1997), p. 1102, and Vijverberg *et al.* (1997), p. 270.

possible simultaneity bias, the two cost function models were re-estimated for comparative purposes with Q instrumented using real military spending, the world oil price and the political party of the President.[32] There was very little difference in the magnitude and significance of the resulting parameter estimates.

6.2 The Optimal Infrastructure Stock

Like Berndt and Hansson (1992), the main reason for estimating the model is to obtain parameter estimates that can be inserted into the optimal infrastructure stock equation, (33), along with data on the price of labour, the user costs of private and public capital and private business output. Once the optimal infrastructure stock is estimated it can be determined whether there was a surplus or shortage of this type of capital over the sample period. It is also possible, using optimal capital stocks, to estimate the output elasticities of public and private capital, ε_{QG^*} and ε_{QK^*}. Using (21) and (22) the elasticities were calculated at each sample point by replacing the term λ (the marginal cost of output) with the observable output price, P_Q, obtained by dividing GDP expressed in current prices by GDP expressed in constant prices. The estimates are reported in Table 5. It is worth commenting on both the relative and absolute magnitude of infrastructure's output elasticity. The average value of 0.04 implies that a 1 per cent increase in the stock of core public capital (if optimally provided) leads to a 0.04 per cent increase in business sector output. This estimate is at the very low end of those reported in the literature review in Chapter 1. Those researchers who regarded Aschauer's (1989) and Munnell's (1990a) estimates of

[32] See Chapter 4 for a more complete discussion of these instruments.

Table 5. *Output Elasticities: Infrastructure and Private Capital*

	ε_{QG^*}	ε_{QK^*}		ε_{QG^*}	ε_{QK^*}
1959	0.024	0.208	1977	0.046	0.341
1960	0.024	0.216	1978	0.055	0.360
1961	0.024	0.220	1979	0.063	0.376
1962	0.025	0.208	1980	0.074	0.439
1963	0.026	0.210	1981	0.078	0.474
1964	0.026	0.212	1982	0.072	0.474
1965	0.026	0.212	1983	0.060	0.419
1966	0.029	0.229	1984	0.063	0.415
1967	0.030	0.241	1985	0.055	0.374
1968	0.032	0.264	1986	0.042	0.321
1969	0.037	0.300	1987	0.043	0.359
1970	0.043	0.328	1988	0.043	0.364
1971	0.039	0.301	1989	0.040	0.350
1972	0.038	0.299	1990	0.039	0.349
1973	0.042	0.310	1991	0.037	0.335
1974	0.055	0.356	1992	0.033	0.315
1975	0.054	0.364	1993	0.028	0.289
1976	0.047	0.352	1994	0.031	0.302
			Average	**0.042**	**0.319**

ε_{QG^*} is the output elasticity of core G (optimally provided); ε_{QK^*} is the elasticity for K.

the output elasticity of public capital to be too high (0.39 and 0.34 respectively), including Munnell herself, were more convinced by estimates from regional production function studies which revealed a much smaller role for public capital (eg, Munnell, 1990b; Eisner, 1991; and McGuire, 1992). An output elasticity of 0.15-0.20 was considered to be far more realistic. However, the above estimates imply that infrastructure's impact can be halved and then halved again. It is also interesting to compare the output elasticities of the two types of capital when optimally provided. The average estimate of 0.32 for private capital is of a reasonable magnitude. However, it is almost 8 times higher than the estimate for public capital. This compares with certain production function studies (eg, Berndt and Hansson's (1992) application of Munnell's (1990a) specification to Swedish data) in which public capital was found to have an output elasticity as high as or higher than that of private capital.

Dividing the optimal infrastructure stock, G^*, by the actual stock, G, it is possible to determine the extent of any surplus or shortage in any particular year.[33] Numbers greater than one imply that the actual capital stock is smaller than the optimal capital stock and that there is therefore an infrastructure shortage. Numbers less than unity signify an infrastructure surplus. Note that four different ratios are calculated. The first two are obtained using the tax-adjusted wage rate (Nadiri and Mamuneas, 1994) and the parameter estimates from Model 1 in Table 4. The first of these uses before-tax measures of private and public capital (Berndt and Hansson, 1992; Lynde and Richmond, 1992; Seitz, 1994). The second adjusts the user cost of private capital to take account of corporate tax provisions (Morrison and Schwartz, 1997; Nadiri and Mamuneas, 1994) and the cost of public capital to take account of the excess burden of taxation (Morrison and Schwartz, 1997). The second pair of ratios was obtained using the pre-tax wage rate (Morrison and Schwartz, 1997; Seitz, 1994; Lynde and Richmond, 1992; Berndt and Hansson, 1992) and the parameter estimates from Model 2. The results are best illustrated graphically. All four sets of ratios have the same *pattern* over time so, before examining the effect of adjusting input prices on the *level* of the ratios, it is interesting to examine this pattern using just one of the measures. Arguably, the most accurate set of ratios is that derived using all input prices (labour and both types of capital) adjusted for tax purposes. These ratios reflect most closely the firm's cost of labour and capital and the opportunity cost of new infrastructure. The ratios calculated with these adjustments are illustrated graphically in Figure 5.

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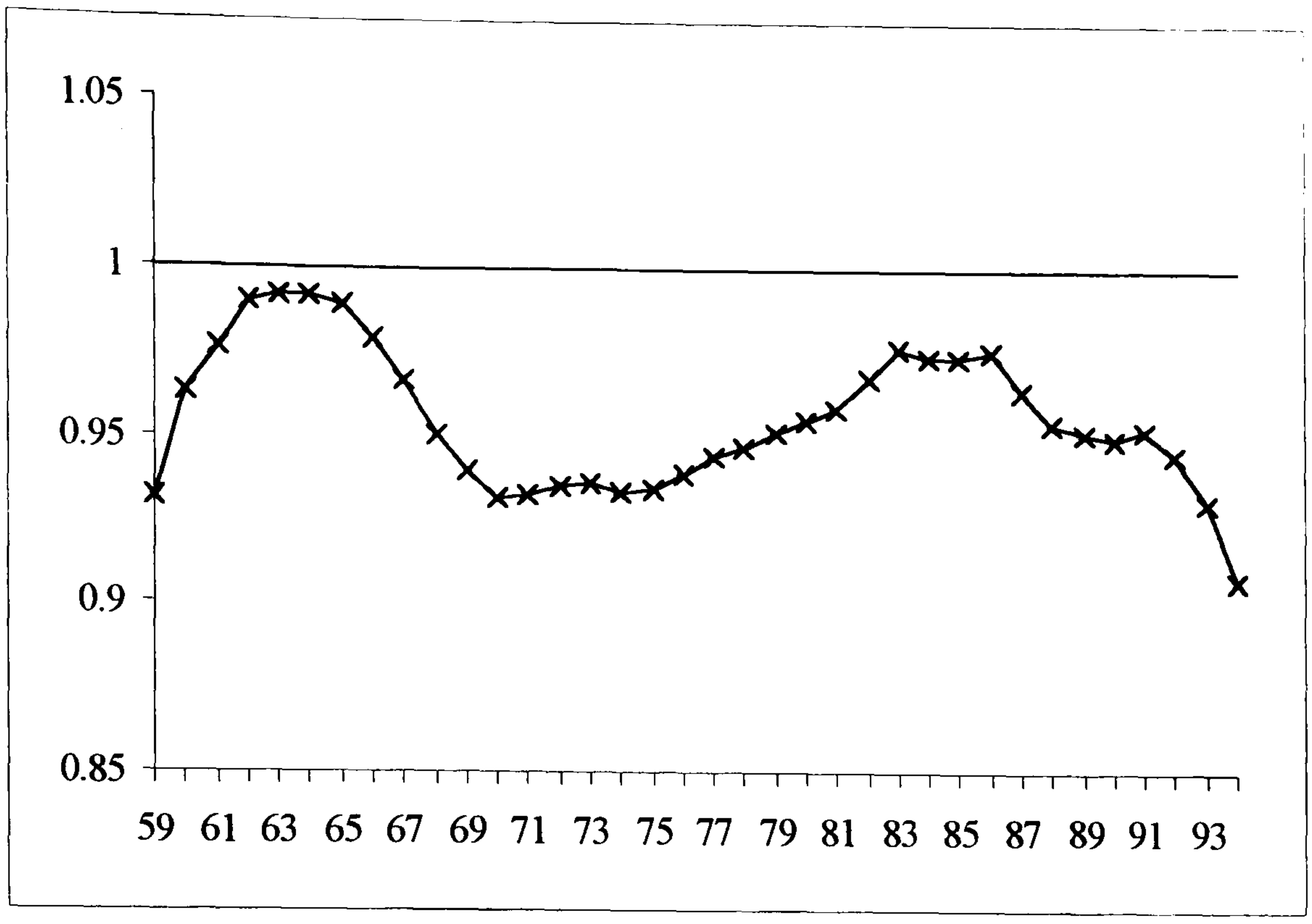
[33] Note that the actual capital stock is the Divisia index of core public capital

Figure 5. *Ratio of Optimal to Actual Core Infrastructure Stock, 1959-94.*



On average, the infrastructure stock was close to optimal over the entire sample period. The average optimal/actual ratio was 0.95, pointing to a small surplus. The ratios do not vary greatly in magnitude. The highest value of G^*/G over the course of the sample period is 0.992, observed in 1964; its lowest value is 0.907, observed in 1994. However, there was substantial variation in the growth rate of G and the growth rates of the various variables that influence G^* over the period. Figure 5 provides two interesting pieces of evidence. First, even though public capital may have a positive output elasticity, when the marginal cost of public capital, P_G, is taken into consideration (as it is in deriving G^*), the benefits derived by firms may not cover the cost of providing the additional capital. In fact it is quite feasible for the infrastructure surplus to be deepening at the same time that its output elasticity is increasing. For example, from 1964 to 1974 the optimal/actual ratio fell from 0.99 to 0.93 while ε_{QG^*} increased from 0.03 to 0.06. These movements are due to the complex mix of factors that influence G^*/G and ε_{QG^*}. It is possible, for example, that a decrease in P_K, the user cost of private capital, will lead to an increase in ε_{QG*} but G^*/G will fall because the change in the actual public capital stock, G, is greater than the P_K-induced increase in G^*.

Second, it is interesting to observe that for part of the period in which the optimal/actual ratios were rising and therefore moving closer to underprovision (eg, 1959-64), the actual capital stock was also growing at a rapid rate. Similarly, for part of the time that the ratios were falling (eg, 1969 to 1974) public investment was also falling. These apparent contradictions can be explained by the fact that φ, the deviation of G from G^*, depends not just on the quantity of infrastructure investment but on the level of economic activity and the prices of infrastructure complements and substitutes (eg, private capital and labour). For example, from 1959-64 the movement in the optimal/actual ratio towards a state of underprovision took place partly because of the 23 per cent increase in the labour wage rate, P_L, over this period. This increase was far higher than those in P_G and P_K (4 per cent and -8 per cent respectively). If G and L are substitutes and G and K are complements these price movements would have contributed to the large increase in G^* at the beginning of the sample period. These relationships will be explored further in the subsections that follow.

Although public investment fell significantly from 1968-82, the resulting fall in the growth rate of G did not lead to a significant increase in the G^*/G ratio. This is because the growth rate of G^* also slowed significantly over this period. From the late 1960s the user costs of private and public capital increased markedly, fuelled mainly by increases in long-term interest rates (see Figure 3).[34] The variables P_G and P_K both

[34] For example, the interest rate on 10-year Treasuries increased from 5.07 per cent in 1967 to 13.91 per cent in 1981.

appear in the optimal infrastructure equation thus, to the extent that K and G are complements and increases in P_G lead to a fall in the demand for infrastructure (see Figure 4), it is not surprising that the G^*/G ratio rose by only a small amount despite the year-on-year declines in investment. The ratio did not increase in the early 1980s despite the gradual decline in the two rental price measures, however. Although these falls led to an increase in G^*, the actual public capital stock, G, was growing faster in this time period due to the large increases in public investment that took place from 1984 onwards (see Table 18, Appendix E).

The slowdown in infrastructure investment during the 1970s and the persistence of an infrastructure surplus during the sample period must also be viewed against the backdrop of events in the previous two decades.[35] There was substantial infrastructure investment in the 1950s and 1960s. From 1950-68 the core infrastructure stock (measured in constant dollars) grew by 4.09 per cent per year, more than doubling in size from \$335 billion to \$719 billion. Thus although infrastructure investment declined from 1969 to 1982, it could be argued that sufficient capital had been accumulated in previous decades to support the level of economic activity that existed in the 1970s. For example, in 1968 before the start of the infrastructure investment decline, the ratio of public capital to GDP, G/Q, was 0.31; in 1982 after almost 14 years of consecutive declines in infrastructure investment the ratio was still 0.31.

An important question is whether the optimal/actual ratios provide valuable information to policymakers formulating infrastructure spending plans. First, it must

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[35] See Chapter 2.

again be emphasised that the analysis focuses solely on the infrastructure benefits (cost savings) that accrue to the private business sector. To the extent that the core infrastructure stock provides consumption benefits, the optimal/actual ratios are potentially understated.[36] Second, the discovery of an overall shortage or surplus of public capital does not imply that the U.S. Government should invest in infrastructure or curtail spending aimlessly. This is because the focus is not on the demand-side benefits of infrastructure investment but on the supply-side effects. Different types of G will have different effects on private production which would first have to be identified. Then it would have to be established whether any of these measures are in shortage or oversupplied. This is the main reason for also estimating the model with disaggregated infrastructure data.

It must also be remembered that infrastructure investments are lumpy and have long lives. This means that the appearance of an infrastructure shortfall in any one year does not necessarily justify extra spending by the Government. Policymakers must first be satisfied that the shortfall is likely to persist. It is clear from the optimal infrastructure stock equation that even if the actual infrastructure stock remains constant the optimal/actual ratios will change in size from year to year. For example, if the prices of factors that are public capital substitutes or complements change significantly, this will affect the size of the optimal infrastructure stock. Thus policymakers have to be aware that changing economic conditions affect the demand for infrastructure. For example, in 1965 the optimal/actual ratio was 0.99, implying that the public capital stock was very close to its optimal level. By 1975 a surplus had appeared – the optimal/actual ratio fell to 0.93. However, this surplus was generated

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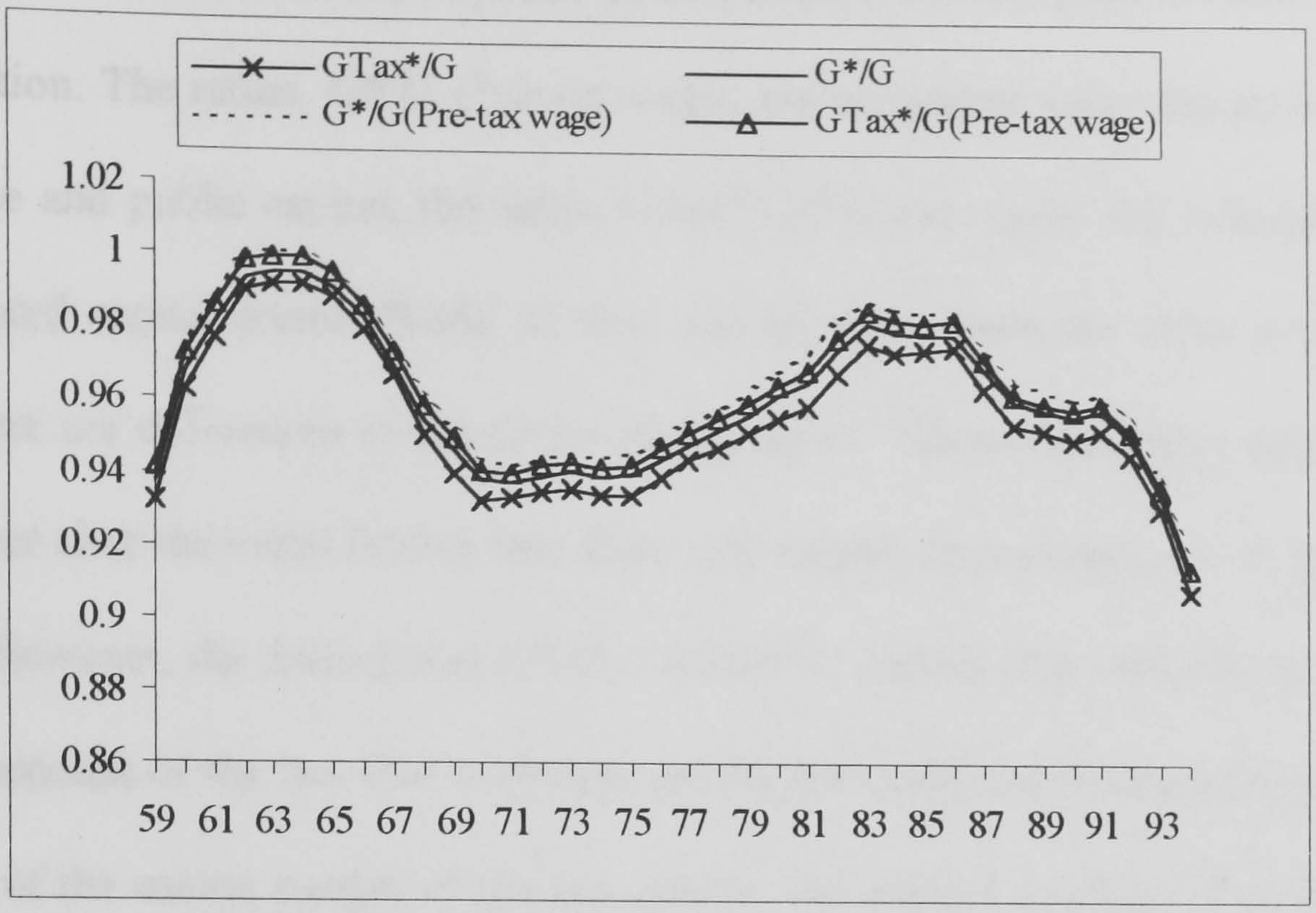
[36] They are also understated to the extent that the discount rate, r, used to calculate P_G is too high.

Figure 6. *Comparison of Optimal/Actual Ratios, Pre-tax and Tax-adjusted Rental Price Measures*



without significant increases in infrastructure investment after 1965 (Table 18, Appendix E). From 1966 to 1968 there was some growth in investment but from 1969 to 1975 there were year-on-year declines. Yet this level was still high enough to cause a swing from an optimal state to a surplus of roughly 7 per cent.

6.3 Tax-Adjusted Input Prices versus Pre-tax Prices

It is interesting to compare optimal/actual ratios calculated under different assumptions concerning the effect of taxation on the prices of labour, private capital and public capital. The ratios are illustrated graphically in Figure 6. The ratios *G*/G* and *GTax*/G* are calculated using the coefficient estimates from Model 1 and by inserting the after-tax price of labour in (33), the equation for *G**. The ratios *G*/G* are calculated using the pre-tax prices of private and public capital; the ratios *GTax*/G* are calculated using tax-adjusted capital prices.

The ratios *G*/G(Pre-tax wage)* and *GTax*/G(Pre-tax Wage)* are calculated using the coefficient estimates from Model 2 and by inserting the pre-tax price of labour into the G^* equation. The ratios *G*/G (Pre-tax wage)* are calculated using the pre-tax prices of private and public capital; the ratios *GTax*/G(Pre-tax wage)* are calculated using tax-adjusted capital prices. While all four sets of ratios have the same pattern over time, there are differences in the *levels* of the ratios. These differences are not large and do not alter the initial finding that there was surplus infrastructure over the sample period. However, the finding that $G^*/G > GTax^*/G$ implies that, once P_K is increased to take account of the fact that corporate profits are taxed and P_G is increased to take account of the excess burden of the tax system, the desired quantity of public capital falls.

6.4 Public Capital: Complement or Substitute?

It is clear that Figure 6 provides interesting information regarding the relationship between private and public inputs. The ratios *G*/G* and *G*/G(Pre-tax wage)* both use the same user costs of capital but the former uses the lower tax-adjusted wage rate. It is clear that lowering the wage rate decreases the desired capital stock (leading to smaller optimal/actual ratios), implying that labour and public capital are substitutes (a similar result was obtained by Berndt and Hansson, 1992; Deno, 1988; Shah, 1992). Similarly, increasing the user cost of private capital by adjusting it for tax, lowers the desired amount of public capital, implying that public and private capital are complements (the same result was obtained by Deno, 1988; Conrad and Seitz, 1992; Lynde and Richmond, 1992; and Shah, 1992). It is possible to calculate the elasticity of G^* with respect to P_K and P_L and therefore measure the responsiveness of G^* with respect to changes in the prices of private inputs.

Table 6. *Optimal Infrastructure Elasticities, 1959-94*

	$\varepsilon_{G^*P_L}$	$\varepsilon_{G^*P_K}$		$\varepsilon_{G^*P_L}$	$\varepsilon_{G^*P_K}$
1959	0.0208	-0.0231	1977	0.02147	-0.0246
1960	0.0200	-0.0222	1978	0.02257	-0.0280
1961	0.0193	-0.0214	1979	0.02257	-0.0269
1962	0.0176	-0.0196	1980	0.02602	-0.0310
1963	0.0172	-0.0192	1981	0.02858	-0.0340
1964	0.0163	-0.0182	1982	0.02789	-0.0326
1965	0.0154	-0.0173	1983	0.02509	-0.0291
1966	0.0166	-0.0187	1984	0.02568	-0.0301
1967	0.0169	-0.0190	1985	0.02356	-0.0276
1968	0.0202	-0.0227	1986	0.02083	-0.0239
1969	0.0222	-0.0251	1987	0.02400	-0.0272
1970	0.0216	-0.0245	1988	0.02494	-0.0283
1971	0.0190	-0.0215	1989	0.02430	-0.0275
1972	0.0186	-0.0211	1990	0.02434	-0.0275
1973	0.0194	-0.0222	1991	0.02300	-0.0259
1974	0.0216	-0.0253	1992	0.02194	-0.0245
1975	0.0223	-0.0258	1993	0.02053	-0.0228
1976	0.0220	-0.0252	1994	0.02174	-0.0244
			Average	**0.02156**	**-0.02467**

Note: $\varepsilon_{G^*P_L}$ and $\varepsilon_{G^*P_K}$ are the elasticities of the optimal infrastructure stock with respect to labour and private capital respectively.

The computed elasticities are reported in Table 6. They all have the anticipated signs, confirming that G and K are complements and G and L are substitutes.[37] It is also clear that G^* is inelastic with respect to P_K and P_L. Taking the average values of $\varepsilon_{G^*P_L}$ and $\varepsilon_{G^*P_K}$, a 10 per cent increase in the price of labour leads to a 0.22 per cent increase in G^* and a 10 per cent increase in the price of private capital leads to a 0.25 per cent fall in G^*.

[37] Although substitutability between L and G suggests declining employment given the level of output Q, to the extent that increases in G induce increases in Q, the negative effect on L may be countered by an increase in output supply.

7. Empirical Results – Disaggregated Infrastructure

7.1 Estimation Results

The study using aggregate core infrastructure data points to there having been a small surplus of infrastructure in terms of the cost savings this type of capital generates for private business. On balance, however, the infrastructure stock was very close to optimal. An important question is whether some types of public capital were oversupplied and others were in shortage at various times over the sample period. To determine this, the core infrastructure stock has to be divided into its component parts (highways and streets, G_H, water and sewers, G_{WS}, and other structures, G_O) and the disaggregated model, consisting of equations (28) and (29), is estimated using SUR. The resulting parameter estimates are used to derive the optimal infrastructure stocks.

Once again two separate models are estimated so that the effects of adjusting input prices for tax purposes can be analysed: Model 1 uses the tax-adjusted wage rate; Model 2 uses pre-tax wages. The estimation results are reported in Table 7. Most of the coefficient estimates are significantly different from zero at the 5 per cent level at least. The model fits the data well, as indicated by the high values of $\overline{R}^2$ and the cost and labour input-output equations do not suffer from serially correlated, heteroskedastic or non-normally distributed errors. Once again ADF tests on the residuals of the two equations lead to rejection of the null hypothesis of a unit root. The ADF test statistic for the cost equation of Model 1 is -7.69 and the test statistic for the labour input-output equation is -5.53, both of which exceed the MacKinnon (1991) critical value of -4.25, leading to rejection of the null hypothesis at the 1 per cent level.

Table 7. *Parameter Estimates: Disaggregated Infrastructure Model, 1959-94*

Parameter	Model 1: After-tax wages		Model 2: Pre-tax Wages	
	Estimate	*t-stat*	*Estimate*	*t-stat*
α_{LL}	-22.48	(5.81)***	-22.08	(5.67)***
δ_{Lt}	1.48	(3.87)***	1.50	(3.86)***
δ_{LQ}	0.02	(5.36)***	0.01	(5.21)***
γ_{tQ}	0.0005	(3.69)***	0.0005	(3.67)***
γ_{tt}	-0.03	(2.54)**	-0.03	(2.65)**
γ_{QQ}	-0.26E-05	(4.93)***	-0.25E-05	(4.80)***
δ_{LK}	-10.67	(4.16)***	-10.65	(4.04)***
δ_{LG_H}	-5.59	(1.03)	-5.22	(0.99)
$\delta_{LG_{WS}}$	55.23	(2.38)**	57.92	(2.50)**
δ_{LG_O}	113.35	(4.66)***	107.23	(4.79)***
γ_{tK}	-0.40	(3.89)***	-0.39	(3.94)***
γ_{QK}	0.0039	(4.26)***	0.0040	(4.16)***
γ_{tG_H}	-0.27	(1.37)	-0.25	(1.27)
γ_{QG_H}	0.002	(1.57)	0.002	(1.55)
$\gamma_{tG_{WS}}$	2.29	(2.09)**	2.44	(2.24)**
$\gamma_{QG_{WS}}$	-0.018	(2.32)**	-0.019	(2.42)**
γ_{tG_O}	3.60	(4.16)***	3.39	(4.27)***
γ_{QG_O}	-0.04	(6.06)***	-0.04	(6.27)***
γ_{KK}	-1.52	(2.21)**	-1.57	(2.30)**
$\gamma_{G_HG_H}$	-15.69	(5.82)***	-15.07	(5.81)***
$\gamma_{G_{WS}G_{WS}}$	-44.18	(1.82)*	-47.11	(1.96)**
$\gamma_{G_OG_O}$	-218.92	(4.55)***	-208.53	(4.60)***
γ_{G_HK}	-1.86	(1.66)*	-1.91	(1.75)*
$\gamma_{G_{WS}K}$	11.55	(3.04)***	11.41	(2.91)***
γ_{G_OK}	30.74	(3.93)***	31.15	(3.91)***
$\gamma_{G_HG_{WS}}$	6.61	(1.36)	5.42	(1.19)
$\gamma_{G_HG_O}$	76.75	(4.71)***	74.25	(4.66)***
$\gamma_{G_{WS}G_O}$	-118.13	(4.71)***	-116.53	(4.53)***

	Model 1			Model 2		
	$\bar{R}^2$	*DW*	$JB\sim\chi^2(2)$	$\bar{R}^2$	*DW*	$JB\sim\chi^2(2)$
C	0.9999	3.39	0.40	0.9999	3.41	0.35
L/Q	0.9997	3.06	0.02	0.9998	3.11	0.02

Note: *JB* = Jarque-Bera normality test statistic; t-stats are computed using White robust heteroskedastic-consistent standard errors. *** Significant at the 1 % level at least, ** Significant at the 5 % level at least, * Significant at the 10 % level at least.

Table 8. *Hypothesis Test Results – Infrastructure Variables*

Wald Test	Model 1	Model 2
$W_G \sim\chi^2(18)$	3262.39	3168.01
$W_H \sim\chi^2(7)$	128.23	133.10
$W_{WS} \sim\chi^2(7)$	90.55	96.85
$W_O \sim\chi^2(13)$	196.48	190.06
$W_{H,WS} \sim\chi^2(13)$	1871.22	1990.94
$W_{H,O} \sim\chi^2(13)$	493.90	507.78
$W_{WS,O} \sim\chi^2(13)$	838.66	861.01

Note: Subscripts denote variables omitted for test purposes. For example, $W_{WS,O}$ tests the exclusion of the water and sewer and other structures stocks, ie, whether roads are the only type of infrastructure that affect private sector costs. Degrees of freedom in parentheses.

The importance of the various infrastructure variables in each of the models was established by carrying out a series of Wald tests. The results are reported in Table 8. The statistic W_G results from testing whether all three infrastructure terms should be included in the models. The highly significant chi-square values indicate that infrastructure as a whole is an important component of the models. Hypothesis tests were then conducted to determine whether any of the individual infrastructure stocks should be excluded. Specifically, W_H tests whether the highways and streets variable should be omitted and W_{WS} and W_O test for the inclusion of water and sewer systems capital and other structures respectively. All three tests reject in favour of including the relevant infrastructure variable in the model. Tests were also carried out by excluding pairs of infrastructure variables. For example, $W_{H,O}$ tests whether water and sewer systems are the only type of infrastructure that determines private costs. The restriction is strongly rejected. Restrictions on other pairs of disaggregated infrastructure are also strongly rejected. The conclusion therefore is that each type of infrastructure affects private costs.[38] The finding that $W_{\mathrm{WS,O}}$ is significantly different from zero is of particular interest. This is the statistic obtained from testing whether highways and streets are the only type of infrastructure that affects private sector costs. There are numerous studies in the transportation literature that seek to establish the importance of various measures of highways and other roads on different measures of economic development.[39] In particular, Holleyman (1996) examines the relationship between highways and manufacturing costs using a translog specification. However, values of the $W_{\mathrm{WS,O}}$ test statistic imply that omitting the water and sewer and other structures variables omits important infrastructure effects.

There are a number of possible drawbacks to estimating the cost function model using disaggregated infrastructure data. First, degrees of freedom are quickly consumed because of the addition of cross-product terms. Second, there is the issue of near multicollinearity. As Greene (1993) points out, the higher the correlation between the regressors, the less precise the estimates will be. When the regressors are highly correlated, small changes in the data can produce wide swings in the parameter estimates, and coefficients have low significance levels in spite of the fact that the R^2 in the regression may be quite high. The estimated models do not suffer from these problems. Most of the coefficients are significant and alterations to the data do not affect the estimates substantially.[40] However, a joint significance test on parameter

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[38] Other restrictions to the model to test the appropriateness of the specification are also rejected. These include constraints on the "t" parameters and the fixed effects (both independently and grouped). The assumption of constant returns to scale is also strongly rejected.

[39] See Fisher (1997) for a survey of the literature.

[40] For example, there is little difference between the parameter estimates of Model 1 and Model 2. Furthermore, parameter estimates that appear in the optimal capital stock equations and that are common to both the aggregate and disaggregated infrastructure models have the same signs. I examined correlations using detrended infrastructure variables. The correlation coefficient between G_H and G_{WS} is -0.52; between G_H and G_O it is 0.85; and between G_{WS} and G_O it is -0.67.

estimates with insignificant t-stats, ie $\delta_{LG_H} = \gamma_{tG_H} = \gamma_{QG_H} = \gamma_{G_H G_{WS}} = 0$, produces a chi-square value that rejects in favour of including these variables in the models. Thus there does appear to be some collinearity between the variables which will lead to increases in the variance of the estimated coefficients. It is important to point out, however, that the estimates are unbiased. Furthermore, it must be remembered that the parameter estimates determine the *level* of the optimal actual ratios but not the *pattern* of the ratios. Thus, to the extent that some of the parameter estimates from the disaggregated infrastructure model have higher standard errors, leading potentially to less accurate measures of the optimal infrastructure stocks, this has no effect on the analysis of whether some types of infrastructure were becoming suboptimal while others were moving towards a state of excess supply. This is one of the main uses of the ratios calculated in this section.

There is an alternative method of estimating the effect of individual infrastructure stocks on private sector costs. The aggregate infrastructure model (equations (28) and (29)) can be re-estimated using *individually* the stocks of roads, water and sewer systems capital and other structures capital. In this way, the degrees of freedom are increased because the number of cross-product terms is dramatically reduced. Furthermore, because only one infrastructure variable is included in each model any problems caused by near multicollinearity are remedied. However, this estimation method omits the important cross-effects between infrastructure variables. For example, using the estimates from the models in Table 7, the optimal infrastructure stocks are obtained by solving four equations simultaneously:

$$-\frac{\partial C}{\partial H} = P_H, \quad -\frac{\partial C}{\partial WS} = P_{WS}, -\frac{\partial C}{\partial O} = P_O, -\frac{\partial C}{\partial K} = P_K. \qquad (52)$$

The resulting optimal capital stocks are functions of the same private sector variables as the aggregate optimal infrastructure stock (ie, P_L, P_K, and Q) as well as the rental prices of each of the three different types of public capital:

$$H^* = F(P_L, P_K, Q, t, P_H, P_{WS}, P_O), \tag{53}$$

$$WS^* = F(P_L, P_K, Q, t, P_H, P_{WS}, P_O), \text{ and} \tag{54}$$

$$O^* = F(P_L, P_K, Q, t, P_H, P_{WS}, P_O). \tag{55}$$

Estimating the model with infrastructure variables included one at a time ignores the cross effects of infrastructure rental prices, which are important to the extent that one type of infrastructure may act as a complement or substitute for another type of public capital. The optimal infrastructure stocks and optimal infrastructure elasticities were computed using the parameter estimates reported in Table 7. The results are reported in the subsections that follow.

7.2 Output Elasticities

Estimates of the output elasticities of the different infrastructure stocks (calculated using optimal values) are reported in Table 9. The estimates reveal that highways and streets have the highest elasticity, followed by water and sewer structures and other structures. The average values imply that a 1 per cent increase in the stock of roads leads to an increase of 0.03 per cent in business output; a 1 per cent increase in water and sewer structures leads to an increase of approximately 0.01 per cent; and a 1 per cent increase in other structures capital also leads to an increase of approximately 0.01. These estimates are lower than those obtained in previous infrastructure research. For example, it was reported in Chapter 1 that Munnell (1990b, 1993) obtained estimates of 0.12 and 0.15 for the output elasticity

Table 9. *Output Elasticities: Disaggregated Infrastructure*

	ε_{QH^*}	ε_{QWS^*}	ε_{QO^*}		ε_{QH^*}	ε_{QWS^*}	ε_{QO^*}
1959	0.017	0.004	0.002	1977	0.029	0.010	0.005
1960	0.017	0.004	0.002	1978	0.036	0.011	0.006
1961	0.017	0.004	0.002	1979	0.042	0.013	0.007
1962	0.017	0.004	0.002	1980	0.049	0.015	0.008
1963	0.018	0.005	0.002	1981	0.050	0.017	0.009
1964	0.018	0.005	0.002	1982	0.045	0.016	0.008
1965	0.018	0.005	0.002	1983	0.037	0.014	0.007
1966	0.020	0.005	0.003	1984	0.039	0.014	0.008
1967	0.020	0.006	0.003	1985	0.035	0.012	0.007
1968	0.022	0.006	0.003	1986	0.026	0.010	0.005
1969	0.025	0.007	0.004	1987	0.026	0.010	0.006
1970	0.029	0.008	0.004	1988	0.026	0.010	0.006
1971	0.025	0.008	0.004	1989	0.024	0.010	0.005
1972	0.025	0.008	0.004	1990	0.024	0.010	0.005
1973	0.028	0.008	0.004	1991	0.022	0.009	0.005
1974	0.037	0.011	0.006	1992	0.019	0.008	0.005
1975	0.036	0.011	0.006	1993	0.016	0.007	0.004
1976	0.030	0.011	0.005	1994	0.018	0.008	0.005
				Average	**0.027**	**0.009**	**0.005**

ε_{QH^*}, ε_{QWS^*} and ε_{QO^*} are, respectively, the elasticities of roads, water and sewers and other structures.

of *WS*, implying that a 1 per cent increase in water and sewer structures leads to an increase of between 0.12 and 0.15 per cent in output. Munnell obtained estimates of 0.06 and 0.04 for the output elasticity of highways and streets. These estimates for roads are much closer to those reported in Table 9. Munnell's estimate of the output elasticity of other infrastructure (which included a variety of infrastructure measures not contained in *O*) was found to have a negative value.

7.3 Complements or Substitutes?

Before illustrating the optimal/actual ratios it is worthwhile analysing the elasticities of the optimal infrastructure stocks with respect to the prices of private capital and labour. The results are reported in Table 10. In Table 6 the elasticities for *aggregate* infrastructure were reported and it was shown that the core infrastructure stock complements private capital and substitutes for labour. When the public capital data is disaggregated the findings are the same: each of the infrastructure stocks complements private capital and acts as a labour substitute. The mean values of the elasticities imply that a 10 per cent fall in the price of private capital leads to an increase of 0.15 per cent in the optimal stock of highways, an increase of 0.33 per cent in the optimal stock of water and sewer capital and an increase of 0.50 per cent in the stock of other structures. Similarly, a 10 per cent increase in the wage rate leads to increases of 0.10 per cent, 0.33 per cent and 0.51 per cent in the respective optimal stocks. It is also clear that the elasticities do not vary much over the sample period. From the figures reported in Table 10 it can be seen that

$$\left|\varepsilon_{H^*P_K}\right| < \left|\varepsilon_{WS^*P_K}\right| < \left|\varepsilon_{O^*P_K}\right|, \text{ and} \tag{56}$$

$$\left|\varepsilon_{H^*P_L}\right| < \left|\varepsilon_{WS^*P_L}\right| < \left|\varepsilon_{O^*P_L}\right|. \tag{57}$$

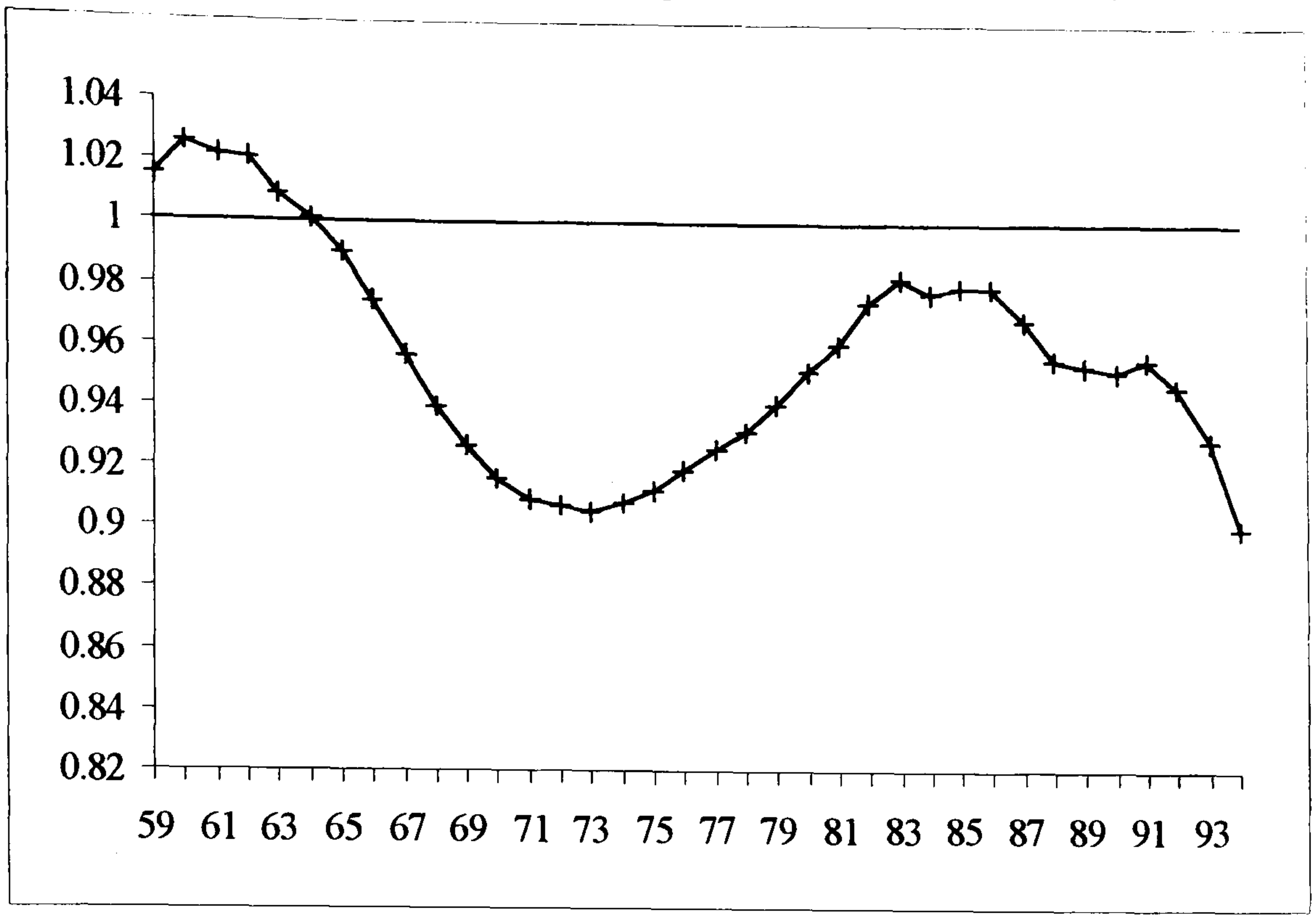
Of course, this does not imply that a given change in the price of one of the private inputs leads to a smaller absolute increase in the optimal stock of highways and streets than in water and sewers or other structures. Highways and streets accounted for, on average, 66 per cent of core infrastructure over the sample period, water and sewers and other structures accounted for, on average, 22 per cent and 12 per cent respectively. Weighting the elasticities by the shares of the different infrastructure stocks in the total measure of G allows the elasticities to be compared from a slightly different perspective. The weighted average elasticities are also reported in Table 10.

Table 10. *Optimal Infrastructure Elasticities, 1959-1994*

	ε_{H*P_K}	ε_{WS*P_K}	ε_{O*P_K}	ε_{H*P_L}	ε_{WS*P_L}	ε_{O*P_L}
1959	-0.0118	-0.0277	-0.0417	0.0083	0.0271	0.0424
1960	-0.0115	-0.0282	-0.0411	0.0082	0.0276	0.0417
1961	-0.0111	-0.0283	-0.0404	0.0080	0.0277	0.0411
1962	-0.0102	-0.0265	-0.0379	0.0070	0.0259	0.0386
1963	-0.0100	-0.0262	-0.0375	0.0068	0.0257	0.0382
1964	-0.0095	-0.0250	-0.0362	0.0065	0.0245	0.0369
1965	-0.0090	-0.0237	-0.0347	0.0061	0.0233	0.0354
1966	-0.0100	-0.0256	-0.0376	0.0067	0.0251	0.0383
1967	-0.0103	-0.0263	-0.0384	0.0069	0.0258	0.0392
1968	-0.0129	-0.0311	-0.0452	0.0089	0.0304	0.0461
1969	-0.0148	-0.0343	-0.0497	0.0103	0.0336	0.0506
1970	-0.0145	-0.0342	-0.0490	0.0097	0.0335	0.0499
1971	-0.0124	-0.0303	-0.0438	0.0084	0.0297	0.0447
1972	-0.0121	-0.0294	-0.0433	0.0082	0.0288	0.0442
1973	-0.0131	-0.0305	-0.0456	0.0085	0.0298	0.0466
1974	-0.0154	-0.0351	-0.0512	0.0094	0.0343	0.0524
1975	-0.0160	-0.0366	-0.0524	0.0102	0.0357	0.0536
1976	-0.0155	-0.0353	-0.0515	0.0105	0.0345	0.0526
1977	-0.0151	-0.0341	-0.0506	0.0102	0.0333	0.0517
1978	-0.0167	-0.0360	-0.0541	0.0104	0.0350	0.0554
1979	-0.0172	-0.0367	-0.0552	0.0099	0.0357	0.0566
1980	-0.0209	-0.0426	-0.0626	0.0124	0.0414	0.0642
1981	-0.0238	-0.0464	-0.0740	0.0149	0.0451	0.0694
1982	-0.0225	-0.0456	-0.0661	0.0150	0.0443	0.0677
1983	-0.0194	-0.0406	-0.0597	0.0130	0.0396	0.0611
1984	-0.0205	-0.0409	-0.0618	0.0132	0.0398	0.0634
1985	-0.0186	-0.0374	-0.0574	0.0117	0.0364	0.0588
1986	-0.0153	-0.0325	-0.0507	0.0103	0.0317	0.0518
1987	-0.0181	-0.0364	-0.0571	0.0129	0.0356	0.0583
1988	-0.0192	-0.0372	-0.0593	0.0137	0.0364	0.0605
1989	-0.0186	-0.0362	-0.0579	0.0134	0.0354	0.0591
1990	-0.0187	-0.0364	-0.0580	0.0135	0.0356	0.0592
1991	-0.0173	-0.0348	-0.0551	0.0127	0.0341	0.0562
1992	-0.0163	-0.0330	-0.0526	0.0122	0.0323	0.0536
1993	-0.0150	-0.0304	-0.0495	0.0114	0.0297	0.0504
1994	-0.0164	-0.0317	-0.0526	0.0122	0.0310	0.0536
Average	**-0.0153**	**-0.0334**	**-0.0503**	**0.0103**	**0.0326**	**0.0512**
Weighted	**-0.0100**	**-0.0075**	**-0.0060**	**0.0067**	**0.0074**	**0.0061**

Note: *H*, *WS*, and *O* denote highways & and streets; water & sewer structures and other structures respectively. ε_{H*P_K} is the elasticity of the optimal stock of highways & streets with respect to the price of private capital. Weighted averages calculated using the respective infrastructure shares.

Figure 7. *Highways & Streets: Optimal to Actual Ratios, 1959-94*



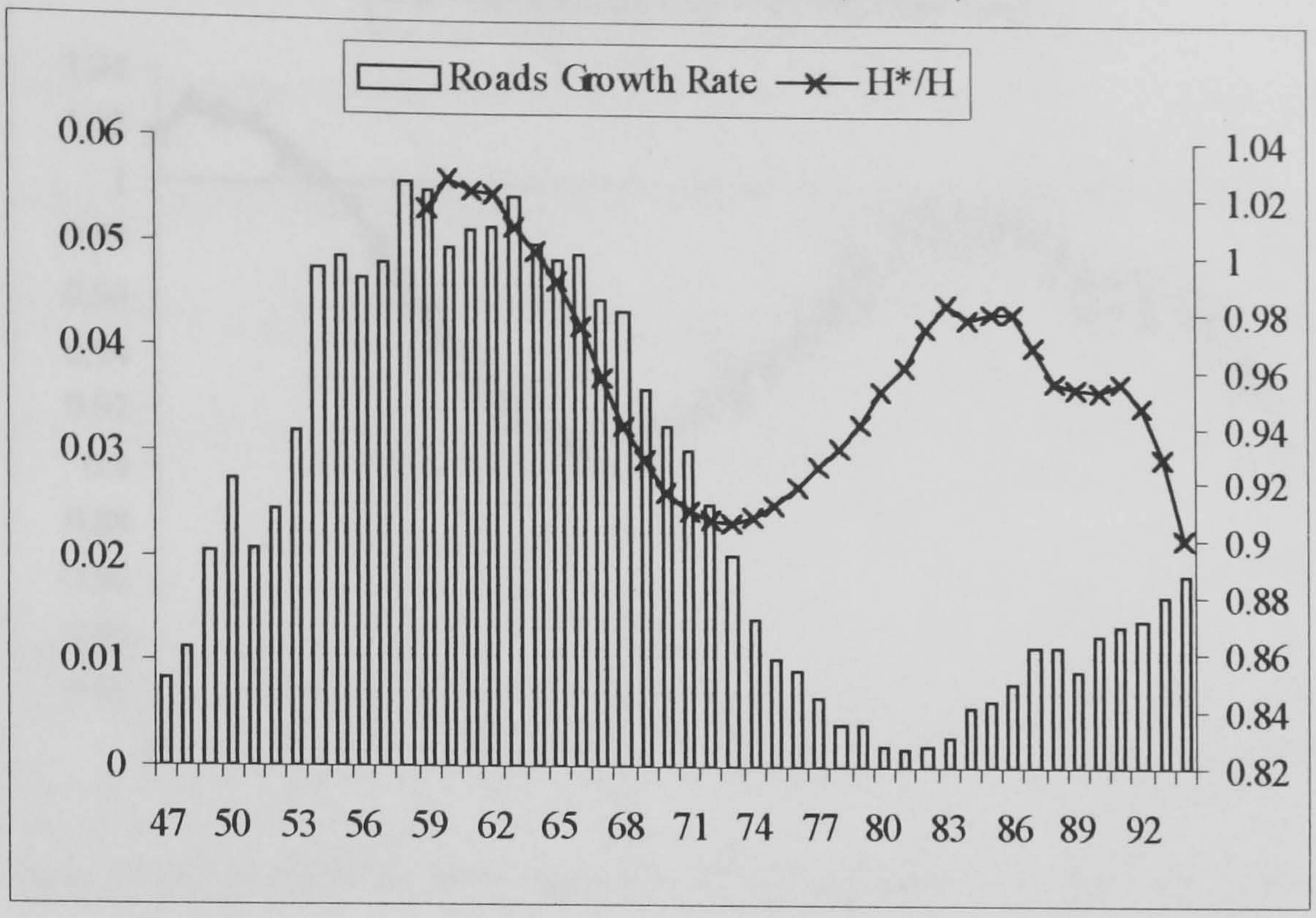
7.4 Optimal Infrastructure Stocks

7.4.1 Highways & Streets

The set of optimal/actual ratios for streets and highways is illustrated graphically in Figure 7. The ratios were calculated using tax-adjusted data. From 1959 to 1964 there was a small shortage of road capital, as indicated by ratio values greater than unity. From then until the end of the sample period there was excess capital. However, with an average ratio value of 0.96, the road stock was close to optimal over the period. Ignoring the level of the ratios, it is clear that they have a similar pattern to those of the aggregate core infrastructure stock (see Figure 5). This can be explained by the fact that roads account for almost two thirds of the aggregate measure.

It is interesting to observe the pattern of the optimal/actual ratios in relation to the development of the U.S. interstate highway system (Figure 8). For example,

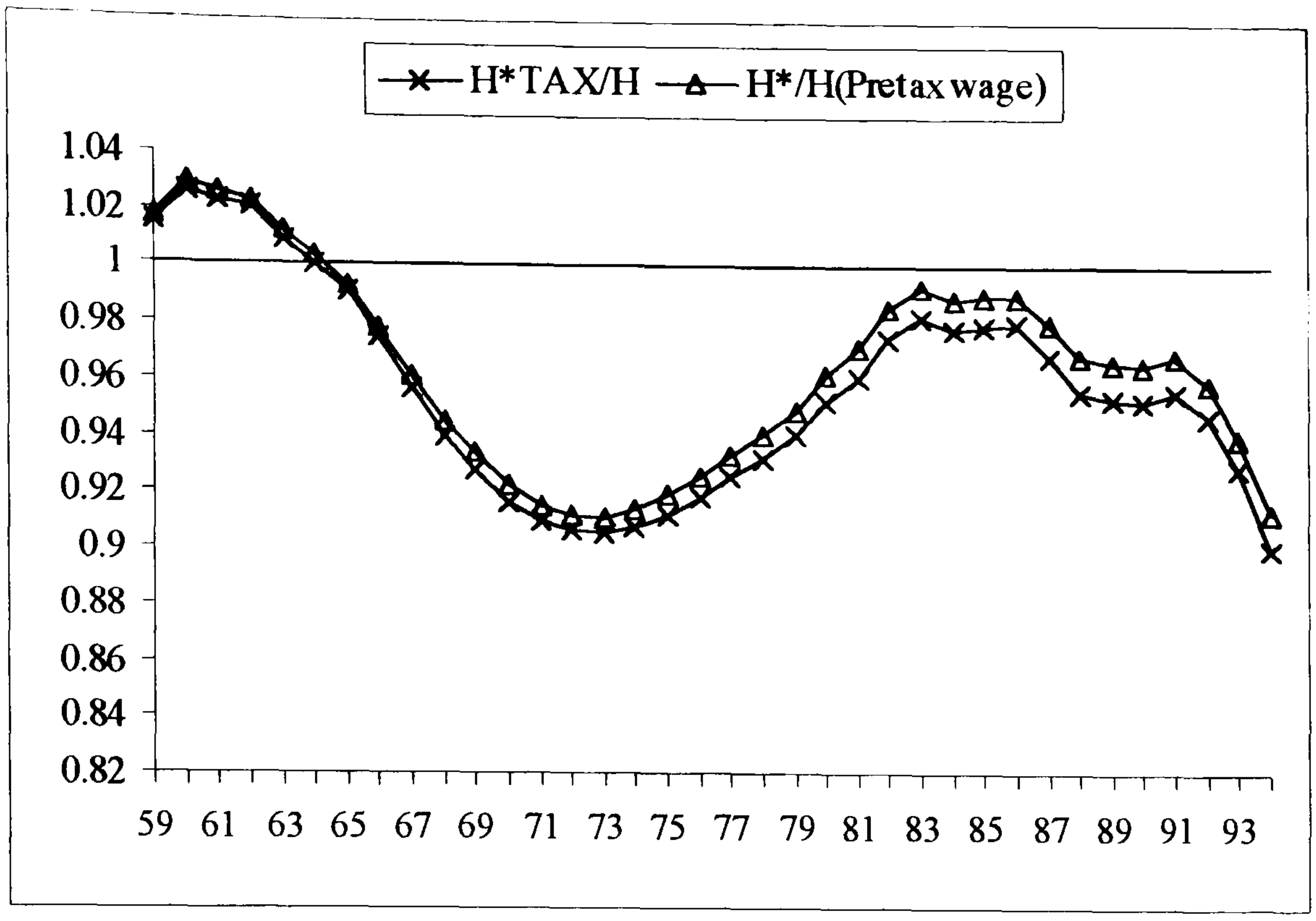
Figure 8. *Highways & Streets: Optimal/Actual ratios (R.H.S) Compared with Roads Growth Rate (L.H.S), 1947-94.*



between 1960 and 1973 the H^*/H ratio fell from 1.03 to 0.91. The road surplus deepened in spite of the fact that the optimal stock of roads, H^*, was growing by 3.1 per cent per year during this period. This can be explained by the fact that, from the mid-1950s, there was large-scale investment in the U.S. interstate highway system which saw the stock of roads grow by 4.6 per cent per year between 1953 and 1969. In the period 1960-73 the average annual growth rate was lower but, at 3.9 per cent per year, enough to cause the optimal/actual ratio to fall steadily from 1960. Growth in H^* was induced mainly by growth in Q of 3.8 per cent per annum.

Between 1974 and 1983 the H^*/H ratio rose from 0.91 to 0.98. It is interesting to observe that this trend towards underprovision occurred in spite of the fact that H^* was growing by only 1.3 per cent per year over this period. However, cutbacks in capital expenditure on roads, following almost two decades of rapid expansion, meant that the ratio's denominator, H, grew by only 0.5 per cent per year from 1974. The

Figure 9. *Comparison of Optimal/Actual Ratios: Highways & Streets*



Note: *HTAX*/H* and *H*/H(Pretax wage)* are tax-adjusted and pre-tax ratios respectively

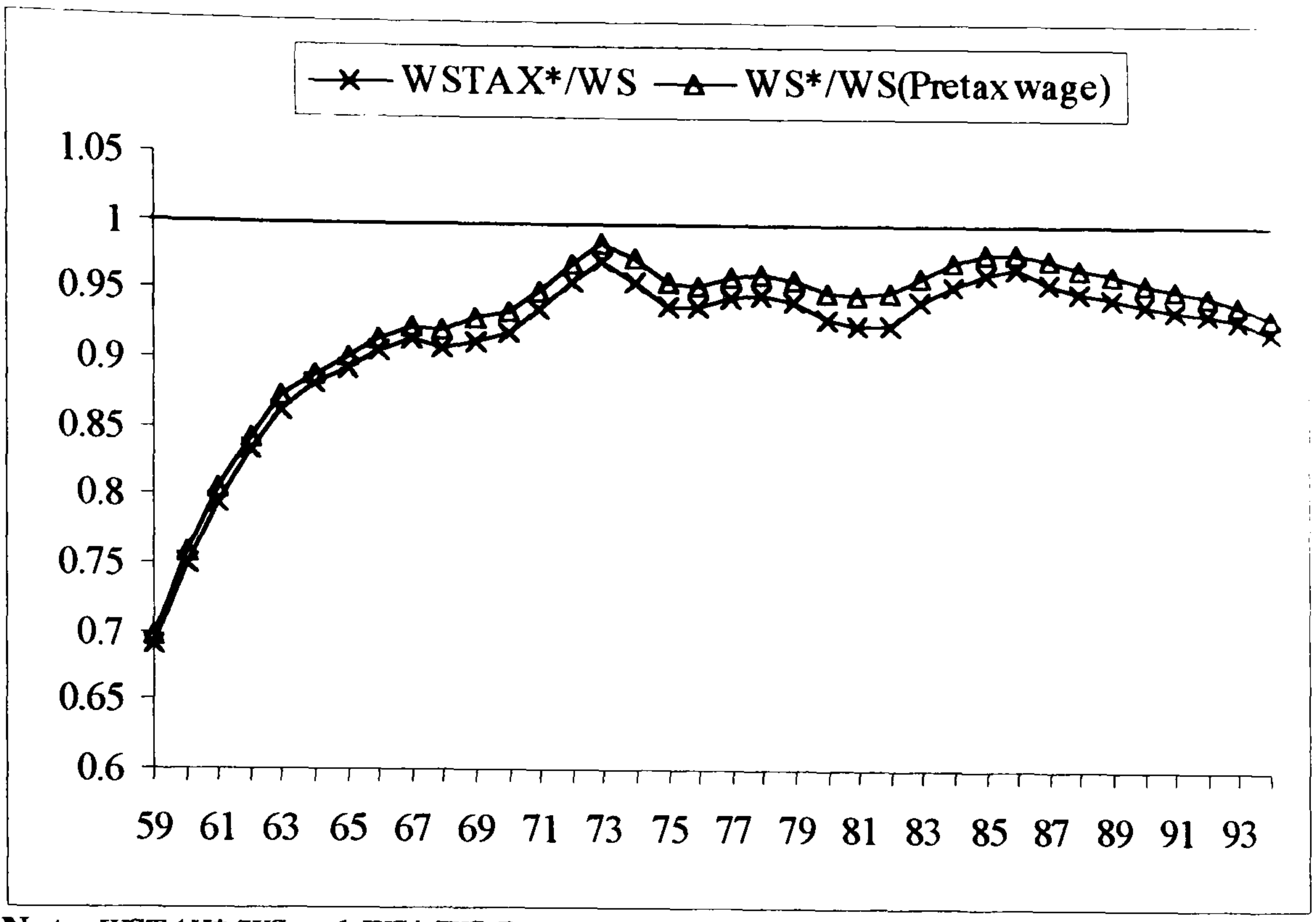
decline in the growth rate of H^* was caused by a slowdown in the average annual growth rate of output to 1.7 per cent per year and a substantial increase in the user costs of public and private capital. Although the price of labour (a substitute for roads) rose by 7.0 per cent per year between 1974 and 1983, average annual increases in the price of K (a complement) and increases in P_H were 9.8 per cent and 10.0 per cent respectively. Coupled with the fact that $|\varepsilon_{H^*P_L}| < |\varepsilon_{H^*P_K}|$, the relative increase in capital rental prices had the effect of pulling the growth rate of H^* down. It is also interesting to comment on the average level of the ratios during the infrastructure slowdown. Although road investment fell dramatically from \$33.5 billion in 1968 to \$15.2 billion in 1982, this slowdown seems to have had little effect on the private business sector, as illustrated by the fact that the optimal/actual ratio only increased by 5.4 per cent from 0.93 to 0.98. The fact that street and highway capital grew very slowly from the mid-1970s until 1985 does not necessarily mean that roads were neglected. This slowdown may have been a natural consequence of the large-scale investment that took place from the late 1950s and throughout the 1960s and a rational response to increases in P_H.

Figure 9 compares ratios calculated using tax-adjusted factor input prices with ratios calculated using only pre-tax prices. Clearly, there is very little difference in the results. This can be explained by the elasticities reported in Table 10, which reveal that the optimal roads stock is relatively insensitive to changes in input prices.

7.4.2 Water and Sewer Systems

Figure 10 compares the optimal and actual stocks of water and sewer systems capital. The figure contains two sets of ratios. The lower line is drawn using ratios calculated with after-tax input prices; the second line consists of ratios computed using only pre-tax prices. In each case the ratio levels point to a surplus of water and sewer capital over the entire sample period. The average values of the after-tax and pre-tax ratios are 0.92 and 0.93 respectively. Again the most interesting information derives from analysing the pattern of the ratios. In 1959 there was a significant surplus of water and sewer capital, as indicated by optimal/actual ratios of 0.69 and 0.70. The existence of a surplus can in part be explained by events after the Second World War. The stock of water and sewer systems not only grew at a slower rate from 1942-46 but shrank as depreciation exceeded investment as resources were channelled from non-military public investment into military investment. From 1950 investment in water and sewer structures took off, growing by 4.8 per cent per year over the next nine years. Thus it is not surprising that by 1959 these types of capital were in surplus as far as private business costs were concerned. The ratios moved steadily towards

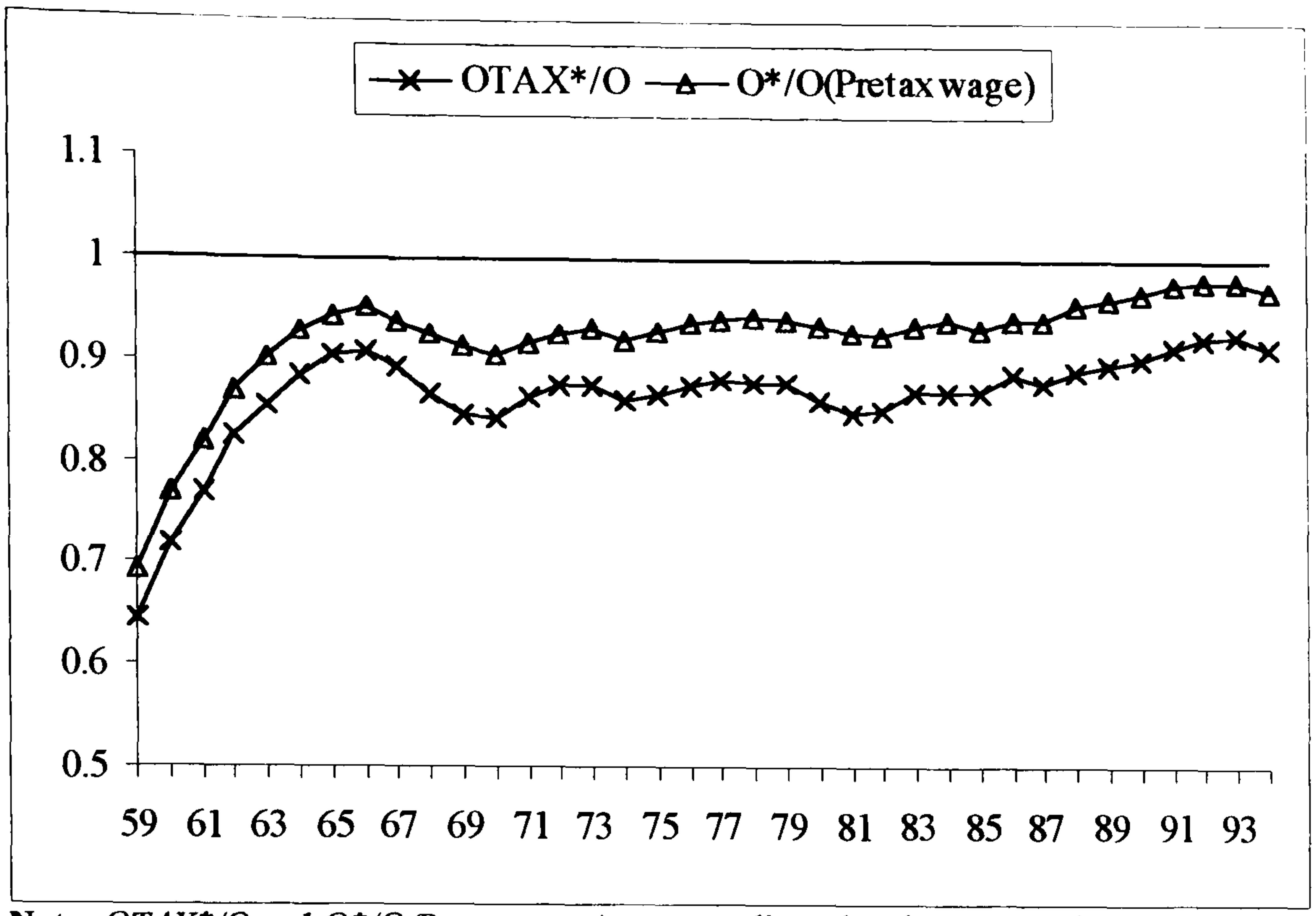
Figure 10. *Water & Sewers: Optimal to Actual Ratios, 1959-94.*



Note: *WSTAX*/WS* and *WS*/WS(Pretax wage)* are tax-adjusted and pre-tax ratios respectively.

a state of underprovision from 1959, however, with the surplus having almost entirely disappeared by 1973. It is interesting to note that this trend occurred despite a significant increase in the stocks of these two types of capital: from 1959-73 the average annual growth rate of *WS* was 3.4 per cent per year. On the other hand, the desired capital stock *WS** grew by 5.8 per cent per year during this period, fuelled in part by growth of the private economy (Q grew by 3.9 per cent per year) and changes in factor prices. Although the prices of both labour (a substitute for *WS*) and private capital (a complement) increased during this period, the growth rate of P_L outstripped that of capital by a significant margin (0.9 per cent per year). With the elasticities of *WS** with respect to P_L and P_K being almost identical, the most significant effect of the input price changes on *WS** was felt on the upside. Unlike certain types of infrastructure, there is little evidence of a slowdown in the growth of these types of public capital from the 1970s. The actual stock of water and sewer structures, *WS*, grew by 2.6 per cent per year between 1974 and 1994. This growth was

Figure 11. *Other Structures: Optimal Stock Divided by Actual, 1959-94.*



Note: *OTAX*/O* and *O*/O(Pretax wage)* are tax-adjusted and pre-tax ratios respectively

sufficient to keep pace with the growth of the private economy over this period. In 1974 the ratio of water and sewer investment to private GDP was 6.6 per cent. In 1994 it was still 6.6 per cent. This may explain why there was little change in the optimal/actual ratios from the early 1970s.

7.4.3 Other Structures

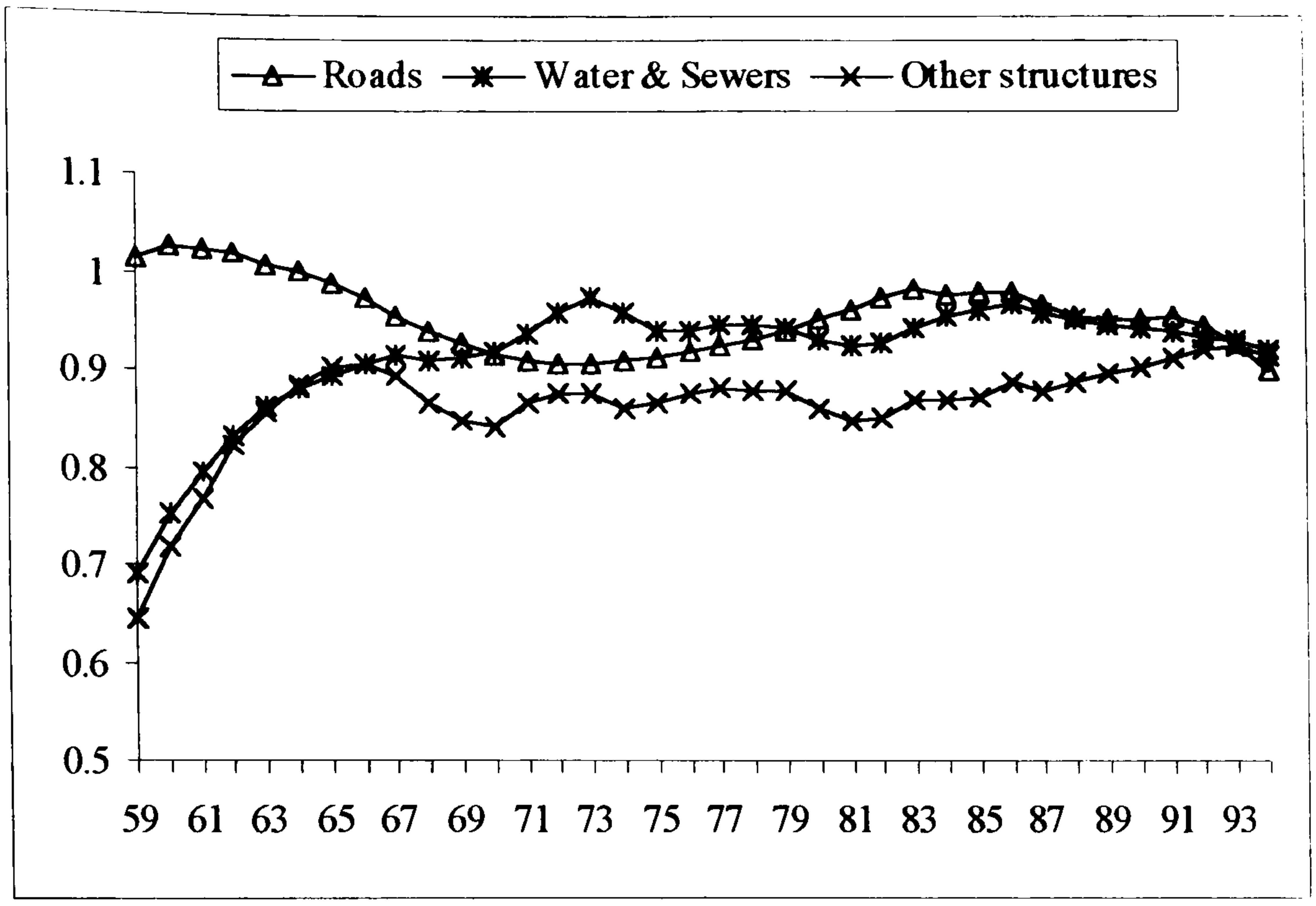
The optimal/actual ratios for "other structures" capital are illustrated in Figure 11. Again two sets are reported: those computed using after-tax data (*OTAX*/O*) and those computed using pre-tax data (*O*/OPretax wage*). Although electric and gas facilities, mass transit facilities and other publicly owned structures have a significant effect upon private sector costs, these types of capital were not in shortage over the sample period. The average ratios were 0.86 and 0.92 respectively, pointing to a not insignificant surplus of these types of capital.

The optimal/actual ratios increased at the beginning of the sample period, for the same reason that the *WS*/WS* ratios increased: although the actual stock of other structures was growing, the desired stock, O^*, grew at a faster rate, fuelled by increases in the price of labour relative to capital and increases in private output. Since 1982 the optimal stock has been growing at a faster rate than the actual stock and, as a result, the optimal/actual ratio has gradually risen from 0.85 to 0.92 in 1994. Although the actual stock of other structures, O, grew by 2.2 per cent per year, the desired capital stock grew by 2.8 per cent per year due to a significant decrease in the prices of capital relative to labour (eg, P_L grew 2.9 per cent per year, P_K declined by 0.7 per cent per year between 1982 and 1994).

7.4.4 Summary of Results

The stocks of roads, water and sewer systems and, to a lesser extent, other structures were, on average, all close to optimal over the sample period. However, there is quite a lot of variation in the patterns of the ratios (Figure 12). In particular, it is clear that at the beginning of the sample period the optimal/actual ratios for roads were moving in the opposite direction to those of water and sewer structures and other structures. This can be explained by the fact that H was growing at a rapid rate as the interstate highway system was under construction. However, as the previous discussion made clear, it is not just changes in ratio denominators (the actual growth rates of the different types of infrastructure) that explain variations in the ratios. The optimal infrastructure elasticities reveal that some types of capital are more responsive to factor price changes than others. For example, the elasticities for other structures are between three and five times higher than the elasticities for highways and

Figure 12. *Comparison of Optimal/Actual Ratios: Roads, Water & Sewer Systems and Other Structures*



streets. This partly explains why the 40 per cent decline in the price of private capital relative to the price of labour induced a bigger increase in O^* than in H^* or WS^*, leading to a rise in O^*/O between 1981 and 1994.

In Chapter 2 the "infrastructure slowdown" was highlighted. From 1969 to 1982 annual investment in public infrastructure fell from $109 billion to $77 billion and only returned to 1969 levels at the end of the 1980s. As a result, all the infrastructure stocks grew at slower rates from the early 1970s than in the previous two decades. Many researchers believe that this infrastructure slowdown had a significant effect upon private production. However, it appears from the results reported in the preceding subsections that the private sector would not have benefited much from increases in total G or any of its components. Examining this issue further, the first part of Table 11 lists the annual growth rates of the various components of the core infrastructure stock over the sample period. The sample has been divided into two parts: the first is a period of rapid growth in the

Table 11. *Comparison of Infrastructure Growth Rates and Optimal/Actual Ratios*

	1959-72	1973-94
Growth in Public Capital Stock(% p.a.)		
Highways & Streets	4.04	0.84
Water & Sewers	3.50	2.64
Other Structures	5.30	2.69
Optimal/Actual Ratios (averages)		
Highways & Streets	0.97	0.95
Water & Sewers	0.87	0.94
Other Structures	0.84	0.88

Note: (1) During each of the years 1959-1972 the growth rate of core infrastructure was above average; from 1973-1994 it was below average. (2) Optimal/actual ratios are averages.

infrastructure stock; the second is a period of slow growth. The second part of the table contains average optimal/actual ratios for the different types of infrastructure over the same time periods. Each type of infrastructure grew rapidly from 1959-72 and each grew at a slower rate from 1973-94. As discussed in Chapter 2, the slowdown was particularly marked in the case of highways and streets. The growth rate of other structures almost halved and the growth rate of water and sewer structures fell by over 25 per cent. If the different types of infrastructure had continued to grow at their 1959-72 rates, by 1994 the stock of roads would have been 98 per cent higher than it actually was; the stock of water and sewers capital would have been 20 per cent higher and the stock of other structures would have been 74 per cent higher. The crucial question is whether the private business sector would have benefited from extra infrastructure. In terms of the optimal/actual ratios the conclusion is that the private business sector would not have benefited. Looking at the average optimal/actual ratios reported in Table 11 and ignoring the values of the ratios (ie, whether they are numbers greater than or less than unity) and concentrating instead on the extent to which they change between the two periods, it is clear that the infrastructure slowdown did not have a significant effect on private business sector costs. The average ratio for highways and streets hardly moved between time periods (in fact it decreased), implying that once the interstate highway system was completed there was no need to increase the stock of roads by 4 per cent a year. Although the growth rate of water and sewer systems slowed by almost one percentage point for 20 years, this led to an increase of only 8 per cent in the optimal/actual ratio. Furthermore, the level of the ratios implies that the stocks of these types of capital remained close to optimal after 1973. Finally, despite the fact that the growth rate of this type of capital fell by 50 per cent between 1973 and 1994 there was only a 5 per cent increase in the optimal/actual ratio. Furthermore, to the extent that faith can be placed in the levels of the ratios, the increase in the optimal/actual ratio was not large enough to justify extra spending on other structures: the average level of the ratios points to the existence of a not insignificant surplus.

Finally, it is worth commenting on the comparability of the results from the aggregate and disaggregated infrastructure models. The weighted average of the disaggregated optimal/actual ratios can be compared with those derived from the aggregate infrastructure model.[41] Obviously the two sets are not identical because the relevant optimal equations contain a number of different variables and parameter estimates. However, the two sets are similar in a number of respects. The simple correlation coefficient between the two sets has a value of 0.93, which is very high considering the relevant variables are ratios. The average ratios are also of a similar

[41] The disaggregated optimal/actual ratios are weighted by their respective infrastructure shares.

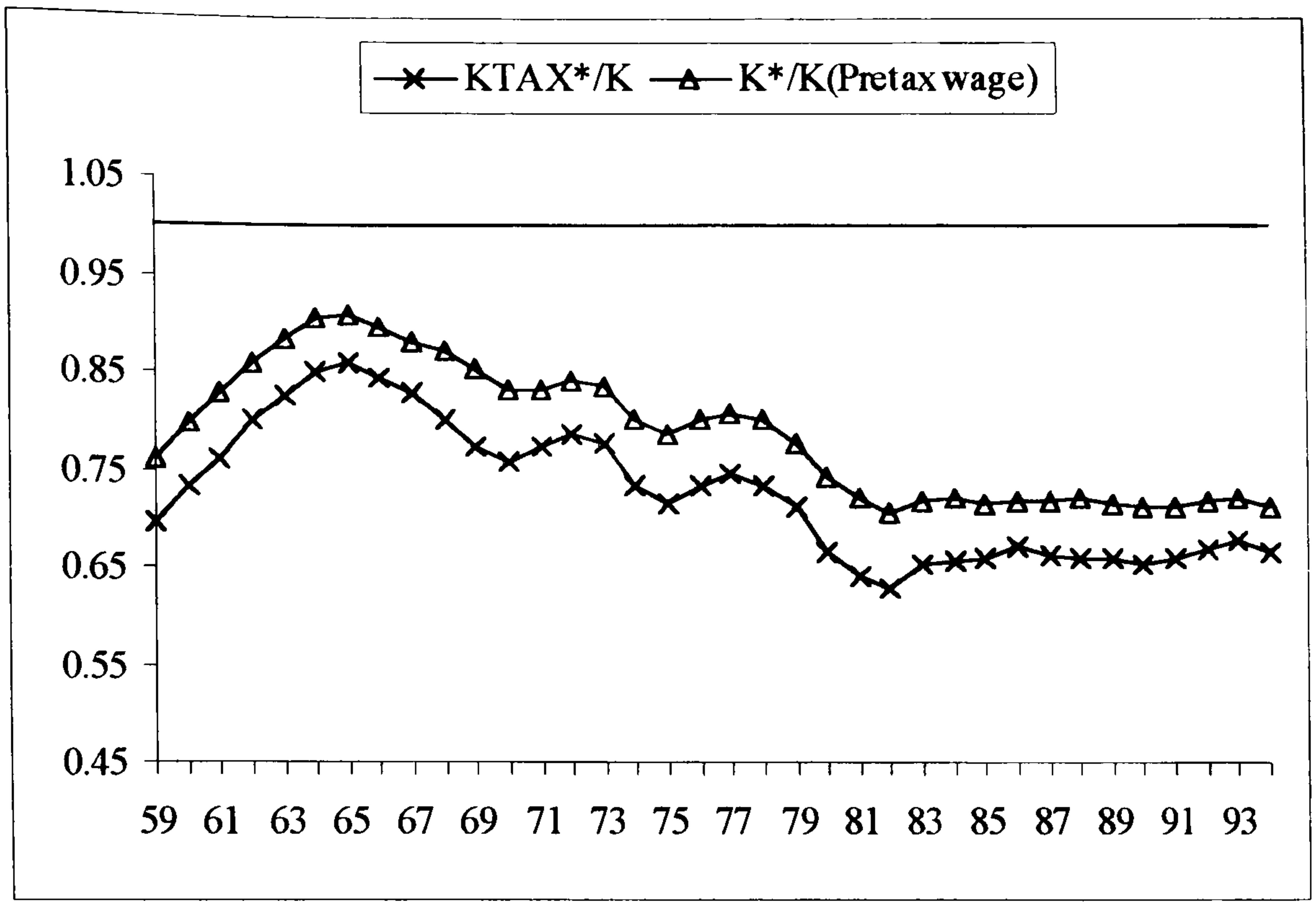
magnitude: 0.94 for the disaggregated model compared with 0.96 for the aggregate infrastructure model. I also carried out a likelihood ratio test to select between the restricted (aggregate) and unrestricted (disaggregated) models.[42] The resulting chi-square value of 37.3 (13 degrees of freedom) rejects in favour of the disaggregated model.

8. Private Capital

Although the focus is on calculating optimal infrastructure stocks, the optimal stock of private capital was also calculated for comparative purposes.[43] Figure 13 graphically illustrates the optimal/actual ratios for private capital. One set uses after-tax measures, the other uses pre-tax measures. The average optimal/actual ratios are 0.73 and 0.79 respectively. These ratios provide some guidance as to whether faith should be placed in the *levels* of the optimal/actual infrastructure ratios. To the extent that firms are cost minimisers one would expect the private sector in the long run to attempt to accumulate capital up to the point where $K = K^*$. In the short run the two measures may not be equal due to specific failures in the market mechanism. It may be that $K \neq K^*$ not because individual firms in the economy do not make efficient use of their labour and capital but because the allocation of labour or of capital among firms or sectors is not efficient. An external shock to the economy may alter the relative profitability of labour or capital used in different

[42] See Enders (1995), pp. 312-315 for a description of this test.
[43] To derive the optimal private capital stocks, parameter estimates from the disaggregated infrastructure model were inserted into the K^* equation.

Figure 13. *Ratio of Optimal to Actual Private Capital Stock, 1959-94.*

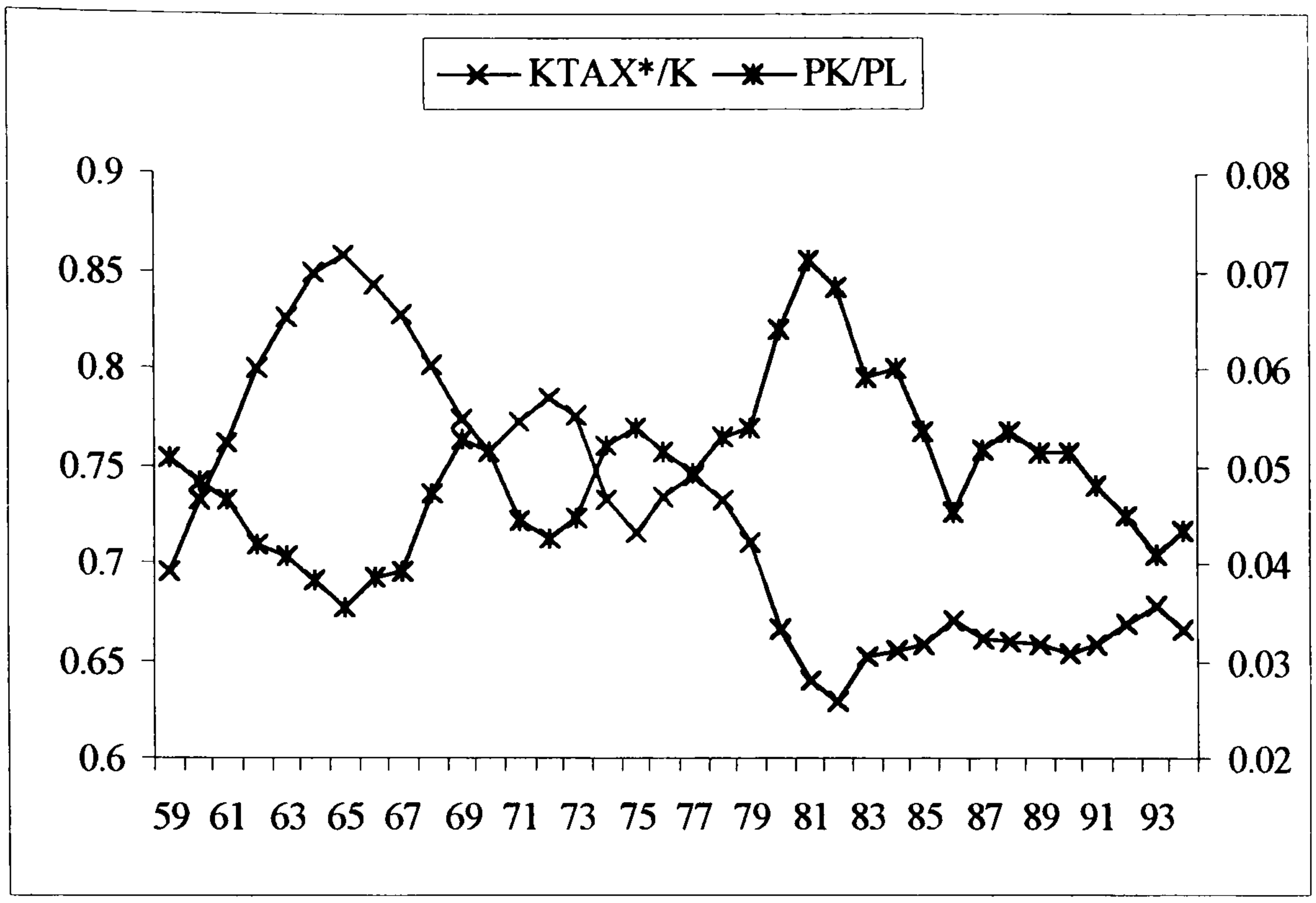


Note: KTAX*/K and K*/K(Pretax wage) are tax-adjusted and pre-tax ratios respectively

activities but the adjustment process in terms of which labour and capital are reallocated to achieve aggregate efficiency may fail to take place because of institutional or marketplace price rigidities. It is also likely that $K \neq K^*$ in the short run because investment in many types of private capital is lumpy. Nevertheless, in the long-run, one would expect the private capital stock to be close to optimal.

The fact that there was surplus private capital throughout the sample period may be due to a number of factors, eg, mismeasurement of input prices (in particular those of private and public capital) or estimation issues. Adjusting variables for tax purposes clearly has little effect on the outcome. Regardless of whether the ratio levels provide reliable information, it is still possible to glean interesting insights by analysing the pattern of the optimal/actual ratios and by examining the effect of changes in various private economic measures on the optimal

Figure 14. *Comparison of the Relative Price of Private Capital (RHS) with the Optimal/Actual Private Capital Ratio (LHS), 1959-94.*



infrastructure stocks, both of which form the backbone of the analysis in preceding sections.[44] The pattern of the private capital optimal/actual ratios is also worthy of further examination. If the relative price of private capital is defined as P_K/P_L, the price of capital divided by the labour wage rate, then one would expect an increase in the private capital optimal/actual ratio (signalling the need to accumulate capital at the expense of labour) if there were a decrease in the relative price of capital. It is clear from Figure 14 that this inverse relationship between K^*/K and P_K/P_L existed throughout the sample period. The relative price of capital declined until 1965 as hourly wages rose from $0.97 to $1.28 and the user cost of capital declined by 7.3 per cent (see Table 15 in Appendix C). This led to an increase in the private capital optimal/actual ratio. The trend in the relative price of capital was upwards from 1965

[44] Note that the finding that the optimal/actual ratios for G have a value closer to unity than those for K does not imply that the public sector is better at allocating resources than the private sector. It has already been stated that the optimal infrastructure stock ignores benefits accruing to private consumers and is possibly understated to the extent that the estimates of P_G are too low. If these factors were taken into consideration the finding may be that the relative divergence of G from G^* is greater than the divergence of K from K^*.

to 1981. Although wages were rising by 6.8 per cent per year on average, the user cost of capital was rising at an even faster rate, fuelled by a tripling in interest rates between 1965 and 1981.[45] As a result the optimal/actual ratio fell from 0.86 to 0.64 in 1981. From the early 1980s the relative price of private capital fell by 39 per cent because of reductions in the user cost of capital, coupled with wage growth of approximately 3 per cent per year. This led to a 49 per cent rise in K^* between 1981 and 1994. However, this did not lead to a dramatic increase in the optimal/actual ratio after 1981 due to the fact that the actual capital stock, K, was growing by almost 3 per cent per year.

9. Conclusion

In this chapter the cost function approach has been used to calculate the optimal quantity of core infrastructure in the U.S., where optimality is expressed in terms of cost savings enjoyed by the private business sector. The motivation for calculating optimal stocks is to compare the marginal benefit of infrastructure investment with the marginal cost of this investment. The finding that infrastructure has a significant effect on private costs does not necessarily justify extra public investment. The derivation of the optimal infrastructure stock, G^*, reveals that the optimal quantity of public capital depends on a number of variables: the prices of private factor inputs, the level of output and public capital's own user cost, P_G. Thus the level of public investment must not be examined in isolation but in the context of changes to variables that determine the optimal level of infrastructure. Following Morrison (1988), Morrison and Schwartz

[45] As measured by Moody's Aaa rate.

(1997) and Seitz (1994), a two-equation model based on the Generalised Leontief cost function was estimated and the parameter estimates were inserted into the optimal capital stock equations. A similar approach was followed by Berndt and Hansson (1992) using data for the Swedish private business sector.

The output elasticities of G and K (evaluated where $G = G^*$ and $K = K^*$) reveal that infrastructure has a positive but small elasticity compared with previous estimates obtained by infrastructure researchers and compared with private capital. Estimates of the optimal infrastructure elasticities reveal that G and K are complements and G and L are substitutes. The ratios of the optimal core infrastructure stock to the actual infrastructure stock reveal that, despite the slowdown in the growth of the public capital stock from the early 1970s, a shortage of infrastructure capital never developed. The user cost of private capital increased substantially from the early 1970s and, because G and K are complements, the slow growth in G was coupled with slow growth in G^*. It was also illustrated that the different ways of treating the input prices of public and private capital and labour for tax purposes has an effect on the levels of the optimal/actual ratios but does not alter any of the findings significantly.

The next step was to disaggregate the core infrastructure variable and compute the optimal quantity of highways and streets, water and sewer systems and other structures. The motivation for calculating the optimal quantity of each type of infrastructure is that if there is, for example, a surplus of core infrastructure this does not justify cutting back on public investment. Some of the individual infrastructure stocks may be oversupplied while others are in shortage. Furthermore, some types of infrastructure may be moving towards a state of underprovision while the surplus of others may be deepening. It is precisely this diversity that is uncovered when the optimal infrastructure stocks are calculated. There are also a number of similarities between the different components of core infrastructure. Each type of capital has a significant effect on private sector costs and each has a positive, though small, output elasticity. The highest elasticity is 0.027 for roads followed by 0.009 for water and sewer systems and 0.005 for other structures. None of the individual stocks was undersupplied on average over the sample period. The average optimal/actual ratio for roads was 0.96; the average ratio for water and sewers was 0.92 and the average ratio for other structures was 0.86. Each type of infrastructure complements private capital and substitutes for labour.

The optimal infrastructure equation (11) provides some insights into the appropriate policy response to a finding that $G^* \neq G$. It is clear that G^* can vary without any change in public investment. Thus before the public investment policy is altered to address any shortfall or surplus of G, policymakers must ensure that the change in the variable(s) responsible for causing G^* to increase or decrease will not be reversed. This is especially important given that infrastructure investments are lumpy and long lived.

Estimates of the private capital stock indicate that there was a significant surplus of this type of capital over the sample period. To the extent that the optimal/actual ratio for private capital should, in the long run, be close to unity, it may be argued that too much faith should not be placed in the *levels* of the optimal/actual ratios for the different types of infrastructure. However, the *patterns* (whether G, H, WS and O are moving closer to or further away from G^*, H^*, WS^* and O^*) do provide interesting information. Some types of infrastructure are more sensitive to changes in private economic variables than others. This, coupled with the fact that there were significant variations in the growth rates of the actual infrastructure stocks over the sample period, ensured that the optimal/actual ratios moved in different directions at different times. Variations in the K^*/K ratio can be explained by the cost of private capital relative to labour: the lower the relative cost of capital, P_K/P_L, the higher the desired capital stock.

While the results obtained in this chapter provide interesting insights into public capital's role in production there are a number of issues that have to be addressed in future research. For example, the focus on value-added inputs ignores changes in labour composition and energy price responses.[46] This omission can be explained partly by data availability and partly by the need to preserve degrees of freedom in the estimated models. This problem could be overcome using data for a set of manufacturing industries. The focus on the total private business sector is justified on the grounds that sectors other than manufacturing are likely to benefit from infrastructure investment. Furthermore, in calculating the optimal quantity of an aggregate national measure such as G with respect to the cost savings generated for only one sector, it would not be surprising to find that there is an infrastructure surplus. Nevertheless given the availability of a wider set of data on the various inputs and the advantages of using gross data rather than value-added data, it may be worthwhile conducting a similar analysis using data for the manufacturing sector.

The rental price of public capital, P_G, is an important variable in the analysis. Substantial care was taken in constructing this measure: the economic depreciation rates are asset specific and the discount rate reflects the lower opportunity cost of public sector funds. Optimal stocks were calculated using measures of P_G with and without adjustment for the

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[46] This point is emphasised by Lynde and Richmond (1993a) who incorporate intermediate price effects in their analysis of the slowdown in U.S. labour productivity growth.

excess burden of the tax system. Nevertheless it could be argued that more research is required into constructing measures of the marginal cost of public capital which take fuller account of social preferences.

Finally, a criticism of most cost function studies is that the shadow value of infrastructure, $-\partial C_V/\partial G$, does not take account of the fact that the benefits in the first year after the investment may not be representative of the annual benefits over the life of the investment. For example, it may take time for firms to adjust their mix of inputs and other aspects of the production process in response to changes in the public investment policy and it is possible that they do not take full advantage of such investments in the first year. Larger cost savings may only be realised several years after the investments take place. The time lag between new investment taking place and the realisation of benefits by the private sector provides scope for further research. This issue will be mentioned again in Chapter 4.

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Appendix A

Data Sources

Private and Public Capital Data

Data for the separate components of the private and public capital stocks was obtained from the Bureau of Economic Analysis' (BEA) diskettes: *Fixed Reproducible Tangible Wealth in the United States 1925-1994*. All stock measures are net of economic depreciation. The private capital data excludes residential capital. To calculate investment deflators for use in the rental price measures, current dollar stocks were divided by constant dollar stocks (measured in 1987 dollars). The BEA also provides economic depreciation totals for each type of capital and these were used to calculate the economic depreciation rates.

Value-added Output

This data was obtained from the *Economic Report of the President*. It includes only the output of the private business sector (excluding farms) and is measured in 1987 dollars. Data on hours was obtained from the same source.

Wages, Interest Rates

The wage rate in the non-farm private business sector, P_L, was obtained from the *Economic Report of the President*. Following Nadiri and Mamuneas (1994), it was multiplied by one minus the corporate income tax rate to convert it into an after-tax measure. The interest rate on ten-year treasuries (used to calculate the user cost of public capital) and Moody's Aaa ten-year rate (used to calculate the user cost of private capital) were also obtained from the *Economic Report of the President*.

Corporate Taxation Data

The data used to calculate the after-tax user cost of private capital comes from the same sources as that used by Nadiri and Mamuneas (1994). Data on the corporate income tax rate was obtained from Auerbach (1983) and Jorgenson and Sullivan (1981). Following Nadiri and Mamuneas (1994), after 1983 the corporate tax rate is taken to be 0.46, the constant rate over 1979-1982. The investment tax credit until 1980 is taken from Jorgenson and Sullivan (1981); for 1981 8 per cent is used and for 1982 to 1986 a rate of 7.5 per cent is used. Data on capital consumption allowances was obtained from the *Economic Report of the President*.

Appendix B

Comparison of Capital Aggregation Methods

In Section 3 the construction of aggregate measures of public and private capital using Divisia aggregation is discussed. In Table 12 the stock of core calculated from an unweighted summation of its components is compared with the stock of core calculated by Divisia aggregation. Dividing the latter by the former results in what Jorgenson and Griliches (1967) refer to as the average quality of capital.

Two points are worth noting. First, the two stocks of capital were almost identical at the beginning of the sample period. In fact the difference is a mere $124 million. Secondly, there has been virtually no change in the average quality of capital over time. This is not what one would expect at first glance because the composition of the core infrastructure stock has changed significantly over the sample period. In 1959 the stock of roads accounted for 69 per cent of the core infrastructure stock; by 1994 it accounted for 60 per cent. Predictably, the share of the remaining components has increased. The sewers' percentage has increased from 12 per cent to 16 per cent; the water percentage from 9.4 to 9.8 per cent; and other structures from 9 per cent to 14 per cent.

The reason there has been no change in the average quality of core capital is that most of its components have the same length of life (ie, the same depreciation rates and hence the same prices and marginal productivities). In Table 13 the average quality of the private capital stock is calculated. It is clear that the average quality of private capital has increased over time, rising from 0.93 in 1959 to 1.01 in 1994. This reflects the fact that the weighted-average depreciation rate of private capital has increased gradually over time, reflecting a slight shift to shorter-lived (more productive) assets.

Table 12. *Comparison of Core Infrastructure Stocks: Unweighted Summation and Divisia Aggregation, 1959-94 (millions of 1987 dollars)*

Date	(1) Unweighted Summation	(2) Divisia Aggregation	(2)/(1) Average Quality
59	468364	468488	1.0002
60	490379	490338	0.9999
61	514240	514042	0.9996
62	539105	538667	0.9991
63	566643	566139	0.9991
64	595458	594931	0.9991
65	625241	624831	0.9993
66	655787	655396	0.9994
67	685944	685820	0.9998
68	718971	719063	1.0001
69	746926	747250	1.0004
70	772364	772839	1.0006
71	795481	796005	1.0007
72	816555	817185	1.0008
73	835739	836484	1.0009
74	854149	854699	1.0006
75	870554	870789	1.0003
76	886548	886955	1.0005
77	899942	900698	1.0008
78	911551	912368	1.0008
79	923917	924325	1.0004
80	935293	935059	0.9997
81	945828	945275	0.9994
82	955610	955154	0.9995
83	964943	964707	0.9997
84	975413	975302	0.9998
85	989300	989290	0.9999
86	1003545	1003530	0.9999
87	1020817	1020817	1.0000
88	1036012	1035933	0.9999
89	1051600	1051525	0.9999
90	1069562	1069480	0.9999
91	1089087	1089010	0.9999
92	1108708	1108716	1.0000
93	1131093	1131324	1.0002
94	1154682	1155064	1.0003

Table 13. *Comparison of Private Capital Stocks: Unweighted Summation and Divisia Aggregation, 1959-94 (millions of 1987 dollars)*

Date	**(1) Unweighted Summation**	**(2) Divisia Aggregation**	**(2)/(1) Average Quality**
59	1435368	1328974	0.9258
60	1482360	1371622	0.9252
61	1525999	1409320	0.9235
62	1577726	1456945	0.9234
63	1630569	1507307	0.9244
64	1700296	1575388	0.9265
65	1798061	1671679	0.9297
66	1909431	1785207	0.9349
67	2007885	1884004	0.9383
68	2110868	1991646	0.9435
69	2222308	2108231	0.9486
70	2317864	2203560	0.9506
71	2402373	2287325	0.9521
72	2495899	2384049	0.9551
73	2619173	2516157	0.9606
74	2732005	2633671	0.9640
75	2801513	2705511	0.9657
76	2867289	2777423	0.9686
77	2956523	2876981	0.9730
78	3080649	3017671	0.9795
79	3228687	3183854	0.9861
80	3363903	3328005	0.9893
81	3502157	3475714	0.9924
82	3605328	3582688	0.9937
83	3687820	3672113	0.9957
84	3824699	3820636	0.9989
85	3985629	3983704	0.9995
86	4110354	4111516	1.0002
87	4213285	4213285	1.0000
88	4324264	4328943	1.0010
89	4439731	4447983	1.0018
90	4543085	4547630	1.0010
91	4602904	4606550	1.0007
92	4655956	4664140	1.0017
93	4760779	4788893	1.0059
94	4924247	4984440	1.0122

Table 14. *Comparison of Different Private Capital Stock Aggregation Methods*

Time span	------ Growth Rates ------ (1) Divisia aggregation	(2) Direct aggregation	Composition effect: (1)-(2)
1959-1994	3.7	3.5	0.2
1959-1969	4.3	4.1	0.2
1970-1979	3.7	3.4	0.3
1980-1989	2.9	2.8	0.1
1990-1994	1.9	1.6	0.3

In Table 2 the two capital stock aggregation methods were compared. The figures were taken from Harper *et al.* (1995). An updated version of this table is reproduced in Table 14. It is clear that the effect of Divisia aggregation is felt more in some periods than others. This reflects the fact that the weighted-average depreciation rate of private capital has increased gradually over time, reflecting a slight shift to shorter-lived (more productive) assets.

Over the entire sample period the Divisia index of private capital grew 0.2 per cent per year faster than the aggregate capital stock calculated in the usual way. Although small in absolute terms, over the 36-year sample period this translates into 7 per cent more capital.

Appendix C

Rental Prices of Private and Public Capital

Table 15. *Estimates of the Prices of Private and Public Capital, 1959-94*

	P_K	$P_K(Tax)$	P_G	$P_G(Tax)$	P_H	P_{WS}	P_O	$P_H(Tax)$	$P_{WS}(Tax)$	$P_O(Tax)$
1959	0.0357	0.0492	0.0164	0.0240	0.0156	0.0168	0.0177	0.0228	0.0246	0.0259
1960	0.0357	0.0486	0.0159	0.0232	0.0151	0.0165	0.0173	0.0220	0.0241	0.0253
1961	0.0356	0.0477	0.0155	0.0226	0.0146	0.0161	0.0170	0.0214	0.0235	0.0248
1962	0.0358	0.0447	0.0162	0.0236	0.0154	0.0164	0.0176	0.0225	0.0240	0.0257
1963	0.0359	0.0445	0.0166	0.0242	0.0159	0.0167	0.0180	0.0232	0.0244	0.0263
1964	0.0368	0.0449	0.0172	0.0250	0.0164	0.0172	0.0187	0.0239	0.0252	0.0274
1965	0.0378	0.0454	0.0180	0.0263	0.0173	0.0180	0.0190	0.0253	0.0262	0.0277
1966	0.0412	0.0511	0.0207	0.0301	0.0201	0.0202	0.0223	0.0293	0.0295	0.0325
1967	0.0438	0.0544	0.0219	0.0320	0.0215	0.0211	0.0236	0.0313	0.0309	0.0345
1968	0.0481	0.0634	0.0247	0.0360	0.0241	0.0240	0.0265	0.0352	0.0351	0.0388
1969	0.0531	0.0755	0.0297	0.0433	0.0292	0.0284	0.0318	0.0426	0.0415	0.0464
1970	0.0597	0.0845	0.0352	0.0514	0.0351	0.0329	0.0370	0.0512	0.0481	0.0540
1971	0.0606	0.0793	0.0331	0.0483	0.0323	0.0327	0.0351	0.0472	0.0478	0.0512
1972	0.0635	0.0820	0.0353	0.0515	0.0344	0.0352	0.0373	0.0502	0.0514	0.0545
1973	0.0693	0.0913	0.0426	0.0622	0.0424	0.0405	0.0442	0.0619	0.0591	0.0645
1974	0.0851	0.1145	0.0589	0.0859	0.0599	0.0535	0.0596	0.0875	0.0781	0.0870
1975	0.0949	0.1265	0.0614	0.0896	0.0608	0.0600	0.0639	0.0888	0.0876	0.0933
1976	0.0987	0.1300	0.0588	0.0859	0.0568	0.0611	0.0624	0.0829	0.0891	0.0911
1977	0.1035	0.1348	0.0625	0.0912	0.0606	0.0639	0.0658	0.0885	0.0933	0.0961
1978	0.1174	0.1563	0.0832	0.1215	0.0840	0.0792	0.0843	0.1226	0.1157	0.1230
1979	0.1352	0.1788	0.1057	0.1544	0.1092	0.0950	0.1052	0.1595	0.1386	0.1536
1980	0.1690	0.2304	0.1324	0.1933	0.1365	0.1197	0.1323	0.1993	0.1747	0.1932
1981	0.2047	0.2786	0.1537	0.2244	0.1542	0.1480	0.1573	0.2252	0.2160	0.2297
1982	0.2095	0.2833	0.1429	0.2086	0.1401	0.1439	0.1493	0.2045	0.2100	0.2179
1983	0.1952	0.2553	0.1276	0.1863	0.1243	0.1293	0.1335	0.1815	0.1887	0.1950
1984	0.2049	0.2698	0.1474	0.2152	0.1461	0.1450	0.1521	0.2133	0.2117	0.2220
1985	0.1951	0.2478	0.1358	0.1982	0.1358	0.1303	0.1394	0.1983	0.1902	0.2035
1986	0.1762	0.2134	0.1068	0.1559	0.1057	0.1034	0.1106	0.1544	0.1509	0.1615
1987	0.1834	0.2512	0.1158	0.1691	0.1142	0.1134	0.1195	0.1668	0.1655	0.1744
1988	0.1942	0.2677	0.1252	0.1828	0.1240	0.1220	0.1288	0.1810	0.1780	0.1880
1989	0.1951	0.2683	0.1236	0.1804	0.1218	0.1203	0.1285	0.1779	0.1756	0.1877
1990	0.2006	0.2775	0.1255	0.1832	0.1237	0.1212	0.1322	0.1806	0.1769	0.1930
1991	0.1958	0.2682	0.1176	0.1717	0.1155	0.1134	0.1254	0.1686	0.1656	0.1831
1992	0.1909	0.2569	0.1089	0.1591	0.1049	0.1096	0.1159	0.1531	0.1600	0.1692
1993	0.1831	0.2392	0.0988	0.1442	0.0941	0.1011	0.1053	0.1373	0.1476	0.1537
1994	0.1942	0.2599	0.1164	0.1699	0.1116	0.1183	0.1234	0.1629	0.1727	0.1801

Note: P_K, P_G, P_H, P_{WS}, P_O are the pre-tax prices of private capital, core public capital, highways and streets, water and sewer systems and other structures respectively. $P_K(Tax)$, $P_G(Tax)$, $P_H(Tax)$, $P_{WS}(Tax)$, and $P_O(Tax)$ are after-tax prices.

Appendix D

Average Economic Depreciation Rates, BEA Data.

Table 16. *Average Rates of Economic Depreciation, 1959-94, BEA Data*

Private Business Sector	Equipment	Structures
Mining	0.162	0.117
Manufacturing:		
Durables	0.103	0.055
Nondurables	0.117	0.056
Transportation & Public Utilities		
Railroad	0.083	0.052
Local &Interurban	0.127	0.075
Trucking & Warehousing	0.186	0.050
Water Transportation	0.079	0.046
Transportation by Air	0.102	0.039
Pipelines Except Gas	0.209	0.047
Transportation Services	0.079	0.053
Communications	0.122	0.043
Electric, Gas & Sanitary	0.090	0.040
Wholesale Trade	0.168	0.042
Retail Trade	0.167	0.050
Finance, Insurance & Real Estate	0.150	0.041
Services	0.157	0.049

Public Sector	Capital Type
Equipment	0.116
Industrial Buildings	0.071
Educational Buildings	0.034
Hospital Buildings	0.035
Other Buildings	0.033
Highways & Streets	0.028
Sewer Systems	0.027
Water Supply	0.028
Other Structures	0.034

Table 17. *Comparison of Public Capital Economic Depreciation Rates, 1959-94*

	BEA	Berndt & Hansson
Private Capital		
Mining Structures	0.117	0.056
Manufacturing Structures	0.055	0.036
Railroad Structures	0.052	0.018
Service Structures	0.049	0.029
Retail Equipment	0.167	0.206
Wholesale Equipment	0.168	0.206
Finance, Insurance & Real Estate Equipment	0.150	0.206
Public Capital		
Highways & Streets	0.028	0.100
Sewer Systems	0.027	0.100
Water Supply	0.028	0.100
Other Structures	0.034	0.030

Table 17 compares some economic depreciation rates calculated using BEA data with rates used by Berndt and Hansson (1992), based on Hulten & Wykoff (1981). It is especially among the infrastructure stocks that the depreciation rates calculated using BEA data diverge significantly from those used by Berndt and Hansson.

Appendix E

Investment Figures

Table 18. *Annual Investment Figures: Core Infrastructure, 1960-94 (Millions of 1987 Dollars)*

Date	Total	% Δ	Roads	% Δ	WatSew	% Δ	Other	% Δ
60	35416	0.195	25032	-1.846	6291	-1.100	4093	17.513
61	37891	6.988	26844	7.238	6603	4.959	4444	8.575
62	39441	4.091	28286	5.371	7254	9.859	3901	-12.219
63	42823	8.574	30769	8.778	7391	1.888	4663	19.533
64	44797	4.609	30521	-0.806	9255	25.219	5021	7.677
65	46322	3.404	31372	2.788	9669	4.473	5281	5.178
66	48021	3.667	33131	5.606	9097	-5.915	5793	9.695
67	48424	0.839	32635	-1.497	8639	-5.034	7150	23.424
68	52170	7.735	33526	2.730	10967	26.947	7677	7.370
69	47616	-8.729	31222	-6.872	9092	-17.097	7302	-4.884
70	45908	-3.587	30472	-2.402	8383	-7.798	7053	-3.410
71	44093	-3.953	30215	-0.843	8150	-2.779	5728	-18.786
72	42935	-2.626	28311	-6.301	8086	-0.785	6538	14.141
73	41334	-3.728	26343	-6.951	8525	5.429	6466	-1.101
74	41154	-0.435	23067	-12.436	11185	31.202	6902	6.742
75	39699	-3.535	21591	-6.398	12631	12.928	5477	-20.646
76	39842	0.360	21258	-1.542	12037	-4.702	6547	19.536
77	37767	-5.208	19930	-6.247	10810	-10.194	7027	7.331
78	36476	-3.418	18646	-6.442	10891	0.749	6939	-1.252
79	37714	3.394	18812	0.890	11820	8.529	7082	2.060
80	37214	-1.325	17812	-5.315	12327	4.289	7075	-0.098
81	36861	-0.948	17779	-0.185	11526	-6.497	7556	6.798
82	36565	-0.803	18211	2.429	10432	-9.491	7922	4.843
83	36576	0.030	19002	4.343	9908	-5.023	7666	-3.231
84	38176	4.374	20963	10.320	9851	-0.575	7362	-3.965
85	42087	10.244	21492	2.523	10807	9.704	9788	32.953
86	43016	2.207	22853	6.332	12173	12.640	7990	-18.369
87	46619	8.375	25304	10.725	13377	9.890	7938	-0.650
88	45120	-3.215	25751	1.766	13627	1.868	5742	-27.664
89	47280	4.787	25888	0.532	13663	0.264	7729	34.604
90	49033	3.707	27118	4.751	14127	3.396	7788	0.763
91	51241	4.503	28160	3.842	14803	4.785	8278	6.291
92	51997	1.475	29026	3.075	14594	-1.411	8377	1.195
93	55446	6.633	30956	6.649	15091	3.405	9399	12.200
94	57377	3.482	32997	6.593	15005	-0.569	9375	-0.255

Note: Total=total core; Roads=highways & streets; Watsew=water & sewers; Other=other structures

Chapter 4

The Relationship Between Infrastructure Investment and Adjusted Total Factor Productivity: Results from Causality Tests and the Estimation of Autoregressive Models

1. Introduction

Several reviews of the infrastructure literature[1] have questioned whether public capital affects productivity or whether the relationship between the variables runs in the opposite direction: if infrastructure is a normal good, high rates of productivity growth which lead to higher levels of income will lead to increased demand for infrastructure services. It is important to determine the direction of causation. Causation one way implies that public investment is a macro policy variable that can have an important supply-side effect on economic growth; causation the other way supports "Wagner's Law", that public expenditure is merely a passive variable, responding to changes in the level of income in the economy.[2] There is only one study (Tatom, 1993) in which the causal relationship between the two variables has been tested. All other causality

[1] For example, Eisner (1991), Federal Highway Administration (1992), Gillen (1996), Gramlich (1994), Hurst (1994), Munnell (1993), and Musgrave (1990).

[2] See Sahni and Singh (1984).

testing in the infrastructure literature attempts to identify the nature of the relationship between public investment and *private investment*, rather than total factor productivity.[3] The purpose of this chapter is to examine the relationship between infrastructure investment and total factor productivity (TFP) in U.S. manufacturing.

The differential effects of infrastructure in more disaggregated analyses is a focus of this thesis. Thus, apart from determining the direction of causation, there are a number of other issues that have to be addressed. If infrastructure "causes" productivity growth, which types of infrastructure are the most productive? Does infrastructure account for a significant portion of the variation in productivity? Has this effect declined over time? Which industries rely most on public capital? An attempt is made to answer all these questions in this chapter.

Use is made of a multivariate autoregressive framework that incorporates dynamic effects and allows each variable to be treated as endogenous within a multi-equation system. In addition to the obvious advantage of not imposing a priori exogeneity assumptions, this framework also relieves the researcher of the burden of having to specify the structural relationship between public capital and productivity, as the autoregressive model can be interpreted as a general system of reduced form equations for the variables. However, within this framework meaningful economic hypotheses can be tested.

The Final Prediction Error Criterion of Akaike (1969a,b) is used to construct the models by statistically determining the appropriate number of lags for each of the variables. Causality tests are then carried out within this framework. As in previous chapters, the focus is on the importance of different infrastructure aggregates. In

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[3] For example, Eberts and Fogarty (1987), Erenburg and Wohar (1995), Looney and Frederiksen (1981) and Ramirez (1994).

Chapter 2 it was shown how stocks of the different types of public capital have grown at very different rates since the 1950s. In Chapter 3 it was shown that if the core infrastructure stock is in some sense optimal, this does not rule out the existence of a shortage or surplus of some of its components. Thus it is possible that the choice of infrastructure variable will influence the results of the causality testing procedure. Three different measures of infrastructure investment are included in the analysis: total public investment, investment in core infrastructure and disaggregated core investment.[4]

The results overturn Tatom's (1993) finding and other researchers' stated view that infrastructure does not cause productivity growth. Growth in both total and core infrastructure investment Granger causes the TFP growth rate. Using disaggregated core infrastructure data it is possible to establish which of the individual infrastructure stocks are the most productive. Causality tests reveal that only road investment affects TFP growth. The results also provide evidence to support the "reverse causation" hypothesis but the evidence is mixed: the TFP growth rate causes growth in total public investment but not in core investment. A similarly ambiguous relationship is found using disaggregated data – infrastructure is found to be both a normal good and an inferior good.

Several authors, including Hicks (1979), Zellner (1979) and Simon (1970) have emphasised that the results of any causality testing procedure cannot be viewed in isolation from economic theory. In other words, they argue against the mechanical application of causality tests in favour of "measurement with theory". For example, there is consensus in the infrastructure literature (see Aschauer, 1989, and Morrison and Schwartz, 1997) that core public investment will have a greater effect on the TFP

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[4] Investment in highways and streets, water and sewer systems structures and other structures

growth rate than total investment. Thus one would expect inclusion of core investment to lead to a lower mean square error than inclusion of total investment. Similarly, the finding that productivity gains result in spending on some types of infrastructure but not others does not conform to economic theory, indicating that further investigation is required.[5] To refute claims that the results are a function of the lag-length selection criterion used, causality tests are carried out using four other criteria. The results are identical – the TFP growth rate causes some types of public investment but not others. The next step is to analyze the variables used in the analysis more closely, in particular the TFP measure, which is constructed under a number of simplifying assumptions. As Malley *et al.* (1998) point out, standard constructions of TFP ignore considerations pertaining to market power, returns to scale and variable factor utilization over the business cycle. If the Solow residual does not measure "true" productivity growth, it is possible that conclusions drawn about the relationship between productivity and any other variable are invalid.[6] This observation has important implications for many other studies in the infrastructure literature, most of which use a measure of TFP based on Solow (1957).[7]

Since Solow's seminal work, substantial progress has been made in the construction of alternative TFP measures. For example, Hall (1990) modifies the Solow residual to take account of departures away from constant returns to scale and perfect competition. Basu (1996), building on Hall's work, adjusts the residual to take

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[5] See Rubinfeld (1987) and Cornes and Sandler (1996) on the demand for public goods and near public goods.

[6] For example, examining the interaction between employment and TFP growth, Malley *et al.* (1998) illustrate that the common practice of including Solow residuals in VARs picks up an artificial correlation over the cycle between TFP and employment which arises due to factor utilisation effects.

[7] For example, Aschauer, 1989; Munnell 1990a; Ford and Poret, 1991; Hulten and Schwab, 1991b; Moomaw and Williams, 1991; and Tatom, 1993. An exception is Lynde and Richmond (1993) who analyse a productivity measure that incorporates increasing returns to scale.

account of variations in factor usage. These developments are used to construct a second TFP measure that allows the relationship between infrastructure and productivity to be re-examined. The results are quite different to those obtained using the standard Solow residual. No evidence of feedback between the variables is found using the new measure; a one-way relationship exists from infrastructure investment to the TFP growth rate. The results are also robust to the use of infrastructure data at different levels of aggregation. Furthermore, when the infrastructure data is disaggregated, it is not just road investment which is found to cause productivity – investment in other structures also affects the TFP growth rate.

The productivity data is also disaggregated and causality tests are performed using the adjusted TFP measure calculated for each of the 20 two-digit SIC industries. The results reveal that infrastructure investment affects productivity growth in some industries far more than in others. The spread of results is explained by structural differences between industries – infrastructure determines the productivity growth rates of the most capital-intensive industries, in particular those that use the road network the most intensively.

Apart from qualitative evidence of infrastructure's relationship with productivity, *quantitative* evidence of infrastructure's impact on the TFP growth rate is also provided. The estimates obtained using adjusted multifactor productivity impute to infrastructure a much smaller role than those obtained using the Solow residual. Thus it is difficult to agree with, for example, Aschauer (1993) that up to a quarter of the productivity growth slowdown can be explained by the fall in infrastructure investment. Nor, however, is it possible to agree with Hulten and Schwab (1991a) or Jorgenson (1991) and others that the relationship between the variables is purely spurious. It is likely that infrastructure investment has a positive effect on private productivity but this effect is quite small, smaller even than that implied by the results of regional production function and cost function studies.[8]

Due to data availability the focus is only on the manufacturing sector. However, because the data is in differences (growth rates) there is no danger of underestimating infrastructure's importance simply because the manufacturing sector is only one component of the private business sector.[9] However, to the extent that manufacturing productivity and productivity in the rest of the economy are determined by different factors, the results obtained in this chapter cannot be extrapolated to the other sectors.

The chapter is divided up as follows. In Section 2 the Solow residual is derived and estimated. In Section 3 the causality testing procedure is described and tests are conducted using the total manufacturing Solow residual and different infrastructure aggregates. Infrastructure's impact on productivity is estimated using a number of autoregressive models. In Section 4 the adjusted measure of TFP is derived. Following Hall (1990), the original Solow residual is first modified to allow for imperfect competition and varying returns to scale. Next, following Basu (1996), a measure is derived that takes account of variations in labour and capital usage. In Section 5 this measure is compared with the original Solow residual and the variations of it (for example, labour and capital productivity) used in the infrastructure literature. In Section 6 the relationship between infrastructure investment and adjusted TFP growth is re-examined. The impact of different types of public investment (total, core and disaggregated) on the TFP growth rate is also estimated. In Section 7 individual industry TFP measures are constructed and the causality testing procedure is repeated.

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[8] The results of these studies are discussed in the literature review in Chapter 1.
[9] This was an issue in Chapter 3, where data in levels were employed.

Finally, the findings are summarised in Section 8 and a number of issues are addressed in the appendices.

2. Derivation of TFP (Solow, 1957)

The starting point is the standard neoclassical production function

$$Q_t = \Theta_t F(L_t, M_t, K_t), \tag{1}$$

where Θ_t represents an index of Hicks neutral technical change, implying that the ratio of marginal products remains unchanged for a given capital/labour ratio; F is a homogeneous constant returns to scale production function, Q_t is real gross output; and L_t, M_t and K_t are real labour, material and capital inputs. Most of the production functions in the infrastructure literature use value-added data. Basu (1996), however, notes that much of the empirical literature estimating production functions from gross-output data tests and rejects the conditions needed for the existence of a value-added function.[10] Taking logs of (1) and differentiating with respect to time gives

$$\frac{d\ln Q_t}{dt} = \frac{d\ln \Theta_t}{dt} + \frac{d\ln F(L_t, M_t, K_t)}{dt}, \tag{2}$$

which is the same as

$$\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \frac{\partial F}{\partial L}\frac{1}{F(.)}\dot{L} + \frac{\partial F}{\partial M}\frac{1}{F(.)}\dot{M} + \frac{\partial F}{\partial K}\frac{1}{F(.)}\dot{K}, \tag{3}$$

where $\Theta_t \geq 0$ and $F(.)=F(L_t, M_t, K_t)$.

[10] See Jorgenson, Gollop and Fraumeni (1987). Basu and Fernald (1997) show that using value-added data creates bias when estimating returns to scale, a matter that is taken up in Section 4.

From (1) it can be seen that

$$\frac{1}{F(.)}=\frac{\Theta_t}{Q_t}. \tag{4}$$

Substituting (4) into (3) and multiplying the second term of (3) by *L/L*, the third by *M/M* and the fourth by *K/K*:

$$\frac{\dot{Q}}{Q}=\frac{\dot{\Theta}}{\Theta}+\Theta\frac{\partial F}{\partial L}\frac{L}{Q}\frac{\dot{L}}{L}+\Theta\frac{\partial F}{\partial M}\frac{M}{Q}\frac{\dot{M}}{M}+\Theta\frac{\partial F}{\partial K}\frac{K}{Q}\frac{\dot{K}}{K}. \tag{5}$$

The marginal products of the various inputs $\Theta\partial F/\partial L$, $\Theta\partial F/\partial M$ and $\Theta\partial F/\partial K$ are replaced with revenue shares by solving the firm's cost-minimisation problem. Total costs are equal to

$$C = P_L L + P_M M + P_K K, \tag{6}$$

where P_L is the nominal labour wage rate, P_M is the price of materials and P_K is the rental price of capital. If a profit-maximising firm seeks to minimise the cost of producing a given level of output, *Q*, its profit-maximising problem can be expressed as

$$\underset{L,M,K}{Min}\ C = P_L L + P_M M + P_K K \quad s.t.\, Q=\Theta F(L,M,K). \tag{7}$$

The Lagrangean function used to solve this cost-minimisation problem is

$$\Lambda = P_L L + P_M M + P_K K + \lambda\left(Q-\Theta F(L,M,K)\right), \tag{8}$$

and the corresponding first order conditions are

$$\frac{\partial\Lambda}{\partial L}=P_L-\lambda\Theta\frac{\partial F}{\partial L}=0, \tag{9}$$

$$\frac{\partial\Lambda}{\partial M}=P_M-\lambda\Theta\frac{\partial F}{\partial M}=0,\text{ and} \tag{10}$$

$$\frac{\partial\Lambda}{\partial K}=P_K-\lambda\Theta\frac{\partial F}{\partial K}=0. \tag{11}$$

Rearranging (9), (10) and (11):

$$\Theta \frac{\partial F}{\partial L} = \frac{P_L}{\lambda}, \tag{12}$$

$$\Theta \frac{\partial F}{\partial M} = \frac{P_M}{\lambda}, \text{ and} \tag{13}$$

$$\Theta \frac{\partial F}{\partial K} = \frac{P_K}{\lambda}. \tag{14}$$

Substituting these values into (5) gives

$$\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \frac{P_L L}{\lambda Q}\frac{\dot{L}}{L} + \frac{P_M M}{\lambda Q}\frac{\dot{M}}{M} + \frac{P_K K}{\lambda Q}\frac{\dot{K}}{K}. \tag{15}$$

The term λ is marginal cost. Under the assumption of perfect competition,

$P_Q = \lambda$ and (15) becomes

$$\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \frac{P_L L}{P_Q Q}\frac{\dot{L}}{L} + \frac{P_M M}{P_Q Q}\frac{\dot{M}}{M} + \frac{P_K K}{P_Q Q}\frac{\dot{K}}{K}, \tag{16}$$

where $P_L L/P_Q Q$, $P_M M/P_Q Q$ and $P_K K/P_Q Q$ are the respective costs of labour, materials and capital in relation to total revenue, $P_Q Q$. Because perfect competition implies that constant returns to scale (CRS) are present, (16) can be rewritten as

$$\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \alpha_t^L \frac{\dot{L}}{L} + \alpha_t^M \frac{\dot{M}}{M} + \alpha_t^K \frac{\dot{K}}{K}, \text{ where} \tag{17}$$

$$\alpha_t^L = \frac{P_L L}{P_Q Q},\ \alpha_t^M = \frac{P_M M}{P_Q Q} \text{ and } \alpha_t^K = (1 - \alpha_t^L - \alpha_t^M) = \frac{P_K K}{P_Q Q}.$$

Rearranging (17) the growth rate of TFP is obtained:

$$\frac{\dot{\Theta}}{\Theta} = \frac{\dot{Q}}{Q} - \alpha_t^L \frac{\dot{L}}{L} - \alpha_t^M \frac{\dot{M}}{M} - \alpha_t^K \frac{\dot{K}}{K}. \tag{18}$$

Total factor productivity is expressed as the excess of the growth rate of output over the growth rates of the labour, material and capital inputs, where these are weighted by their relevant revenue shares.

Equation (18) can be expressed more simply as

$$\Delta\theta_t = \Delta q_t - \alpha_t^L \Delta l_t - \alpha_t^M \Delta m_t - \alpha_t^K \Delta k_t. \tag{19}$$

where θ, l and m and k are the logs of Θ, L, M and K respectively.

2.1 Calculating TFP for U.S. Manufacturing, 1959-91

The continuous time formula (19) for calculating the Solow residual has to be modified slightly for empirical purposes so that it is valid in discrete time. Tornqvist (1936) measured growth between two points in time by using logarithmic differences and uses arithmetic averages as weights. The residual is transformed as follows

$$\Delta\theta_t = \Delta q_t - \overline{\alpha}_t^L \Delta l_t - \overline{\alpha}_t^M \Delta m - \overline{\alpha}_t^K \Delta k_t, \text{ where} \tag{20}$$

$$\Delta\theta_t = \ln\left(\frac{\Theta_t}{\Theta_{t-1}}\right), \Delta q_t = \ln\left(\frac{Q_t}{Q_{t-1}}\right), \Delta l_t = \ln\left(\frac{L_t}{L_{t-1}}\right), \Delta m_t = \ln\left(\frac{M_t}{M_{t-1}}\right), \Delta k_t = \ln\left(\frac{K_t}{K_{t-1}}\right),$$

$$\overline{\alpha}_t^L = \left(\alpha_t^L + \alpha_{t-1}^L\right)/2,\ \overline{\alpha}_t^M = \left(\alpha_t^M + \alpha_{t-1}^M\right)/2, \text{ and } \overline{\alpha}_t^K = \left(\alpha_t^K + \alpha_{t-1}^K\right)/2.$$

Thus far it has been assumed that TFP growth is completely deterministic. A random term υ_t can be added to reflect the stochastic nature of productivity growth. TFP growth can then be viewed as the sum of a constant underlying growth rate $\Delta\theta_t$ plus a random component υ_t. Thus the estimated residual is

$$\Delta\theta_t + \upsilon_t = \Delta q_t - \overline{\alpha}_t^L \Delta l_t - \overline{\alpha}_t^M \Delta m_t - \overline{\alpha}_t^K \Delta k_t. \tag{21}$$

Estimates of the growth rate of TFP for aggregate manufacturing were obtained using the NBER productivity database.[11] Figure 1 is a plot of the Solow residual over the period 1959-91. The graph gives the impression that the TFP growth rate is procyclical: in years of expansion the residual is large and positive; in years of

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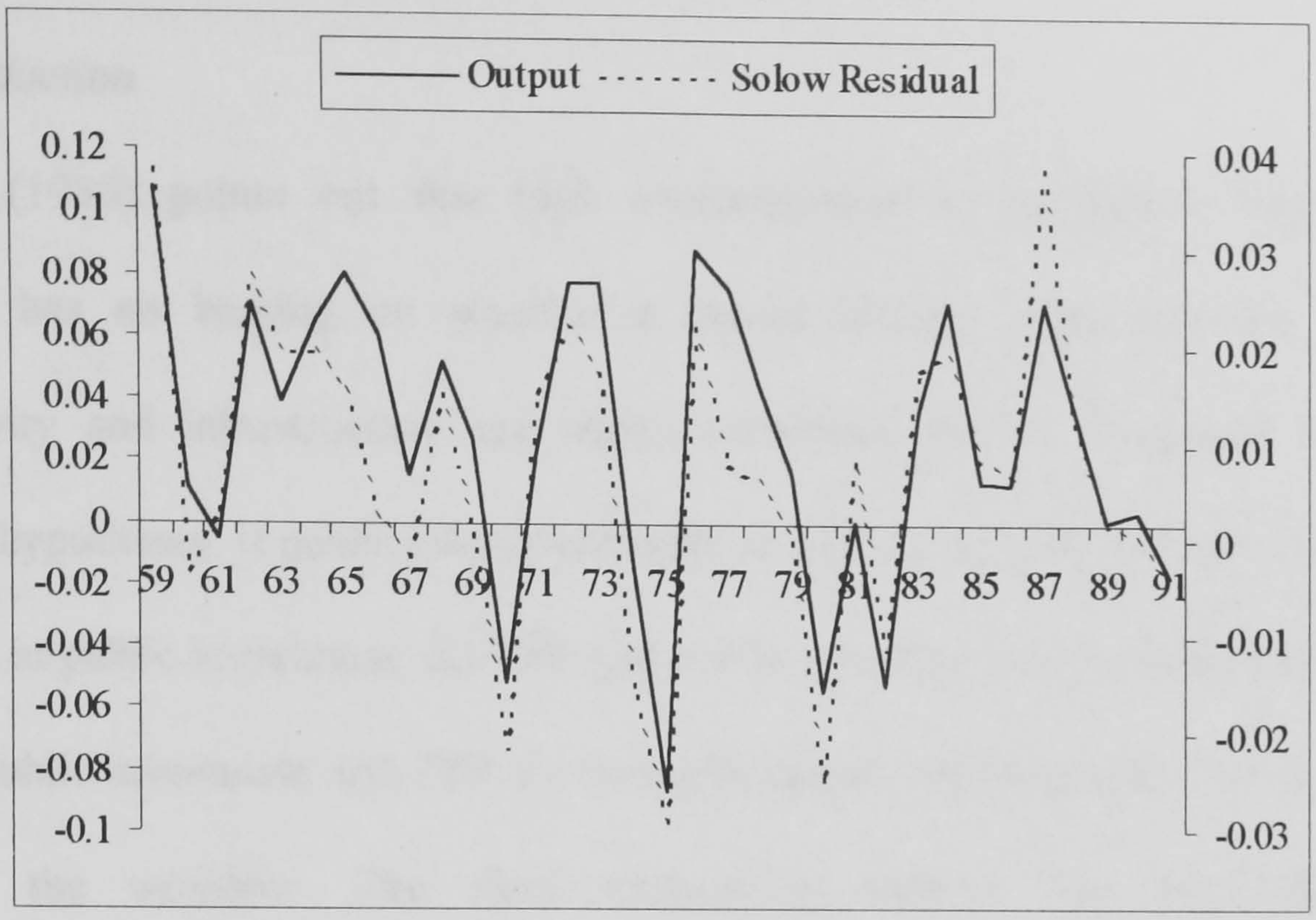
[11] Data sources are listed in Appendix A.

Figure 1. *Manufacturing Output Growth (Left Scale) versus Solow Residual, 1959-91*



contraction the residual is low or negative. Basu (1996) lists three reasons why the productivity growth rate maybe procyclical. First, measured fluctuations in productivity may reflect exogenous changes in production technology. Second, productivity (correctly measured) may be procyclical because of increasing returns to scale – the economy endogenously becomes more efficient by moving to higher levels of activity. Third, if inputs are systematically mismeasured, measured productivity may be procyclical even if true productivity doesn't change. I return to the issue of whether the Solow residual is an accurate measure of TFP in Section 4. First the relationship between this variable and public investment will be examined.

3. Causality Testing and Estimation of Autoregressive Models

3.1 Introduction

Granger (1980) points out that high contemporaneous correlation between two variables has no bearing on whether a causal linkage exists between them. If productivity and infrastructure are highly correlated this is consistent with four different hypotheses: i) public investment leads to TFP growth, ii) TFP growth leads to increases in public investment, iii) TFP and public investment are causally independent, and iv) public investment and TFP are mutually causal, implying that there is feedback between the variables. The third explanation implies that productivity and infrastructure are themselves influenced by other common factors. The second scenario – that productivity growth may lead to increased infrastructure investment – has been highlighted by a number of authors in response to large estimates of public capital's output elasticity. Eisner (1991) observed that U.S. regions with relatively high productivity have a relatively higher stock of infrastructure. He puts the higher level of infrastructure capital down to the "reverse relationship" between productivity growth and public investment. The argument is that higher income voters normally demand more of all goods, including public capital. Although many authors allude to the possibility of reverse causation, only Tatom (1993) conducts tests to establish the nature of the relationship. His conclusion is that:

> "Neither the growth rate of the public capital stock nor the level of public sector investment cause total factor productivity growth. On the contrary, the growth of private sector productivity causes both measures of public capital formation." (p. 6)

Causality tests have been performed in other studies in the infrastructure literature but with *private investment*, not productivity, as the secondary variable. The aim of these studies is to establish whether infrastructure investment crowds out or crowds in private investment and thus whether it is what Seitz and Licht (1996) refer to as a "strategic weapon for interregional competition".[12] However, like Aschauer (1989) who sparked off interest in the role of public capital in production, the focus in this thesis is on the relationship between infrastructure and productivity. Although Tatom's (1993) study generated interest in the causality issue, it did not make use of developments in the causality literature, in particular those related to lag-length selection.[13] When Batten and Thornton (1985) investigated the extent to which different lag-length selection criteria can be relied upon in testing Granger causality between money and income, they found that ad hoc approaches, such as considering a few arbitrary lag structures or using some "rule of thumb", can produce misleading results.[14] Even models using different *statistical criteria* for selecting the lag structure

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[12] See Chapter 1.

[13] In fact, it appears that proper Granger causality tests were not even performed with the arbitrarily chosen lag structures. Variables were added to each equation simply according to whether their t-stats were significant. Furthermore, Granger causality tests require that the data be stationary (see Nelson and Kang, 1981, Lütkepohl, 1982b, and Kang, 1985). This issue was not addressed by Tatom (1993). Since the variables used in this chapter are already rates of change they are likely to be stationary. However, following Lütkepohl (1991), stability tests were carried out on each of the systems estimated. See Appendix B for further details. Engle and Granger (1987) and Kearney and MacDonald (1987) have pointed out the importance of testing for cointegration prior to conducting causality tests. Engle and Granger point to the fact that the "standard" vector autoregression estimates derived from differenced data are mis-specified if the variables are cointegrated because the error correction term is excluded. I tested for cointegration in the various systems using the Johansen and Juselius (1990) procedure and in each case find that I cannot reject the null hypothesis of no cointegration. Thus there appears to be no stable long-run relation between the various variables. This does not, however, preclude the existence of a short-run causal linkage between them. See Enders (1995) for a discussion of this procedure.

[14] For example, in tests of M2 on nominal income, the lag structure of 4-4 suggests that income does not Granger cause M2, while the 8-8 structure produces the opposite result. Batten and Thornton (1985) also note that: "The evidence also suggests that the intuitively appealing rule of thumb – that the lag on the dependent variable be relatively long to account for possible autocorrelation, while the lag on the hypothesised independent variable be relatively short to conserve degrees of freedom – does not perform well either" (p. 170).

can yield contradictory conclusions. The typical model selection criteria trade off the bias associated with a parsimonious parameterisation against the inefficiency associated with overparameterisation. Because various criteria give different weights to the bias/efficiency trade off, they can select quite different lag structures. Several methods for identifying the system of equations are suggested in the literature. As Ramanathan (1993) explains[15], the different criteria are all based on the mean square error (*ESS/T*), multiplied by some penalty factor that depends on the complexity of the model as measured by the number of regression coefficients to be estimated.[16] Ramanathan compares models chosen by the following statistics: Akaike's Information Criterion (Akaike, 1974), the FPE Criterion (Akaike 1969a,b), HQ (Hannan and Quinn, 1979), Schwarz (1978) and Rice (1984).[17] He emphasises that the above statistics do not answer the question as to whether one of the models should be rejected in favour of the other. In principle such a selection can be made by the testing of nested hypotheses. FPE is the lag-length selection criterion used throughout this chapter. The choice of this statistic is based on its popularity in the causality testing literature[18] and evidence from a number of authors that it performs well in identifying the appropriate

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[15] See pp. 280-281.

[16] As Charezma and Deadman (1997) explain, each criterion has different underlying assumptions. For example $\overline{R}^2$ assumes a "true" model exists and the task is in finding it, given the assumption that the "best" model for this purpose is that which minimizes the *RSS*, adjusted for the number of explanatory variables. The FPE Criterion adopts a more parsimonious position. According to this criterion, even a true model should be reduced in size if this increases the predictive quality of the model. The aim of Akaike's Information Criterion (AIC) and the Schwarz-Bayes Criterion (SBC) is the selection of the model with the maximum information available (where "information" is a precisely defined probability concept) and again do not concern themselves as to whether a true model exists or not. AIC is regarded as being inconsistent in that it does not select the model with maximum information with probability tending to 1 as $T \to \infty$. This problem is overcome by the SB Criterion which is recommended for large samples.

[17] Other studies that compare lag-length selection criteria and are not mentioned elsewhere in this chapter include Kang (1989), Odaki (1986) and Urbain (1989).

[18] Recent papers that make use of this statistic and are not mentioned elsewhere in this chapter include Biswas *et al.* (1992), Darrat and Glascock (1993), Ghatak *et al.* (1997), Gordon and Sakyibekoe (1993), Kam and Lin (1998), Kholdy *et al.* (1993) and Shoesmith (1992).

autoregressive model. For example, Batten and Thornton (1984, 1985) compare the FPE Criterion with a number of lag-length selection criteria – the Bayesian Estimation Criterion (BEC)[19], Pagano and Hartley's (1981) P-H test, the Schwarz Bayesian Information Criterion and the standard F-test – and conclude that:

> "Akaike's FPE Criterion performed well in selecting the model relative to the others. As a result it did a reasonably good job of finding an order for the model which gave evidence of Granger causality, when such an order existed." (p.177)

Jones (1989) also finds that the FPE Criterion outperforms other statistical criteria. However, in order to refute claims that the results of the Granger-causality testing procedure are sensitive to the number of lags on the regressors, other lag-length selection criteria are employed on some of the models for comparative purposes. Tests of the adequacy of the models chosen by the FPE Criterion are also conducted.

Once the lag-length selection method has been chosen, there are a number of ways in which the estimating model can be constructed. Lütkepohl (1982a), for example, assumed that the autoregressive lags for all the variables were identical. Caines, Keng and Sethi (1981) modelled a system of N (>2) variables in stages. First, bivariate autoregressive models were estimated for each ordered pair of variables. The two variables in each bivariate autoregressive process were assumed to have equal lag lengths and the optimal lag length was determined by the FPE Criterion. Hsiao (1979, 1981), Ahking and Miller (1985) and Erenburg and Wohar (1995) also use the FPE Criterion but argue that the assumption of equal lag lengths for all variables is restrictive. By allowing each variable to enter the equation with a different number of

[19] As suggested by Geweke and Meese (1981).

lags there is potentially a reduction in the number of parameters to be estimated and the influence of each variable can be felt at different points in time. The model identification method used in this chapter is based primarily on Hsiao (1979, 1981). I also incorporate several features from Ahking and Miller (1985) and Erenburg and Wohar (1995). Before this method of model identification is discussed, it is necessary to provide some brief background information about the FPE Criterion.

3.2 The FPE Criterion

An example of a bivariate autoregressive model that I attempt to identify in this chapter is that for $\Delta\theta_t$, the growth rate of TFP, and ΔI_t^C, the growth rate of core public investment:

$$\begin{pmatrix}\Delta\theta_t\\ \Delta I_t^C\end{pmatrix}=\begin{pmatrix}a\\ b\end{pmatrix}+\begin{pmatrix}\psi_{11}(L) & \psi_{12}(L)\\ \psi_{21}(L) & \psi_{22}(L)\end{pmatrix}\begin{pmatrix}\Delta\theta_t\\ \Delta I_t^C\end{pmatrix}+\begin{pmatrix}\upsilon_t\\ \nu_t\end{pmatrix}, \tag{22}$$

where L is the lag operator and υ_t and ν_t are zero mean white noise stochastic processes with constant covariance. The focus is primarily on whether the off-diagonal terms are zero, ie whether $\psi_{12}(L)=0$ and $\psi_{21}(L)=0$.

The FPE of the TFP growth rate, $\Delta\theta_t$, is defined as the (asymptotic) mean square prediction error:

$$E\left(\Delta\theta_t-\Delta\hat{\theta}_t\right)^2, \tag{23}$$

where $\Delta\hat{\theta}_t$ is the predictor of $\Delta\theta_t$ from (22):

$$\Delta\hat{\theta}_t=\hat{a}+\hat{\psi}_{11}^m(L)\Delta\theta_t+\hat{\psi}_{12}^n(L)\Delta I_t^C. \tag{24}$$

The superscripts m and n denote the order of lags in $\psi_{11}(L)$ and $\psi_{12}(L)$ respectively. $\hat{\psi}_{11}^m(L)$, $\hat{\psi}_{12}^n(L)$ and $\hat{a}$ are least squares estimates obtained by treating observations from $-M+1$ to 0 fixed on the set of data $(t{:}\,t=-M+1,\dots,0,1,\dots T)$, where M is the a priori specified highest possible order for ψ_{ij}, so $m,n \le M$ and T is the number of observations.[20] Akaike (1969a,b) shows that the FPE is composed of two components: the first is a measure of estimation error, the second is a measure of modelling error. As the values of m and n are increased, the first term will decrease but the second term will increase for a finite number of observations for $\Delta\theta_t$ and ΔI_t^C. Akaike defines the estimate of FPE for the first equation in (22) by:

$$FPE_{\Delta\theta_t} = E\left(\Delta\theta_t - \hat{\psi}_{11}^m(L)\Delta\theta_t - \hat{\psi}_{12}^n(L)\Delta I_t^C - \hat{a}\right)^2$$

$$= \sigma_\upsilon^2\left(1 + \frac{m+n+1}{T}\right), \tag{25}$$

where σ_υ^2 is the variance of υ_t. An estimate of σ_υ^2 is provided by

$$\hat{\sigma}_\upsilon^2 = \frac{RSS_{\Delta\theta_t}(m,n)}{T-m-n-1}, \tag{26}$$

where $RSS_{\Delta\theta_t}(m,n)$ is the sum of squared residuals:

$$RSS_{\Delta\theta_t}(m,n) = \sum_{t=1}^{T}\left(\Delta\theta_t - \hat{\psi}_{11}^m(L)\Delta\theta_t - \hat{\psi}_{12}^m(L)\Delta I_t^C - \hat{a}\right)^2. \tag{27}$$

Substituting (26) into (25) and rearranging produces the estimate of the FPE for $\Delta\theta_t$:

$$FPE_{\Delta\theta_t}(m,n) = \frac{T+m+n+1}{T-m-n-1} \cdot RSS_{\Delta\theta_t}(m,n)/T. \tag{28}$$

The number of lags that minimises the FPE is the specification used in (22). To choose the order of lags in $\psi_{11}^m(L)$ and $\psi_{12}^n(L)$ by the minimum FPE is, according to Hsiao (1981), equivalent to applying an approximate F test with varying significance levels. The major difference between applying Akaike's FPE Criterion to decide whether a

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[20] In this chapter lags are allowed to extend from one to four years.

variable should be included in the equation and the conventional hypothesis testing procedure is in the choice of significance level. The conventional choice of five per cent or one per cent significance level is ad hoc. Here the choice is on an explicit optimality criterion (minimising the mean square prediction error). The minimum FPE is obtained by letting m and n vary between 0 and M.

3.3 The Modelling Procedure

The procedure used to identify models in this chapter involves the following steps:

(i) Each of the dependent variables (productivity growth and public investment growth) is regressed on its own lags to determine the appropriate lag order. For example, for the TFP equation:

$$\Delta\theta_t = a + \psi_{11}^{m}(L)\Delta\theta_t + \upsilon_t, \tag{29}$$

a series of autoregressions is performed by varying the order of the lag, m, in (29) from 1 to the predetermined maximum lag length of four years.[21] The lag that minimises the following FPE value is the appropriate "own" lag, m^*:

$$FPE_{\Delta\theta}(m^*) = [(T + m + 1)/(T - m - 1)].\ RSS(m^*)/T. \tag{30}$$

When an additional lag is added to (30) the first term is increased but simultaneously the second term is decreased. When their product (FPE) reaches a minimum, the opposing forces are balanced.

(ii) Bivariate regressions are estimated consisting of the appropriate own lag determined in (i) and lags of the remaining variable(s). Assuming there is only one other variable, the growth rate of core infrastructure investment, the equation to be

[21] Where the appropriate lag is 4 for any variable, the maximum lag length was allowed to extend beyond four to six years to check whether a longer lag is appropriate. This was never the case, however.

estimated is

$$\Delta\theta_t = a + \psi_{11}^m(L)\Delta\theta_t + \psi_{12}^n(L)\Delta I_t^C + \upsilon_t. \tag{31}$$

The lag order of this variable (denoted by n) is varied from 1 to 4 and the following modified FPE is calculated

$$FPE_{\Delta\theta}(m^*,n) = [(T + m^* + n + 1)/(T - m^* - n - 1)]. RSS(m^*,n)/T. \tag{32}$$

The appropriate lag length for the second variable (n^*) is that which minimises the FPE in (32). The relationship between the variables can then be determined by comparing (30) and (32). If $FPE_{\Delta\theta}(m^*,n^*) < FPE_{\Delta\theta}(m^*)$ (ie, the prediction of $\Delta\theta_t$ using past values of ΔI^C is more accurate than without using past ΔI^C) then it can be concluded that infrastructure investment Granger causes the TFP growth rate, ie $\Delta I^C \Rightarrow \Delta\theta_t$.[22] Similarly, for core infrastructure investment the following equations are estimated

$$\Delta I_t^C = a + \psi_{22}^m(L)\Delta I_t^C + v_t, \text{ and} \tag{33}$$

$$\Delta I_t^C = a + \psi_{21}^n(L)\Delta\theta_t + \psi_{22}^m(L)\Delta I_t^C + v_t. \tag{34}$$

If $FPE_{\Delta I^C}(m^*,n^*) < FPE_{\Delta I^C}(m^*)$ the TFP growth rate Granger causes infrastructure investment, ie $\Delta\theta \Rightarrow \Delta I_t^C$. Finally, if $FPE_{\Delta\theta}(m^*,n^*) < FPE_{\Delta\theta}(m^*)$ and $FPE_{\Delta I^C}(m^*,n^*) < FPE_{\Delta I^C}(m^*)$, the conclusion is that feedback occurs, ie, $\Delta\theta \Leftrightarrow \Delta I^C$. The above modelling procedure lends itself easily to the construction of multivariate models, the construction of which is discussed in further detail in Section 3.8, when the infrastructure data is disaggregated. In the two-variable cases in

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[22] The Granger concept of causality is based on temporal ordering. Granger (1969) defines simple causality such that "x causes y" if knowledge of past x reduces the variance of the errors in forecasting y_t beyond the variance of the errors which would be made from knowledge of past y alone:
$\sigma^2(y_t|y_{t-1},\ldots,x_{t-1},x_{t-2},\ldots) < \sigma^2(y_t|y_{t-1},\ldots)$.
Granger also defines instantaneous causality where current as well as past values of x predict y. If y is related to current or lagged x but not future x, x is exogenous relative to y. If x causes y and y causes x there is feedback between the variables.

Table 1. *The FPEs of Fitting a One-Dimensional Autoregressive Process for the Solow Residual and Growth Rate of Infrastructure Investment*

No. lags	$\Delta\theta_t$	ΔI_t^C	ΔI_t^T
1	**0.000252***	0.002140	0.002427
2	0.000259	**0.001820***	**0.002262***
3	0.000287	0.001997	0.002396
4	0.000301	0.002122	0.002442

Note: Minimum FPEs are denoted by asterisks

which aggregate infrastructure variables are employed, a simple grid search over four lags was also carried out with no alteration to the causality test results obtained using the modelling procedure.

3.4 Results – Aggregate Infrastructure

The FPEs from the treatment of each variable (the growth rate of TFP and the growth rates of core and total investment) as one-dimensional autoregressive processes are presented in Table 1. The number of own lags that minimise the FPEs for $\Delta\theta_t$, ΔI_t^C and ΔI_t^T are 1, 2 and 2 respectively. With the appropriate own lag lengths determined, it is then assumed that the productivity and infrastructure variables are controlled variables and the relevant second variable is treated as the manipulated variable. Holding constant the order of the autoregressive operator on the controlled variable to the one determined in Table 1, the FPEs of the controlled variables are computed by varying the order of lags of the manipulated variable from 1 to 4. The order which gives the smallest FPE is presented in Table 2. For example, the FPE for the autoregressive equation containing the Solow residual as the controlled variable and

Table 2. *FPEs Computed from Including Optimum Lags on Manipulated Variables*

Controlled Variable [a]	*Manipulated Variable*	*Optimum Lag, Manipulated Variable*	*FPE(m*,n*)* [b]	*FPE(m*)*
Solow Residual				
$\Delta\theta_t$ *(1)*	ΔI_t^C	1	**.000236***	.000252
$\Delta\theta_t$ *(1)*	ΔI_t^T	1	**.000242***	.000252
Core				
ΔI_t^C *(2)*	$\Delta\theta_t$	1	.001881	.001820
Total				
ΔI_t^T *(2)*	$\Delta\theta_t$	1	**.002052***	.002262

[a] The number in brackets indicates the order of the autoregressive operator for the controlled variable, determined in Table 1.[b] The FPEs in the *FPE(m*,n*)* column are the minimum ones obtained from inclusion of different lags on the manipulated variables. Asterisks signify that there is a causal relationship from the manipulated variable to the controlled variable.

total infrastructure as the manipulated variable is minimised by including one lagged infrastructure term. It is clear from Table 2 that the FPE Criterion does not impose the same number of lags on variables that appear in the same equation. For example, both investment equations contain a different number of lagged terms for infrastructure investment and the productivity growth rate. Using the results reported in Table 2 it is possible draw some conclusions about causality. The column *FPE(m*)* contains the minimum FPEs from Table 1. Where these numbers are greater than the FPEs from the equations that include a manipulated variable, *FPE(m*,n*)*, it can be concluded that the manipulated variable causes the controlled variable. For example, for $\Delta\theta_t$ and ΔI_t^C, treatment of ΔI_t^C as the input reduces the FPE of the $\Delta\theta_t$ equation, implying that $\Delta I_t^C \Rightarrow \Delta\theta_t$. The same relationship is found between total infrastructure and productivity, ie $\Delta I_t^T \Rightarrow \Delta\theta_t$. Thus the conclusion is that both measures of infrastructure cause the Solow residual.

Table 3. *Comparison of Lag-Length Selection Criteria*

	$\Delta I_t \Rightarrow \Delta\theta_t$			$\Delta\theta_t \Rightarrow \Delta I_t^C$		$\Delta\theta_t \Rightarrow \Delta I_t^T$	
Criterion	$\Delta\theta$	$(\Delta\theta, \Delta I^C)$	$(\Delta\theta, \Delta I^T)$	ΔI^C	$(\Delta I^C, \Delta\theta)$	ΔI^T	$(\Delta I^T, \Delta\theta)$
FPE	0.25157(1)	**0.23602(1)***	**0.24150(1)***	0.1820(2)	0.1881(1)	0.2262(2)	**0.2052(1)***
AIC	0.25153(1)	**0.23589(1)***	**0.24137(1)***	0.1819(2)	0.1879(1)	0.2261(2)	**0.2049(1)***
HQ	0.25928(1)	**0.24688(1)***	**0.25262(1)***	0.1903(2)	0.1996(1)	0.2365(2)	**0.2177(1)***
RICE	0.25368(1)	**0.24069(1)***	**0.24628(1)***	0.1859(2)	0.1951(1)	0.2310(2)	**0.2128(1)***
SBC	0.27566(1)	**0.27064(1)***	**0.27692(1)***	0.2090(2)	0.2256(1)	0.2597(2)	**0.2461(1)***

Note: Values reported in the first three columns omit the first three zero decimal places; values reported in the remaining four columns omit the first two zero decimal places. Asterisks signify a causal relationship; optimal number of lags in parentheses. See Section 3.1 for the sources of the various tests.

However, when the issue of reverse causality is examined, the two infrastructure measures generate different results. No reverse relationship is found between productivity and core investment (ie, $\Delta\theta_t \not\Rightarrow \Delta I_t^C$). However, there is evidence of reverse causation between the Solow residual and total investment, leading one to conclude that there is feedback between the variables, ie $\Delta\theta_t \Leftrightarrow \Delta I_t^T$.

It may be argued that different lag-selection criteria may choose models of different orders that alter the conclusions drawn about causality. To check this, the statistics for four other criteria were computed.[23] The results are reported in Table 3. The first three columns test whether the two infrastructure variables cause the TFP growth rate. The first column contains the minimum statistics computed from treating $\Delta\theta_t$ as a one-dimensional autoregressive process; columns two and three contain the statistics computed from inclusion of the optimum number of lagged infrastructure terms.

[23] See Ramanathan (1993), Section 10.6 and Judge *et al.* (1985), Chapter 16, Section 7.5 and Section 16.6.1a for a more complete discussion of these alternative criteria.

In each case the two-dimensional processes have lower statistics, providing further evidence that $\Delta I_t^C \Rightarrow \Delta\theta_t$ and $\Delta I_t^T \Rightarrow \Delta\theta_t$. The results of the reverse causation tests, reported in the last four columns, are also identical to those carried out using the FPE Criterion. For each criterion the verdict is that $\Delta\theta_t \Rightarrow \Delta I_t^T$ and $\Delta\theta_t \not\Rightarrow \Delta I_t^C$.

3.5 Discussion of Results

The first important point to make is that the results of causality tests cannot be viewed in isolation from economic theory. This point is made by a number of authors, including Hicks (1979), Simon (1970) and Zellner (1979). Some of Zellner's comments about blind faith in causality testing procedures are worth quoting at length:

> "The mechanical application of causality tests is an extreme form of 'measurement without theory,' perhaps motivated by the hope that application of statistical techniques without the delicate and difficult work of integrating statistical techniques and subject matter considerations will be able to produce useful and dependable results. That this hope is generally naïve and misguided has been recognized by econometricians for a long time and is a reason that reference is made to laws in Feigl's definition of causation.[24] In establishing and using these laws in econometrics, there seems to be little doubt but that economic theory, data, and other subject matter considerations as well as econometric techniques, including modern

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24 According to Feigl (1953), "The clarified (purified) concept of causation is defined in terms of *predictability according to a law* (his italics) or, more adequately, according to a set of laws,"(p. 408). According to this philosophical definition of causality, predictability without a law or set of laws or, as econometricians might put it, without theory, is not causation. Linking predictability to a law or set of laws is critical in appraising various tests of causality that have appeared in the econometric literature.

time series analysis, will all play a role. 'Theory without measurement' and 'measurement without theory' are extremes to be avoided." (p. 51)

The message from Hicks, Zellner and Simon is that if the results of causality tests do not make economic sense they should not be accepted. The researcher must then look for potential weaknesses in the analysis. For example, there is consensus in the infrastructure literature (see, for example, Aschauer, 1989, and Morrison and Schwartz, 1997) that core public investment will have a greater effect on productivity than total investment. Core infrastructure makes up roughly 60 per cent of the total, with the balance consisting of spending on publicly owned industrial buildings, schools, hospitals, other buildings and equipment.[25] It is clear from Table 3 that inclusion of core investment leads to lower mean square error than inclusion of total investment, confirming that roads, water and sewer systems, electric and gas facilities and mass transit are the most productive types of public capital.

On the other hand, if it is true that the TFP growth rate determines infrastructure spending, neither type of infrastructure investment is likely to be a bigger beneficiary of productivity growth than the other.[26] If one supports the reverse causation hypothesis, all the components of the public capital stock can be regarded as normal goods, demand for which increases as income goes up due to productivity gains. However, the results do not support this hypothesis. Total infrastructure investment is caused by productivity gains, core investment is not. In conclusion, the results overturn Tatom's (1993) finding that infrastructure does not cause productivity and provide contradictory evidence of reverse causation. This issue will be raised again

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[25] Other buildings include general office buildings, police and fire stations, courthouses, auditoriums, garages and passenger terminals.
[26] For further discussion of the reverse causation hypothesis, see Section 6.3.

when tests are conducted using disaggregated infrastructure data. Tatom's analysis was based on a different time period and used a measure of productivity for the total business sector, not just manufacturing. Furthermore, he included investment data in levels in his analysis whereas I use growth rates. These differences help explain why his results are different to those obtained in this section using the aggregate manufacturing Solow residual.

3.6 Estimating Infrastructure's Impact on Productivity

Thus far only evidence of the qualitative nature of the relationship has been presented. The next step is to provide quantitative information about infrastructure's impact on the TFP growth rate. Two models are estimated, one for total infrastructure and one for core infrastructure. The total infrastructure model takes account of the feedback between the variables and incorporates the minimum FPE lag lengths determined in Table 2:

$$\begin{pmatrix} \Delta\theta_t \\ \Delta I_t^T \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} \psi_{11}^1(L) & \psi_{12}^1(L) \\ \psi_{21}^1(L) & \psi_{22}^2(L) \end{pmatrix} \begin{pmatrix} \Delta\theta_t \\ \Delta I_t^T \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \end{pmatrix}. \tag{35}$$

The model with core infrastructure is

$$\begin{pmatrix} \Delta\theta_t \\ \Delta I_t^C \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} \psi_{11}^1(L) & \psi_{12}^1(L) \\ 0 & \psi_{22}^2(L) \end{pmatrix} \begin{pmatrix} \Delta\theta_t \\ \Delta I_t^C \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \end{pmatrix}. \tag{36}$$

Note that the second equation contains only lags of the dependent variable because of the absence of reverse causality. Following Erenburg and Wohar (1995), each two-equation system is estimated in a seemingly unrelated regression (SUR) framework to gain efficiency by allowing for the cross-equation correlation of disturbances. This is important as each of the dependent variables may be subject to the same external shocks (in particular, to contemporaneous, stochastic disturbances that are not

Table 4. *Autoregressive Estimates*

	Core Infrastructure Model		Total Infrastructure Model	
Dependent Variable:	$\Delta\theta_t$	ΔI_t^C	$\Delta\theta_t$	ΔI_t^T
$\Delta\theta_{t-1}$	0.063		0.005	1.162***
	(0.39)		(0.03)	(3.28)
ΔI_{t-1}^j	0.114**	0.152	0.095*	0.227
	(2.25)	(0.76)	(1.92)	(1.47)
ΔI_{t-2}^j		0.452***		0.251
		(3.12)		(1.62)
Constant	0.004	0.005	0.005	-0.0004
	(1.23)	(0.78)	(1.40)	(0.06)
R^2	0.126	0.265	0.106	0.389
S.E.	0.014	0.039	0.014	0.400

Note: j = C (core infrastructure) or T (total infrastructure), depending on the model; t-stats in parentheses and are computed using heteroskedastic-consistent standard errors.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

captured by the set of explanatory variables). Following Lütkepohl (1991) this idea can be demonstrated by considering the following VAR(1) system

$$\begin{pmatrix} \Delta\theta_t \\ \Delta I_t^C \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} \psi_{11} & \psi_{12} \\ 0 & \psi_{22} \end{pmatrix} \begin{pmatrix} \Delta\theta_{t-1} \\ \Delta I_{t-1}^C \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \end{pmatrix}. \tag{37}$$

In this system core infrastructure does not cause TFP. However, the system may be premultiplied by some nonsingular matrix

$$\boldsymbol{B} = \begin{pmatrix} 1 & 0 \\ -\beta & 1 \end{pmatrix}, \tag{38}$$

so that

$$\begin{pmatrix} \Delta\theta_t \\ \Delta I_t^C \end{pmatrix} = \begin{pmatrix} c \\ d \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ \beta & 0 \end{pmatrix} \begin{pmatrix} \Delta\theta_t \\ \Delta I_t^C \end{pmatrix} + \begin{pmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{pmatrix} \begin{pmatrix} \Delta\theta_{t-1} \\ \Delta I_{t-1}^C \end{pmatrix} + \begin{pmatrix} \mu_t \\ \eta_t \end{pmatrix}. \tag{39}$$

This model is just another representation of $\left(\Delta\theta_t, \Delta I_t^C\right)'$ as it has the same means and autocovariances as the one in (37). However, the conclusions concerning causality are totally different. If the second representation actually describes the true model, the TFP growth rate may affect core infrastructure through the coefficient β in the second equation. There are theoretical reasons why TFP is not likely to have an instantaneous effect on infrastructure investment and thus why $\beta = 0$.[27] Nevertheless, the possibility can be accounted for by estimating the equations in a system framework and by allowing for the possibility that $\gamma_{21} \neq 0$ by including the minimum FPE lags of $\Delta\theta_t$ from the single equation framework even if the initial conclusion was $\Delta\theta_{t-1} \not\Rightarrow I_t^C$.

Estimates from the two models are contained in Table 4. Before discussing the regression results, it is possible to conduct a further causality test within this framework. Geweke, Meese and Dent (1983) present evidence that the Granger causality testing procedure conducted using a Wald chi-square test statistic outperforms other causality tests in a series of Monte-Carlo experiments.[28] Erenburg and Wohar (1995) use Wald tests to draw conclusions about causality in their initially overfitted models.[29] Results from Wald tests of the hypothesis that the off-diagonal parameters in (35) and (36) are zero are presented in Table 5.

[27] For productivity gains to be converted into additional infrastructure investment they first have to be appropriated by the relevant state or local government. There may also be a lag between the political decision to increase investment and the investment taking place.
[28] The authors compared a number of different causality testing procedures: the Wald variant, the likelihood ratio variant and the Lagrange multiplier variant of the Granger, Sims (using a number of corrections for serial correlation) and Sims lagged dependent variable tests.
[29] See Appendix E for an explanation and comparison of results obtained using the Erenburg and Wohar (1995) method of initially overfitting the models.

Table 5. *Wald Tests for Zero Restrictions*

	Wald Statistic $\sim\chi^2$
Core Infrastructure Model	
$\psi^1_{12}(L) = 0$	4.17(1)**
Total Infrastructure Model	
$\psi^1_{12}(L) = 0$	3.38(1)*
$\psi^1_{21}(L) = 0$	5.66(1)**

Note: Degrees of freedom in parentheses.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

They support the causality test results of Section 3.4, indicating that no alterations are required to the models. It is also important to determine whether the FPE Criterion performs satisfactorily in identifying the system of equations. Following Hsiao (1981), Ahking and Miller (1985) and Erenburg and Wohar (1995), the adequacy of the models was checked by sequentially overfitting (35) and (36) by adding one additional lag and then two additional lags to each variable, including those variables that were not significantly different from zero in the final models. For the core infrastructure model the Wald test statistics are respectively 5.86 (4 degrees of freedom) and 9.28 (8 degrees of freedom), indicating that the extra lags are not significantly different from zero. For the total infrastructure model the Wald test statistics are respectively 9.42 (4 degrees of freedom) and 9.43 (8 degrees of freedom). Thus both sets of tests reveal no inadequacy in the models.

As Franses (1996) recommends, the empirical adequacy of the autoregressive models is also investigated. Much of this investigation concerns possibly undetected systematic patterns in the estimated residual process. Serial correlation in the residuals was tested for as was heteroskedasticity, non-normality, specification error and the possibility of temporal instability. Table 6 contains the results of the diagnostic tests, applied to individual equations estimated by OLS. It is necessary to examine whether any contemporaneous correlation of the error terms across equations is affected by serially correlated errors within individual equations. The Durbin Watson statistic (a measure of first-order serial correlation) is not appropriate in this context as it is biased towards 2 because of the presence of lagged dependent variables. As an alternative, the Breusch-Godfrey Lagrange Multiplier test is used to test for the presence of higher order serial correlation. Table 23 indicates that, except for lag two in equation (3), the null hypothesis that the disturbances are serially uncorrelated cannot be rejected for any of the equations. Non-rejection of the normality null hypothesis indicates that there are no outlying observations and that the error process is homoskedastic. The White heteroskedasticity test also indicates that the disturbances have constant variance. To test for the possible omission of important explanatory variables, all equations were re-estimated employing Ramsey's (1969) RESET procedure. In this procedure the estimating equations are augmented with additional explanatory variables. If these variables are found to be jointly insignificant then the null hypothesis of no specification error cannot be rejected. Following Erenburg and Wohar (1995), three different tests are performed using each of the four equations: RESET(2) augments the equation with fitted values of the dependent variable raised to the power of 2; RESET(3) augments the equation with fitted values of the dependent variable raised to the power of 2 and raised to the power of 3; and RESET(4) augments the equation with fitted values of the dependent variable raised to the powers of 2, 3 and 4. In each test the additional variables were found to be jointly insignificant and so the null hypothesis of no specification error could not be rejected.

Table 6. *Diagnostic Tests on Individual Equations*

Breusch-Godfrey LM Tests for Serial Correlation $\sim \chi^2$

	Equation			
Order:	(1)	(2)	(3)	(4)
1	0.01(1)	0.00(1)	0.28(1)	0.43(1)
2	3.73(2)	0.01(2)	6.13(2)*	0.45(2)
3	6.25(3)	0.26(3)	7.78(3)	0.78(3)

White Heteroskedasticity Test $\sim \chi^2$

Equation			
(1)	(2)	(3)	(4)
6.31(5)	6.38(5)	6.36(5)	9.33(9)

Jarque-Bera Normality Test $\sim \chi^2$

Equation			
(1)	(2)	(3)	(4)
1.26(2)	1.14(2)	0.94(2)	1.26(2)

Ramsey RESET Test of Specification Error (F-Statistics)

	Equation			
	(1)	(2)	(3)	(4)
RESET(2)	0.37(1,24)	0.30(1,24)	1.25(1,24)	0.30(1,23)
RESET(3)	0.21(2,23)	0.27(2,23)	0.79(2,23)	0.34(2,22)
RESET(4)	0.40(3,22)	0.18(3,22)	1.12(3,22)	0.56(3,21)

Chow Test for Structural Change (F-Statistics)

Equation			
(1)	(2)	(3)	(4)
0.20(3,22)	0.25(3,22)	0.39(3,22)	0.48(4,20)

Equation 1: Solow residual dependent variable; core infrastructure independent variable.
Equation 2: Core investment dependent variable.
Equation 3: Solow residual dependent variable; total infrastructure independent variable.
Equation 4: Total investment dependent variable; Solow residual independent variable.
* Rejection of the relevant null hypothesis (serial independence, homoskedasticity, normality, no specification error, no structural break) at the 5 % level. Degrees of freedom in parentheses.

Chow tests were also employed to check the temporal stability of the models. The Chow test corresponds to the midpoint of the sample. Farley, Hinich and McGuire (1975) show that the power of the Chow test is maximised when the sample is split at the midpoint. The null hypothesis that the two sets of regression coefficients are equivalent is rejected if the computed F-statistic exceeds the critical value for $(K + 1)$ numerator and $(T_1 + T_2 - 2K - 2)$ denominator degrees of freedom, where K is the number of independent variables, T_1 is the number of observations in the first sample and T_2 is the number of observations in the second sample. The results indicate that all of the equations have stable parameters over the sample period.

3.7 Discussion of Results

The coefficient estimates that are of most interest are those which quantify the impact of core and total investment on productivity growth. Although it is to be expected that total investment is less significant than spending on the productive core, it is surprising that total investment is only significant at the 10 per cent level (for both the t-test and Wald test). After all, more than half of this measure is directly productive. Turning to the size of the coefficient estimates, they imply that a 1 percentage point increase in the growth rate of core infrastructure investment leads to an increase of 0.114 in the growth rate of total factor productivity in the following year. A 1 percentage point increase in the growth rate of total infrastructure investment leads to an increase of 0.095 in the growth rate of TFP in the following period. The parameter estimates and tests of structural change overturn suggestions from some analysts that public capital increases the productivity of private inputs but with diminishing returns (for example, Fox and Murray, 1993, in particular cite a number of studies showing diminishing returns from infrastructure investments). Thus public sector investment may have not only contributed substantially to the growth of factor productivity in the past, but as the stock of public capital has grown, the effect of additional investment appears to have been positive and significant.

It is to be expected that the estimate from the core model is greater than the estimate from the total model. If core investment growth were identical to the growth in other investment the estimates would be the same. However, over the sample period there were years when core and other investment were growing at very different rates. For example, in seven years of the sample period, one measure experienced positive growth while the other experienced negative growth.[30] The estimate of ψ_{21} on $\Delta\theta_t$ implies that an increase in the TFP growth rate of 1 percentage point leads to an increase in the growth rate of infrastructure investment of 1.2 percentage points in the following period.

3.8 Causality Tests – Disaggregated Infrastructure Data

In this section the FPE Criterion is applied to determine whether the different types of core infrastructure (roads, water structures, sewer structures and other structures) cause or are caused by the TFP growth rate. Table 7 is similar to Table 2 in the sense that it reports the minimum FPEs calculated using each variable's own lags, *FPE(m*)*, and the minimum FPEs obtained by also including another variable, *FPE(m*,n*)*. If *FPE(m*,n*)* < *FPE(m*)* then there is a causal relationship between the variables. The first set of FPEs tests whether there is a causal relationship from the infrastructure growth rate to the TFP growth rate. The minimum FPEs imply that only highway and street investment affects TFP. Turning to the tests for reverse causality, it is apparent again that the different infrastructure measures generate different results. While growth in TFP seems to lead to growth in investment in highways and water and sewer systems, it does not cause investment in other structures.

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[30] The relevant years were 1959, 1962, 1973, 1974, 1976, 1978, and 1984.

Table 7. *Optimum Lags of Manipulated Variable and the FPE of the Controlled Variable (Disaggregated Infrastructure Data)*

Controlled Variable [a]	*Manipulated Variable*	*Optimum Lag, Manipulated Variable*	*FPE(m*,n*)* [b]	*FPE(m*)*
Solow Residual				
$\Delta\theta_t\ (1)$	ΔI_t^H	1	**0.000210***	0.000252
$\Delta\theta_t\ (1)$	ΔI_t^W	1	0.000268	0.000252
$\Delta\theta_t\ (1)$	ΔI_t^S	1	0.000267	0.000252
$\Delta\theta_t\ (1)$	ΔI_t^O	1	0.000267	0.000252
Reverse Causality				
$\Delta I_t^H\ (2)$	$\Delta\theta_t$	2	**0.002043***	0.002270
$\Delta I_t^W\ (1)$	$\Delta\theta_t$	4	**0.016218***	0.017957
$\Delta I_t^S\ (1)$	$\Delta\theta_t$	2	**0.019719***	0.021565
$\Delta I_t^O\ (1)$	$\Delta\theta_t$	1	0.019598	0.018863

[a] The number in brackets indicates the order of the autoregressive operator on the controlled variable.
[b] The FPEs in the *FPE(m*,n*)* column are the minimum ones obtained from inclusion of different lags on the manipulated variables. Asterisks signify that there is a causal relationship from the manipulated variable to the controlled variable. ΔI_t^H is the growth rate of investment in highways and streets, ΔI_t^W is the growth rate of water structures, ΔI_t^S is the growth rate of sewer structures and ΔI_t^O is the growth rate of other structures.

3.9 Discussion of Results

It is surprising that road investment is the only type of public investment that affects manufacturing productivity. In Chapter 3 the other components of core infrastructure were shown to have a significant effect on private sector costs. It is to be expected that the services of certain public utilities and mass transit will also affect productivity. The causality test results reported in Table 7 do not reveal whether the variables have a positive or negative effect on each other. It is possible, for example, that road investment has a negative effect on the TFP growth rate. For example, it may be that the *average* effect of highway and street capital is positive, but that the *marginal* effect, given the current stock, is negative. Or it may be that greater highway expenditures are responses to deteriorating road quality and represent declining services from roads. These issues will be resolved in the next section when the relevant autoregressive model is estimated.

The reverse causality results contradict the causality test results obtained earlier using aggregate data. The finding there was that productivity caused total investment but not core investment. However, the results reported in Table 7 indicate that three of the four components of core infrastructure investment are caused by the growth rate of TFP. When the disaggregated model is estimated in the next section it will also be shown that these components of core infrastructure spending are affected both positively and negatively by the TFP growth rate.

3.10 Estimating Infrastructure's Impact on Productivity – Disaggregated Infrastructure Data

The next step is to estimate the impact of investment in roads on TFP. However, this time the construction of the models is made complicated by the fact that there are four variables ($\Delta\theta_t$, ΔI_t^H, ΔI_t^W, and ΔI_t^S). In determining the optimum number of lags for each variable it has to be decided in which order they are added to the equation. To do this I use the "specific gravity" criterion of Caines, Keng and Sethi (1981). The variable that generated the smallest FPE when included as a manipulated variable is included first. In the next stage the variable with the next-smallest FPE is added one lag at a time and the FPE is recalculated. The lag length that generates the smallest FPE enters the estimating model. The outcomes of this procedure, applied to all the equations in the model, are summarised in Table 8.

Table 8. *Construction of Estimating Model, Disaggregated Infrastructure Data*

	(1) *Dependent Variable, $\Delta\theta_t$*		
Controlled Variable	Manipulated Variable	*FPE(m*,n*)*	*FPE(m*)*
$\Delta\theta_t\,(1)$	$\Delta I_t^H\,(1)$	**0.000210***[a]	0.000252
	(2) *Dependent Variable, ΔI_t^H*		
Controlled Variable	Manipulated Variable	*FPE(m*,n*)*	*FPE(m*)*
$\Delta I_t^H\,(2)$	$\Delta\theta_t\,(2)$	**0.0020428***	0.0022703
	(3) *Dependent Variable, ΔI_t^W*		
Controlled Variables	Manipulated Variable	*FPE(m*,n*,p*)*[b]	*FPE(m*,n*)*
$\Delta I_t^W\,(1),\ \Delta\theta_t^1\,(4)$	$\Delta I_t^S\,(2)$	**0.015477***	0.016218
	(4) *Dependent Variable, ΔI_t^S*		
Controlled Variables	Manipulated Variable	*FPE(m*,n*,p*)*	*FPE(m*,n*)*
$\Delta I_t^S\,(1),\ \Delta I_t^W\,(4)$	$\Delta\theta_t\,(4)$	**0.012831***	0.016117

[a] Asterisks signify causality; [b] $p*$ is the optimum lag for variable 3.

Notes:

1. Model consists of four equations: (1) The effect of road investment on TFP; (2)-(4) The effect of different types of public investment on TFP. The model also takes account of possible causal relationships among the three infrastructure variables.
2. Equation (1) only contains ΔI_t^H because the FPEs in Table 24 indicate that the other types of investment do not Granger cause productivity.
3. Equation (2) contains $\Delta\theta_t$ because the bivariate FPE with this variable is lower than the univariate one using only ΔI_t^H. Bivariate regressions with ΔI_t^W and ΔI_t^S produce minimum FPEs of 0.0024105 and 0.0024071 respectively, ie higher than the univariate FPE. Therefore these variables are excluded.
4. Equation (3) contains $\Delta\theta_t$ and ΔI_t^S because the bivariate FPEs are lower than the univariate one. $\Delta\theta_t$'s FPE is the minimum one (0.016218 compared with 0.016555 for ΔI_t^S) so that variable enters the model first. FPEs are than recalculated by adding lags of ΔI_t^S, one at a time. The minimum FPE (0.015477) is obtained using two lags.
5. Equation (4) contains ΔI_t^W and $\Delta\theta_t$ because the bivariate FPEs are lower than the univariate one. ΔI_t^W's is the lower of the two (0.016117 versus 0.019719 for $\Delta\theta_t$) so that variable enters the model first. FPEs are than recalculated by adding lags of $\Delta\theta_t$, one at a time. The minimum FPE (0.012831) is obtained using four lags.

Table 9. *Estimation Results, Disaggregated Infrastructure Data*

	Dependent Variable			
	$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
$\Delta\theta_{t-1}$	0.119	-0.973*	1.949**	2.335**
	(0.70)	(1.65)	(2.09)	(2.40)
$\Delta\theta_{t-2}$		0.893**	2.246*	3.424***
		(2.55)	(1.78)	(3.13)
$\Delta\theta_{t-3}$			-0.279	-1.418
			(0.32)	(1.65)
$\Delta\theta_{t-4}$			-2.05*	1.409
			(1.72)	(1.47)
ΔI_{t-1}^H	0.113***	0.324***		
	(2.64)	(2.66)		
ΔI_{t-2}^H		0.450***		
		(3.89)		
ΔI_{t-1}^W			0.207	.306**
			(1.13)	(2.56)
ΔI_{t-2}^W				-0.606***
				(4.68)
ΔI_{t-3}^W				0.060
				(0.50)
ΔI_{t-4}^W				-0.446***
				(3.75)
ΔI_{t-1}^S			-0.062	-0.264***
			(0.30)	(2.96)
ΔI_{t-2}^S			-0.317**	
			(2.02)	
Constant	0.005*	-0.001	0.022	0.031*
	(1.50)	(0.16)	(1.25)	(1.82)
R^2	0.224	0.478	0.423	0.705
S.E.	0.013	0.039	0.094	0.081

Note: *H, W* and *S* denote highways and streets, water and sewers respectively; t-stats in parentheses and are computed using heteroskedastic-consistent standard errors.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

This modelling procedure produces the following estimating model

$$\begin{pmatrix} \Delta\theta_t \\ \Delta I_t^H \\ \Delta I_t^W \\ \Delta I_t^S \end{pmatrix} = \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix} + \begin{pmatrix} \psi_{11}^1(L) & \psi_{12}^1(L) & 0 & 0 \\ \psi_{21}^2(L) & \psi_{22}^2(L) & 0 & 0 \\ \psi_{31}^4(L) & 0 & \psi_{33}^1(L) & \psi_{34}^2(L) \\ \psi_{41}^4(L) & 0 & \psi_{43}^4(L) & \psi_{44}^1(L) \end{pmatrix} \begin{pmatrix} \Delta\theta_t \\ \Delta I_t^H \\ \Delta I_t^W \\ \Delta I_t^S \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \\ \varepsilon_t \\ \xi_t \end{pmatrix}. \tag{40}$$

Table 10. *Wald Tests for Zero Restrictions*

Equation	Joint Lags: Test	Joint Lags: χ^2 Value	Coefficient Sums: Test	Coefficient Sums: χ^2 Value
$\Delta\theta_t$	$\psi^1_{12}(L)=0$	7.06(1)***	n/a	n/a
ΔI_t^H	$\psi^2_{21}(L)=0$	7.55(2)**	$\sum_{i=1}^{2}\psi^i_{21}=0$	0.03(1)
ΔI_t^W	$\psi^4_{31}(L)=0$	13.25(4)**	$\sum_{i=1}^{4}\psi^i_{31}=0$	0.32(1)
	$\psi^2_{34}(L)=0$	5.51(2)*	$\sum_{i=1}^{2}\psi^i_{34}=0$	3.22(1)*
	$\psi^4_{31}(L)=\psi^2_{34}(L)=0$	23.00(6)***	n/a	n/a
ΔI_t^S	$\psi^4_{41}(L)=0$	22.00(4)***	$\sum_{i=1}^{4}\psi^i_{41}=0$	4.80(1)**
	$\psi^4_{43}(L)=0$	48.39(4)***	$\sum_{i=1}^{4}\psi^i_{41}=0$	6.98(1)***
	$\psi^4_{41}(L)=\psi^4_{43}(L)=0$	79.30(8)***	n/a	n/a

Note: Degrees of freedom in parentheses.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

The results from estimating the model using SUR are reported in Table 9. Wald tests that the off-diagonal terms in (40) are zero reject in favour of the variables chosen by the FPE Criterion (Table 10). Some of the lags of individual variables have different signs, however. Therefore, I also examine whether coefficient *sums* on lagged variables are significantly different from zero. The sum of the coefficients on $\Delta\theta$ in the ΔI_t^S equation is significantly different from zero. The sums of the $\Delta\theta$ coefficients in the ΔI_t^H and ΔI_t^W equations are insignificantly different from zero, indicating that the overall effect of the TFP growth rate on public investment may be ambiguous in terms of the direction of the effects, despite the significance of the joint tests of the lag distributions. Closer inspection of the coefficients reveals a negative impact of $\Delta\theta$ on ΔI_t^H for the first lagged value and a positive impact for the second lagged value. In the ΔI_t^W equation, the first two lags of $\Delta\theta_t$ have a positive impact, the second two have a negative impact. To gain further insights into the Solow residual's relationship with public investment, further tests were conducted to determine the joint significance of the first two lags in the ΔI_t^S equation (and their sum) and the second two lags (and their sum). The respective χ^2 test statistics are 6.22 (2 degrees of freedom), 6.22 (1 degree of freedom), 4.59 (2 degrees of freedom) and 2.77 (1 degree of freedom). The latter two statistics are only significant at the 10 per cent level. Thus there is some evidence that the TFP growth rate has a positive impact on the growth rate of water system investment after the first and second years and a negative effect after the third and fourth years. Tests were also conducted on the first and second lags of $\Delta\theta$ in the ΔI_t^H equation. The respective χ^2 statistics are 3.50 (1 degree of freedom) and 4.77 (1 degree of freedom), indicating again that TFP has a negative effect followed by a positive effect. These findings are discussed below. Further diagnostic tests on the equations in the model reveal that the disturbances are serially uncorrelated, homoskedastic and normally distributed and there is no evidence of a structural break in the sample or of specification error (Table 11).

3.11 Discussion of Results

The coefficient estimate of 0.113 on ΔI_t^H is almost identical to the estimate on ΔI_t^C (0.114) in the aggregate infrastructure model. Although roads were shown to be the only productive type of core infrastructure, they make up, on average, 60 per cent of the aggregate measure and so the growth rate of roads dominates the growth rate of the core infrastructure variable. However, use of disaggregated data leads to a rise in the significance of the infrastructure variable and a near doubling of the R^2 of the productivity equation.

Table 11. *Diagnostic Tests on Individual Equations*

Breusch-Godfrey LM Tests for Serial Correlation $\sim \chi^2$

	Dependent Variable			
	$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
Order: 1	0.10(1)	0.00(1)	0.03(1)	1.35(1)
2	1.95(2)	0.25(2)	0.19(2)	1.94(2)
3	4.86(3)	2.80(3)	0.03(3)	1.32(3)

White Heteroskedasticity Test $\sim \chi^2$

Dependent Variable			
$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
8.59(5)	12.9(14)	n/a	n/a

Jarque-Bera Normality Test $\sim \chi^2$

Dependent Variable			
$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
0.76(2)	0.31(2)	5.11(2)	2.12(2)

Ramsey RESET Test of Specification Error (F-Statistics)

	Dependent Variable			
	$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
RESET(2)	0.05(1,24)	0.01(1,22)	1.08(1,19)	0.43(1,17)
RESET(3)	1.21(2,23)	0.00(2,21)	1.05(2,18)	0.27(2,16)
RESET(4)	0.83(3,22)	0.20(3,20)	0.67(3,17)	0.40(3,15)

Chow Test for Structural Change (F-Statistics)

Dependent Variable			
$\Delta\theta_t$	ΔI_t^H	ΔI_t^W	ΔI_t^S
0.33(3,22)	1.70(5,18)	0.07(8,12)	2.53(10,8)

* Rejection of the relevant null hypothesis (serial independence, homoskedasticity, normality, no specification error, no structural break) at the 5% level. Degrees of freedom in parentheses.
n/a Insufficient degrees of freedom to conduct test.

Table 12. *Summary of Causality Tests*

Infrastructure Variable					
ΔI_t^T	ΔI_t^C	ΔI_t^H	ΔI_t^W	ΔI_t^S	ΔI_t^O
$\Delta I_t^T \Leftrightarrow \Delta\theta_t$	$\Delta I_t^C \Rightarrow \Delta\theta_t$	$\Delta I_t^H \Leftrightarrow \Delta\theta_t$	$\Delta I_t^W \Leftarrow \Delta\theta_t$	$\Delta I_t^S \Leftarrow \Delta\theta_t$	$\Delta I_t^O \not\Leftrightarrow \Delta\theta_t$

Note: *T* denotes total infrastructure investment and *C* denotes core investment. *H, W, S* and *O* are the different components of core investment (Highways and Streets, Water, Sewers and Other structures respectively)

Like the estimate on the core infrastructure variable, the estimate on ΔI_t^H implies that an increase in the growth rate of road investment of 1 percentage point increases the growth rate of total factor productivity by just over one-tenth of 1 percentage point in the following period. The coefficient estimates obtained using aggregate and disaggregated data attribute to infrastructure a smaller role in the determination of productivity growth than some of the production function studies whose results were discussed in Chapter 1. However, the estimates are similar in size to the output and cost elasticities obtained by authors who use regional data or solely manufacturing data (eg, Munnell 1993 and Nadiri and Mamuneas, 1994).

The estimates on lagged $\Delta\theta_t$ terms do not make much sense from an economic standpoint. Wald tests of the estimates in the ΔI_t^H and ΔI_t^W equations establish that in certain periods increases in the TFP growth rate lead to increases in investment growth; in other periods the effect is negative. This implies that certain types of infrastructure are both normal and inferior goods.

Thus far causality tests have been performed using three infrastructure aggregates. The results of Table 2 and Table 7 are summarised in Table 12. It is not surprising that some types of infrastructure investment affect the productivity growth rate more than others. However, it is difficult to reconcile the evidence of reverse causation. TFP growth causes spending on some types of infrastructure but not on others. Furthermore, the results are not robust to the use of data at different levels of aggregation. In summary, it is difficult from the evidence presented in this section to support the view stated by a number of infrastructure researchers that the TFP growth rate causes public investment. In the next section the focus moves temporarily away from causality testing and the estimation of autoregressive models to the comparison of different methods of measuring multifactor productivity.

4. Alternative TFP Measures

4.1 Introduction

The causality tests and estimations carried out in Section 3 provide interesting new evidence concerning infrastructure's effect on productivity growth. The stated view of certain infrastructure researchers that there is a one-way relationship from productivity to infrastructure is overturned – two aggregate infrastructure measures were found to influence the productivity growth rate over the sample period. Use of disaggregated data reveals which types of infrastructure are the most productive – contrary to expectations, only roads are productive. Use of different infrastructure measures also reveals certain ambiguities with respect to the "reverse relationship" between the variables. The results are not sensitive to the use of alternative lag-length selection criteria or different causality testing procedures.

Little mention has been made of the other variable in the analysis, namely the productivity growth rate. Although the Solow residual has been used in many infrastructure studies, it has already been pointed out that the residual possibly doesn't provide an accurate measure of the "true" productivity growth rate. In this section alternative measures of TFP are derived and the relationship with infrastructure is re-examined. Hall (1990) argues that the Solow residual does not reflect true efficiency changes because it fails the Invariance Theorem:

> "Under Solow's assumptions the following theorem holds: *The productivity residual is uncorrelated with any variable that is uncorrelated with the rate of growth of true productivity* (his italics). The theorem is just a restatement of Solow's basic result that the residual measures the shift of the production function. It says in particular that productivity growth should be uncorrelated with any variable that is a driving force for output, provided that the variable is not one that shifts the production function. For example, in the face of an exogenous upward shift in the demand for a particular industry's output, the productivity of that industry should remain unchanged. Or, if the price of one of the factors used by the industry rises sharply, productivity should also remain unchanged. Among U.S. industries the Solow residual is correlated with exogenous product demand and factor price movements. The invariance property fails conspicuously." (p. 71)

There are several explanations for the failure. Some are related to the fact that *true* productivity growth may not fail invariance but because of certain restrictive assumptions (such as perfect competition and constant returns to scale) and mismeasurement of factor inputs, the *measured* residual fails invariance. Other explanations are related to the fact that true productivity growth may be procyclical. For example, Caballero and Lyons (1989) conclude that externalities rather than increasing returns within industries are the most important source of failure of the invariance of the Solow residual. Diamond (1982) discusses how thick-market externalities generate increasing returns even though each firm may have constant returns. In this section the merits of some of the competing hypotheses are evaluated and a measure of TFP growth is derived that takes account of considerations pertaining to market power, non-constant returns to scale and variable factor utilisation over the cycle. The adjusted measure of TFP growth is used to generate new qualitative and quantitative evidence concerning infrastructure's relationship with the productivity growth rate. This exercise is interesting not only because it allows one to get closer to the true relationship between infrastructure and productivity but also because it allows the results to be compared with those obtained using the Solow residual – the TFP measure of preference in the infrastructure literature.

4.2 Deriving TFP – Cost Shares

Invariance of the original Solow residual may fail because of market power coupled with constant returns or because entry is free, but the technology has increasing returns. According to Hall (1990), a simple strategy can be used to distinguish between the two explanations:

> "Under constant returns to scale (no fixed costs) the telltale cyclical behaviour of the Solow residual should disappear once a simple modification is made in the computation of the residual. The modification is to measure labour's share in relation to cost rather than revenue. Because cost will be lower than revenue, the cost-based share will exceed the revenue-based share; the cyclicality of the Solow residual will vanish once a higher share is applied to labour growth. On the other hand, with fixed

> costs and free entry, revenue and cost will be the same, so the cost-based Solow residual will have the same cyclical behaviour as the original revenue-based one. When the cost-based Solow residual has almost as large a failure of invariance as the original residual, it means that technology has increasing returns." (p. 75)

To derive TFP using cost shares, Hall (1990) assumes that marginal cost λ is unobservable as the market price of output, P_Q. If average cost (AC) is given by

$$AC = TC/Q = (P_L L + P_M M + P_K K)/Q, \tag{41}$$

and substituted for λ in (15), the residual becomes

$$\Delta\theta_t = \Delta q_t - \frac{P_L L}{P_L L + P_M M + P_K K}\Delta l_t - \frac{P_M M}{P_L L + P_M M + P_K K}\Delta m_t - \frac{P_K K}{P_L L + P_M M + P_K K}\Delta k_t. \tag{42}$$

In terms of my other notation, the TFP growth rate can be expressed as

$$\Delta\theta_t^2 = \Delta q_t - \alpha_t^{L'}\Delta l_t - \alpha_t^{M'}\Delta m_t - \alpha_t^{K'}\Delta k_t, \tag{43}$$

where $\alpha_t^{L'} = \dfrac{P_L L}{P_L L + P_M M + P_K K}$, $\alpha_t^{M'} = \dfrac{P_M M}{P_L L + P_M M + P_K K}$ and

$$\alpha_t^{K'} = (1 - \alpha_t^{L'} - \alpha_t^{M'}) = \frac{P_K K}{P_L L + P_M M + P_K K}.$$

Unlike the original Solow residual, the cost-based residual measures shifts of the production function in the presence of market power. It may be that the measure of TFP used in Section 3 (and a number of infrastructure studies, for that matter) records false movements of the production function for firms with market power, even in the presence of constant returns to scale. When revenue exceeds cost, because of pure monopoly profit, the revenue share of labour understates the elasticity of output with respect to labour input. When some exogenous event raises labour input relative to capital input, the revenue-based Solow residual fails to account for all of the increase in output because it gives too little weight to labour.

Hall (1990) performs a number of estimations to test the invariance of the original and cost-based Solow residual. Each TFP measure is regressed on one of three instruments: the growth rate of the world price of oil, the growth rate of military spending and a dummy variable that takes the value of 1 when the President is a Democrat and 0 when the President is a Republican.[31] The oil price instrument provides the strongest evidence against invariance – in most of the one-digit industries and a large number of two-digit industries, changes in the world oil price coincide with changes in TFP. Hall (1990) concludes that:

> "Because factor prices do not shift production functions, this finding is a paradox within the assumptions of Solow's approach to productivity measurement." (p. 86)

Furthermore, the results for the original and cost-based residuals are very similar, pointing to the absence of large monopoly profits. If there is market power, Hall argues that it is probably offset by fixed costs or other types of increasing returns.

[31] These instruments are chosen because they should cause important movements in output but be uncorrelated with the random fluctuations in productivity growth.

Table 13. *How the Perfect Competition Assumption May Cause Mismeasurement of TFP*

	Weighted Input Growth	
	Case 1	
	$\alpha_t^L = 0.7$	$\alpha_t^L = 0.6$
$\Delta l_t = 2$	1.4	1.2
$\Delta k_t = 3$	0.9	1.2
%ΔInputs	**2.3**	**2.4**
	Case 2	
$\Delta l_t = 3$	2.1	1.8
$\Delta k_t = 2$	0.6	0.8
%ΔInputs	**2.7**	**2.6**

4.3 Deriving TFP – Market Power

Before deriving a measure of TFP that takes account of increasing returns to scale, it is worth taking a closer look at how failure to take account of market power may cause mismeasurement of the productivity growth rate. To the extent that firms are not price takers but can set $P_Q > MC$, α_t^L from (19) understates labour's elasticity of output and α_t^M underestimates the elasticity of materials.[32] If capital's revenue share is calculated as the residual $1-\alpha_t^L-\alpha_t^M$, its output elasticity is overstated. The overall effect on TFP growth depends on whether the labour and material inputs are growing faster than capital. To see the effect of under- or overstating input shares, consider the example contained in Table 13. It is assumed for simplicity that value-added output is produced

[32] Noting that the elasticity of the production function with respect to labour, for example, is expressed as $\varepsilon_L = \frac{\partial F}{\partial L}\frac{L}{Q} = \frac{P_L}{\lambda}\frac{L}{Q}$.

using two inputs, labour and capital. Assume labour's *true* output elasticity is 0.7 (capital 0.3). Use of revenue shares may lead to it being assigned a number of, for example, 0.6 (with capital claiming the residual, 0.4). If, as in case 1, labour input grows by 2 per cent and capital by 3 per cent, the true weighted input growth is 2.3 per cent. This compares with input growth of 2.4 per cent calculated using revenue shares. The incorrect measure of input growth causes productivity growth to be underestimated, since it is by definition equal to output growth minus weighted input growth. If instead labour input is growing at a faster rate than capital, the false measure underestimates input growth and hence overstates true productivity growth.

If the assumption of zero market power is relaxed the mark up of price over marginal cost can be expressed as

$$\mu = \frac{P_Q}{\lambda}. \tag{44}$$

Substituting the value of λ into the sources-of-growth equation (15) gives

$$\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \mu\frac{P_L L}{P_Q Q}\frac{\dot{L}}{L} + \mu\frac{P_M M}{P_Q Q}\frac{\dot{M}}{M} + \mu\frac{P_K K}{P_Q Q}\frac{\dot{K}}{K}, \tag{45}$$

which in terms of our other notation can be written as

$$\Delta q_t = \Delta\theta_t + \mu\alpha_t^L\Delta l_t + \mu\alpha_t^M\Delta m_t + \mu\alpha_t^K\Delta k_t. \tag{46}$$

Subtracting $\alpha_t^L\Delta l_t + \alpha_t^M\Delta m_t + \alpha_t^K\Delta k_t$ from both sides and rearranging, a new measure of TFP growth is obtained:

$$\begin{aligned}\Delta\theta_t^3 &= \Delta q_t - \alpha_t^L\Delta l_t - \alpha_t^M\Delta m_t - \alpha_t^K\Delta k_t - \\ &(\mu - 1)\left[\alpha_t^L(\Delta l_t - \Delta k_t) + \alpha_t^M(\Delta m_t - \Delta k_t)\right]\end{aligned} \tag{47}$$

The first three terms on the right-hand side represent the Solow residual under the assumption of perfect competition. In the absence of market power $\mu = 1$ and the right-hand side collapses to the original Solow residual, which is now denoted $\Delta\theta_t^S$:

$$\Delta\theta_t^S = \Delta q_t - \alpha_t^L \Delta l_t - \alpha_t^M \Delta m_t - \alpha_t^K \Delta k_t .$$

In the presence of market power, the term $(\mu - 1)[\cdot]$ shows the extent of over- or under-measurement of the original Solow residual. Following on from the example contained in Table 13, this depends on whether there is an increase or decrease in the labour/capital ratio or the materials/capital ratio.

4.4 Deriving TFP – Cost Shares and Increasing Returns to Scale

The second assumption used by Solow (1957) can also be dropped and total factor productivity can be derived in the presence of increasing returns to scale (IRS). Over all levels of output increasing returns to scale implies average cost exceeds marginal cost (ie, $AC > MC$) and thus firms must have market power if they are to cover their total costs. As mentioned in 4.2, use of cost shares accommodates potential market power. To also incorporate increasing returns the firms cost minimisation problem has to be solved. As Silberberg (1978) shows, if the production function $Q = \Theta F(L, M, K)$ is homogeneous of degree γ in L,M and K, the cost function, C^*, can be partitioned into

$$C^*(P_L, P_M, P_K, Q) \equiv Q^{1/\gamma} \cdot A(P_L, P_M, P_K), \tag{48}$$

where $A(P_L, P_M, P_K)$ is a function of factor prices only. The elasticity of C^* with respect to Q is

$$\frac{\partial C^*}{\partial Q}\frac{Q}{C^*} = \frac{1}{\gamma}. \tag{49}$$

Since $\dfrac{\partial C^*}{\partial Q} = \lambda$, (49) can be expressed as

$$\lambda = \frac{C^*}{\gamma Q}, \tag{50}$$

where the term C^*/Q is average cost, AC. Substituting for λ in the first-order conditions (12)-(14) gives:

$$\Theta \frac{\partial F}{\partial L} = \frac{\gamma P_L Q}{C^*}, \tag{51}$$

$$\Theta \frac{\partial F}{\partial M} = \frac{\gamma P_M Q}{C^*}, \text{ and} \tag{52}$$

$$\Theta \frac{\partial F}{\partial K} = \frac{\gamma P_K Q}{C^*}. \tag{53}$$

Substituting (51)-(53) into (5) gives

$$\Delta q_t = \Delta\theta_t + \gamma\alpha_t^{L'}\Delta l_t + \gamma\alpha_t^{M'}\Delta m_t + \gamma\alpha_t^{K'}\Delta k_t. \tag{54}$$

Subtracting $\Delta\theta_t^2 = \Delta q_t - \alpha_t^{L'}\Delta l_t - \alpha_t^{M'}\Delta m_t - \alpha_t^{K'}\Delta k_t$ (the cost-based residual derived under CRS) from both sides and rearranging gives

$$\Delta\theta_t^4 = \Delta q_t - \alpha_t^{L'}\Delta l_t - \alpha_t^{M'}\Delta m_t - \alpha_t^{K'}\Delta k_t - (\gamma - 1)\left[\alpha_t^{L'}\Delta l_t + \alpha_t^{M'}\Delta m_t + \alpha_t^{K'}\Delta k_t\right]. \tag{55}$$

Again, to get closer to the "true" productivity growth rate, the last term has to be subtracted from the cost-based Solow residual. The productivity expression does not provide explicit information regarding the mark-up, μ, since the new shares can accommodate both the perfectly competitive case (where $C^* = P_Q Q$) and the case of monopoly power (where $C^* < P_Q Q$). However, if γ is not unity it can be concluded that there is monopoly power in the industry.

Employing instrumental variable (IV) techniques, estimates of the returns to scale parameter were obtained using data for all 20 industries and imposing the same γ across equations using 3SLS.[33] Like the original Solow residual, the continuous time

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[33] Using data for all the industries leads to a substantial increase in the degrees of freedom in the regression.

formula has to be modified for empirical purposes so that it is valid in discrete time. The following adjustment is made to the cost shares:

$\overline{\alpha}_t^{L'} = \left(\alpha_t^{L'} + \alpha_{t-1}^{L'}\right)/2$, $\overline{\alpha}_t^{M'} = \left(\alpha_t^{M'} + \alpha_{t-1}^{M'}\right)/2$, $\overline{\alpha}_t^{K'} = \left(\alpha_t^{K'} + \alpha_{t-1}^{K'}\right)/2$, where

$$\alpha_t^{L'} = \frac{P_L L}{TC}; \alpha_t^{M'} = \frac{P_M M}{TC}; \alpha_t^{K'} = \left(1 - \alpha_t^{L'} - \alpha_t^{M'}\right) = \frac{P_K K}{TC}; TC = P_L L + P_M M + P_K K.$$

Once again a random term υ_t is added to reflect the stochastic nature of productivity growth and can be viewed as the sum of a constant underlying growth rate plus a random component υ_t.

The estimating equation is

$$\Delta q_t = \gamma X_t + \upsilon_t, \tag{56}$$

where $X_t = \left(\overline{\alpha}_t^{L'} \Delta l_t + \overline{\alpha}_t^{M'} \Delta m_t + \overline{\alpha}_t^{K'} \Delta k_t\right)$. An IV estimator is required because of the endogeneity of the regressors. Use was made of the set of instruments proposed by Ramey (1989) and Hall (1990) and augmented by Caballero and Lyons (1992) and Basu (1996). These include the growth rate of military spending, the growth rate of the price of oil (deflated by the prices of manufacturing durables and nondurables), and the political party of the President. These instruments are chosen because they cause important movements in employment, material costs, capital accumulation and output but are uncorrelated with the random component of TFP growth. Note that estimates of γ were obtained using data for total manufacturing and two sub-aggregates (durable manufacturing and nondurable manufacturing). Estimates of 1.20, 1.18 and 1.15 respectively all point to the existence of increasing returns to scale.[34] This in turn implies that the standard Solow residual provides an inaccurate measure of TFP

[34] t-stats of 51.8, 30.2 and 27.0 imply that the estimates are significant at the 1 per cent level at least.

growth. The growth rate of weighted input growth has to be reduced by a factor of $(\gamma - 1)$.

The preceding estimation assumes that adjusting for market power and increasing returns to scale will result in a more accurate measure of multifactor productivity. However, as will now be demonstrated, there is at least one other reason why the original Solow residual may not measure true efficiency gains.

4.5. Adjusting for Factor Utilisation

Basu (1996) argues that estimates of returns to scale obtained using the above framework are biased upwards by unobserved factor utilisation. He builds on Hall's measures of TFP growth by modifying the production function (1) to include the levels of labour and capital utilisation:

$$Q_t = \Theta F(C_t \cdot L_t, M_t, Z_t \cdot K_t), \tag{57}$$

where C_t is the level of labour utilisation and Z_t is the level of capital utilisation, observable to the firm but not to the econometrician. If productivity growth is measured as output growth minus input growth, use of only L_t and K_t may lead to overmeasurement of inputs during a recession and undermeasurement during a boom. Overmeasurement of inputs implies that productivity is undermeasured and vice-versa, thus explaining partly why productivity growth may be procyclical. Using the same methods employed earlier, the cost-based Solow residual that takes account of factor utilisation is derived. Omitting time subscripts, (3) now becomes

$$\begin{aligned}\frac{\dot{Q}}{Q} = \frac{\dot{\Theta}}{\Theta} + \frac{\partial F}{\partial (C \cdot L)} \frac{1}{F()} \left(\frac{\partial (C \cdot L)}{\partial L} \dot{L} + \frac{\partial (C \cdot L)}{\partial C} \dot{C} \right) + \frac{\partial F}{\partial M} \frac{1}{F()} \dot{M} + \\ \frac{\partial F}{\partial (Z \cdot K)} \frac{1}{F()} \left(\frac{\partial (Z \cdot K)}{\partial K} \dot{K} + \frac{\partial (Z \cdot K)}{\partial Z} \dot{Z} \right),\end{aligned} \tag{58}$$

which is the same as

$$\frac{\dot{Q}}{Q}=\frac{\dot{\Theta}}{\Theta}+\frac{\partial F}{\partial (C\cdot L)}\frac{1}{F(.)}\left(C\dot{L}+L\dot{C}\right)+\frac{\partial F}{\partial M}\frac{1}{F(.)}\dot{M}+\frac{\partial F}{\partial (Z\cdot K)}\frac{1}{F(.)}\left(Z\dot{K}+K\dot{Z}\right), \tag{59}$$

or

$$\begin{aligned}\frac{\dot{Q}}{Q}=\frac{\dot{\Theta}}{\Theta}+\Theta\frac{\partial F}{\partial (C\cdot L)}\frac{CL}{Q}\frac{\dot{L}}{L}+\Theta\frac{\partial F}{\partial (C\cdot L)}\frac{CL}{Q}\frac{\dot{C}}{C}+\\ \Theta\frac{\partial F}{\partial M}\frac{M}{Q}\frac{\dot{M}}{M}+\Theta\frac{\partial F}{\partial (Z\cdot K)}\frac{ZK}{Q}\frac{\dot{K}}{K}+\Theta\frac{\partial F}{\partial (Z\cdot K)}\frac{ZK}{Q}\frac{\dot{Z}}{Z}.\end{aligned} \tag{60}$$

The first-order conditions from the cost minimisation problem are

$$\Theta\frac{\partial F}{\partial (C\cdot L)}=\frac{P_L}{\lambda C}, \tag{61}$$

$$\Theta\frac{\partial F}{\partial M}=\frac{P_M}{\lambda}, \text{ and} \tag{62}$$

$$\Theta\frac{\partial F}{\partial (Z\cdot K)}=\frac{P_K}{\lambda Z} \tag{63}$$

Substituting the right-hand sides of (61)-(63) into (60) and substituting P_Q for λ:

$$\frac{\dot{Q}}{Q}=\frac{\dot{\Theta}}{\Theta}+\frac{P_L L}{P_Q Q}\frac{\dot{L}}{L}+\frac{P_L L}{P_Q Q}\frac{\dot{C}}{C}+\frac{P_M M}{P_Q Q}\frac{\dot{M}}{M}+\frac{P_K K}{P_Q Q}\frac{\dot{K}}{K}+\frac{P_K K}{P_Q Q}\frac{\dot{Z}}{Z}, \tag{64}$$

which can be rearranged and rewritten as

$$\Delta\theta_t^5=\Delta q_t-\alpha_t^L\Delta l_t-\alpha_t^M\Delta m_t-\alpha_t^K\Delta k_t-\left(\alpha_t^L\Delta c_t+\alpha_t^K\Delta z_t\right). \tag{65}$$

The term $\left(\alpha_t^L\Delta c_t+\alpha_t^K\Delta z_t\right)$ corrects the original Solow residual (19) for the growth rates of unobserved capital and labour utilisation. If, for example, labour usage intensifies but employment stays the same, the new measure of productivity growth, $\Delta\theta_t^6$, will be smaller than the one that makes no adjustment for factor usage, $\Delta\theta_t^S$. Using the methods employed earlier it is also possible to derive a measure that incorporates increasing returns to scale and cost shares:

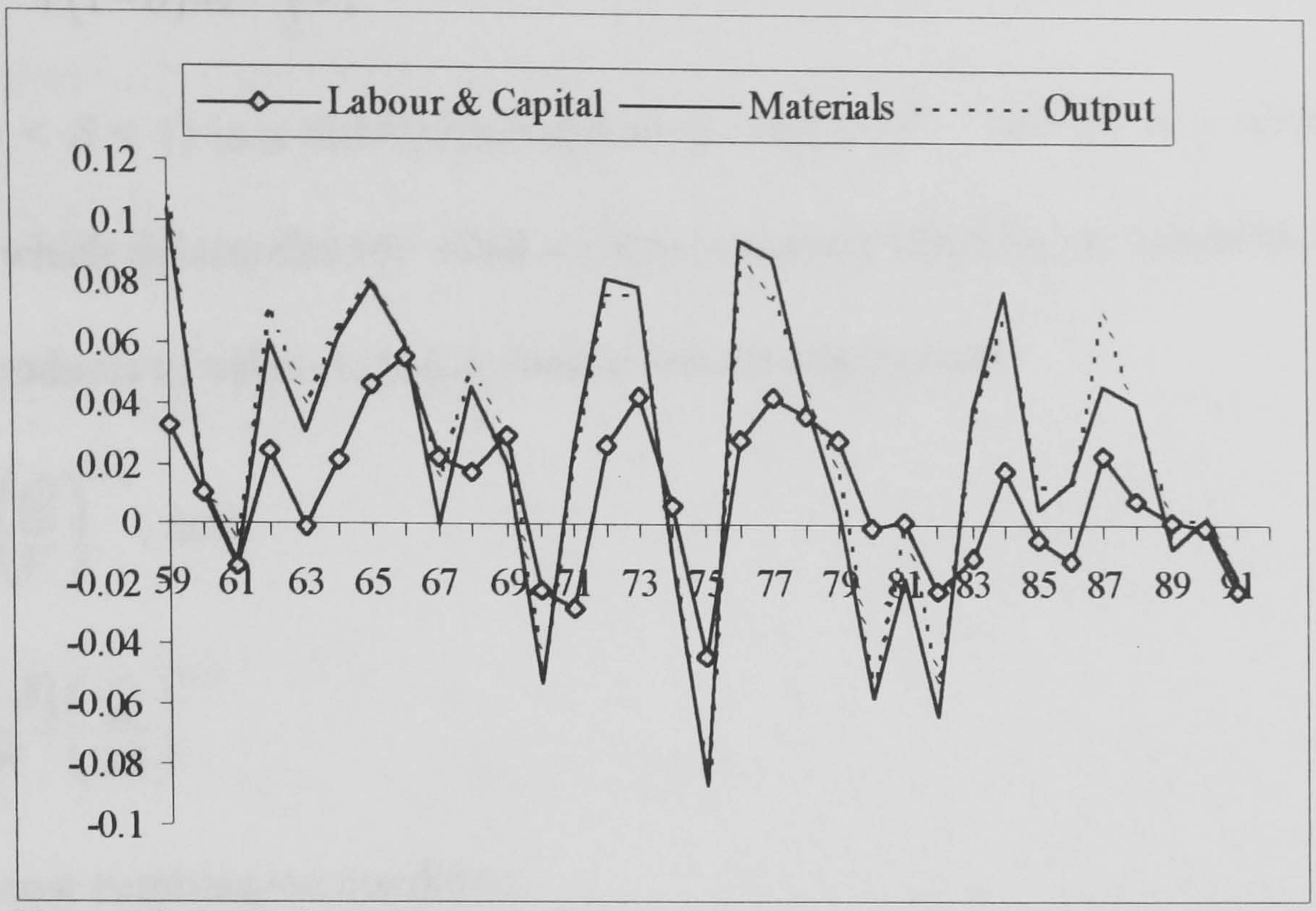
$$\Delta\theta_t^6 = \Delta q_t - \gamma\left(\alpha_t^{L'}\Delta l_t + \alpha_t^{M'}\Delta m_t + \alpha_t^{K'}\Delta k_t\right) - \gamma\left(\alpha_t^{L'}\Delta c_t + \alpha_t^{K'}\Delta z_t\right), \qquad (66)$$

where the second term on the right-hand side of (66) equals the second term on the right-hand side of (54). Thus merely adjusting the original Solow residual for imperfect competition and IRS still results in a biased measure of TFP growth. Changes in the intensity of usage of labour or capital will be attributed to TFP growth. To correct this error, the cost-weighted percentage changes in utilisation rates should be subtracted from Hall's measure. The problem with making this adjustment is that Δc_t and Δz_t are not directly observable. However, there is a solution to the problem. Changes in materials usage, data for which is readily available, can be employed to measure the degree to which labour and capital usage vary over the business cycle. As Basu notes:

> "The idea is a simple one: workers putting in longer hours and more effort, or machines being worked extra shifts, need more materials to create more output. Materials use is a convenient indicator of cyclical factor utilisation because its input does not have an extra effort or time dimension. An hour worked may represent very different amounts of labour input and a machine may be operated at different intensities, but a nail, a sheet of steel, or a piece of lumber always make the same contribution to output: no amount of coaxing can make one nut fit on two bolts." (p. 725)

If cyclical productivity is caused at least in part by unobserved capital and labour utilization, then one would expect materials input to track the business cycle more closely than labour and capital. It is clear from Figure 2 that this is what happens. The graph compares the growth rates of materials, weighted capital and labour and output. The coefficient of correlation between materials and output is 0.99; the coefficient of

Figure 2. *Growth Rates of Factor Inputs and Output, 1959-91*



Note: Labour & Capital input is the sum of the growth rates of these inputs, weighted by their respective cost shares.

correlation between output and capital and labour is 0.78. Thus the initial evidence points to cyclical factor utilization as an important factor explaining procyclical productivity. The next step is to construct a TFP measure that incorporates changes in material input as a proxy for labour and capital usage. To derive the relationship between unobserved capital and labour inputs and observable or measured material inputs, Basu makes use of the following more restricted production function

$$Q = \Theta F\big(V(C \cdot L, Z \cdot K), H(M)\big), \tag{67}$$

where V is the value-added function and H is the materials function. Both V and H are assumed to have constant returns to scale. Note that the function *F(.)* still has the same properties as set out in (1). As Bruno and Sachs (1985) point out, the relationship between relative quantity and relative price change can be expressed in a simple manner by assuming that *F(.)* is CES in V and H:[35]

[35] See Berndt and Christensen (1973) for further discussion of functional separability and elasticities of substitution.

$$Q = \Theta\left[\delta V^{-\rho} + (1-\delta)M^{-\rho}\right]^{-\frac{1}{\rho}}, \tag{68}$$

where δ ($0 < \delta < 1$) is a distribution parameter and ρ ($-1 < \rho \neq 0$) is a substitution parameter which determines the value of the (constant) elasticity of substitution. The marginal products of value-added and materials are respectively

$$\frac{\partial Q}{\partial V} = \frac{\delta}{\Theta^{\rho}}\left(\frac{Q}{V}\right)^{1+\rho}, \text{ and} \tag{69}$$

$$\frac{\partial Q}{\partial M} = \frac{(1-\delta)}{\Theta^{\rho}}\left(\frac{Q}{M}\right)^{1+\rho}. \tag{70}$$

The least-cost combination condition:

$$\frac{\partial Q/\partial M}{\partial Q/\partial V} = \frac{P_M}{P_V}, \tag{71}$$

can be expressed as

$$\frac{1-\delta}{\delta}\left(\frac{V}{M}\right)^{1+\rho} = \frac{P_M}{P_V}, \tag{72}$$

and the optimal input ratio is

$$\frac{V}{M} = \left(\frac{\delta}{1-\delta}\right)^{1/(1+\rho)}\left(\frac{P_M}{P_V}\right)^{1/(1+\rho)} \equiv c\left(\frac{P_M}{P_V}\right)^{1/(1+\rho)}, \tag{73}$$

where c is a constant term. Taking logs and differentiating gives

$$d\ln\left(\frac{V}{M}\right) = \frac{1}{(1+\rho)} d\ln\left(\frac{P_M}{P_V}\right). \tag{74}$$

Rearranging (74) and using previous notation, the growth rate in value-added can be expressed as

$$\Delta v_t = \Delta m_t - \sigma\left(\Delta p_t^v - \Delta p_t^m\right), \tag{75}$$

where Δp_t^v and Δp_t^m are changes in the prices of value-added and materials, expressed in logs, and $\sigma = 1/(1+\rho)$ is the (constant) elasticity of substitution between value-added and materials. Basu expresses the Divisia index of value-added in terms of changes in observed labour and capital input and changes in unobserved utilisation:

$$\Delta v_t = \frac{\alpha_t^{L'}(\Delta l_t + \Delta c_t) + \alpha_t^{K'}(\Delta k_t + \Delta z_t)}{\alpha_t^{L'} + \alpha_t^{K'}}. \tag{76}$$

Substituting the right-hand side of (75) into (76) results in

$$\alpha_t^{L'}(\Delta l_t + \Delta c_t) + \alpha_t^{K'}(\Delta k_t + \Delta z_t) = \left(\alpha_t^{L'} + \alpha_t^{K'}\right)\Delta m_t - \sigma\left(\alpha_t^{L'} + \alpha_t^{K'}\right)\left(\Delta p_t^v - \Delta p_t^m\right). \tag{77}$$

Substituting (77) into (66) gives

$$\Delta\theta_t^B = \Delta q_t - \gamma\left(\Delta m_t - \sigma\left(\alpha_t^{L'} + \alpha_t^{K'}\right)\left(\Delta p_t^v - \Delta p_t^m\right)\right). \tag{78}$$

Note that both the observed and unobserved inputs of labour and capital are omitted from (78). Throughout the rest of the chapter $\Delta\theta_t^B$ is referred to as the adjusted TFP measure or the Basu residual. In all, seven TFP measures have been derived in this chapter. A summary of the different measures (measured in discrete terms and accounting for the stochastic nature of productivity growth) is provided in Table 14. Before the Basu residual can be calculated it is first necessary to obtain new estimates of the returns to scale parameter γ. Once again estimates of γ were obtained using IV techniques and data from all 20 industries. Applying the discrete time formulation and accounting for the stochastic nature of productivity growth, the equation to be estimated is

$$\Delta q_t = \gamma X_t + \upsilon_t, \tag{79}$$

where $X_t = \Delta m_t - \sigma\left(\bar{\alpha}_t^{L'} + \bar{\alpha}_t^{K'}\right)\left(\Delta p_t^v - \Delta p_t^m\right)$. To test the robustness of the estimates of γ in (79), X_t was calculated using various estimates of σ, ranging from 0 (the Leontief case) to 1 (the Cobb-Douglas case). There is no consensus in the literature as to which value is correct. Rotemberg and Woodford (1992) estimate σ at 0.7, Bruno (1984) reviews a number of papers and reports a consensus range for σ between 0.3 and 0.4.

Table 14. *The Different TFP Growth Measures*

	(1)
Revenue shares, perfect competition, CRS	$\Delta\theta_t^S + \upsilon_t = \Delta q_t - \overline{\alpha}_t^L \Delta l_t - \overline{\alpha}_t^M \Delta m_t - \overline{\alpha}_t^K \Delta k_t$
	(2)
Cost shares, CRS	$\Delta\theta_t^2 + \upsilon_t = \Delta q_t - \overline{\alpha}_t^{L'} \Delta l_t - \overline{\alpha}_t^{M'} \Delta m_t - \overline{\alpha}_t^{K'} \Delta k_t$
	(3)
Revenue shares, market power	$\Delta\theta_t^3 + \upsilon_t = \Delta q_t - \overline{\alpha}_t^L \Delta l_t - \overline{\alpha}_t^M \Delta m_t - \overline{\alpha}_t^K \Delta k_t - (\mu - 1)\left[\overline{\alpha}_t^L(\Delta l_t - \Delta k_t) + \overline{\alpha}_t^M(\Delta m_t - \Delta k_t)\right]$
	(4)
Cost shares, IRS	$\Delta\theta_t^4 + \upsilon_t = \Delta q_t - \overline{\alpha}_t^{L'} \Delta l_t - \overline{\alpha}_t^{M'} \Delta m_t - \overline{\alpha}_t^{K'} \Delta k_t - (\gamma - 1)\left[\overline{\alpha}_t^{L'} \Delta l_t + \overline{\alpha}_t^{M'} \Delta m_t + \overline{\alpha}_t^{K'} \Delta k_t\right]$
	(5)
Revenue shares, perfect comp., factor utilisation correction	$\Delta\theta_t^5 + \upsilon_t = \Delta q_t - \overline{\alpha}_t^L \Delta l_t - \overline{\alpha}_t^M \Delta m_t - \overline{\alpha}_t^K \Delta k_t - \left(\overline{\alpha}_t^L \Delta c_t + \overline{\alpha}_t^K \Delta z_t\right)$
	(6)
Cost shares, IRS, factor correction	$\Delta\theta_t^6 + \upsilon_t = \Delta q_t - \gamma\left(\alpha_t^{L'} \Delta l_t + \alpha_t^{M'} \Delta m_t + \alpha_t^{K'} \Delta k_t\right) - \gamma\left(\alpha_t^{L'} \Delta c_t + \alpha_t^{K'} \Delta z_t\right)$
	(7)
Calculable version of (7)	$\Delta\theta_t^B + \upsilon_t = \Delta q_t - \gamma\left(\Delta m_t - \sigma\left(\overline{\alpha}_t^{L'} + \overline{\alpha}_t^{K'}\right)\left(\Delta p_t^v - \Delta p_t^m\right)\right)$

Basu uses 0.7 as his baseline value. Malley *et al.* (1998) set σ equal to 0.5. The estimates are reported in Table 15. It is interesting to note that there is no longer evidence of increasing returns to scale. The estimates indicate that returns to scale are

Table 15. *Estimates of the Returns to Scale Parameter*

	Aggregate	Durable	Nondurable
σ=0	0.94	0.92	0.92
	(56.2)	(31.7)	(31.3)
σ=0.3	0.95	0.93	0.94
	(52.2)	(33.5)	(33.3)
σ=0.5	0.95	0.94	0.95
	(61.7)	(34.7)	(34.0)
σ=0.7	0.96	0.94	0.95
	(64.3)	(36.0)	(34.2)
σ=1	0.96	0.95	0.96
	(67.1)	(37.5)	(33.4)

Note: t-stats in parentheses. Wald tests confirm that all the estimates are significantly different from 1.

decreasing (but not far from constant). Furthermore, the estimates are very robust to changes in σ. The $\hat{\gamma}$s and σs were then inserted into equation 8 in Table 14 to obtain measures of multifactor productivity growth from 1959-91. It is apparent that Basu's measure removes much of the cyclical variation in Solow-based TFP (Table 16). Regardless of the value of σ, correlation of the Basu residual with various measures of the business cycle is significantly lower than that of the Solow residual. Another way of comparing the Solow and Basu measures is to compute the variance of TFP to output and hours growth. The ratios for the Solow residual are of a considerably larger magnitude than those computed using the adjusted measure (regardless of which estimate of σ is used). In conclusion, neither imperfect competition nor increasing returns to scale appear to be responsible for the mismeasurement of TFP growth. Unobserved variations in factor usage do, however, have a significant effect. Of course, the fact that mismeasurement is caused more by variations in factor usage than increasing returns to scale is only of indirect interest to infrastructure researchers. What is important is that the researcher has as accurate a measure of productivity as possible that can be used to examine the relationship with infrastructure.

Table 16. *Correlation Between TFP Measures, Real Gross Output and Production Hours and Variance of TFP to Output and Hours Variance*

		Output, Δq_t Correlation	Variance	Hours, ΔHp Correlation	Variance
Solow					
$\Delta\theta_t^S$	Aggregate	0.95	0.52	0.84	0.50
	Durable	0.95	0.39	0.84	0.42
	Nondurable	0.92	0.71	0.79	0.71
Basu					
$\Delta\theta_t^B$,	Aggregate	0.24	0.02	0.25	0.02
σ=0	Durable	-0.09	0.02	-0.02	0.02
	Nondurable	0.43	0.14	0.41	0.14
$\Delta\theta_t^B$,	Aggregate	0.19	0.02	0.16	0.02
σ=0.3	Durable	-0.19	0.02	-0.13	0.02
	Nondurable	0.40	0.14	0.37	0.14
$\Delta\theta_t^B$,	Aggregate	0.16	0.02	0.12	0.02
σ=0.5	Durable	-0.24	0.02	-0.20	0.02
	Nondurable	0.38	0.14	0.34	0.14
$\Delta\theta_t^B$,	Aggregate	0.16	0.03	0.09	0.02
σ=0.7	Durable	-0.28	0.02	-0.25	0.02
	Nondurable	0.36	0.14	0.32	0.14
$\Delta\theta_t^B$,	Aggregate	0.17	0.03	0.08	0.03
σ=1	Durable	-0.32	0.02	-0.31	0.02
	Nondurable	0.33	0.15	0.28	0.15

5. Basu's TFP Measure versus Measures Used in the Infrastructure Literature

It is interesting to compare the adjusted TFP measure calculated in the previous section with those used in previous infrastructure research.[36] Aschauer (1989) used two measures of productivity for the private business sector: capital productivity and multifactor productivity. Output per unit of labour was the dependent variable in

[36] The comparison is made using adjusted TFP calculated under the assumption that $\sigma = 0.7$.

Table 17. *Correlations between Manufacturing TFP Measures and Measures Used in the Infrastructure Literature, 1959-85.*

	Δq	$\Delta\theta^S$	$\Delta\theta^B$	Δq_{ALL}	$\Delta\theta^S_{ALL}$	$\Delta\theta^{S,K}_{ALL}$
Δq	1.00					
$\Delta\theta^S$	0.90	1.00				
$\Delta\theta^B$	0.10	0.32	1.00			
From Infrastructure Literature:						
Δq_{ALL}	0.95	0.87	0.10	1.00		
$\Delta\theta^S_{ALL}$	0.82	0.85	0.16	0.88	1.00	
$\Delta\theta^{S,K}_{ALL}$	0.92	0.89	0.07	0.96	0.93	1.00
$\Delta\theta^{S,L}_{ALL}$	0.57	0.66	0.23	0.66	0.91	0.70

Note: Δq is output growth in manufacturing; Δq_{ALL} is output growth for the total private business sector; $\Delta\theta^S$ is the Solow residual for aggregate manufacturing; $\Delta\theta^S_{ALL}$ is the Solow residual for the total private business sector. $\Delta\theta^{S,K}_{ALL}$ and $\Delta\theta^{S,L}_{ALL}$ are output per unit of capital and output per unit of labour respectively for the total private business sector.

Munnell (1990a) and gross state product was the dependent variable in Munnell (1993). Aschauer's productivity measures were obtained using Mark and Waldorf (1983) and the *Monthly Labor Review* (1987). I used this data to replicate Aschauer's two total private business sector measures and to construct the dependent variable used in Munnell (1990a).[37] Table 17 compares the growth rates of these measures with those calculated for manufacturing in Sections 2 and 4 for the period 1959-85, the period of overlap between the two sets of data. Manufacturing output and the manufacturing Solow residual, Δq and $\Delta\theta^S$ respectively, are equivalent to Δq_{ALL} and $\Delta\theta^S_{ALL}$, except the latter two use Aschauer's data for the whole private business sector.

[37] Although the specifications are the same as those used by Munnell, the dataset is different (see Chapter 1 for a comparison of Aschauer's and Munnell's datasets).

It should also be pointed out that Δq_{ALL} and $\Delta\theta^S_{ALL}$ were calculated using value-added data. Clearly the two sets of measures, Δq and Δq_{ALL} and $\Delta\theta^S_t$ and $\Delta\theta^S_{ALL}$, are highly correlated. Trends in manufacturing productivity were similar to trends in total productivity over the sample period. It is also not surprising, therefore, that the Solow residual used by infrastructure researchers, $\Delta\theta^S_{ALL}$, and the adjusted TFP measure, $\Delta\theta^B$, are not closely correlated (the correlation coefficient has a value of 0.16). Other studies that use measures of multifactor productivity similar to $\Delta\theta^S_{ALL}$ include Ford and Poret (1991), Hulten and Schwab (1991b), Tatom (1993) and Ho and Sorensen (1994). The measure of capital productivity used by Aschauer (1989), $\Delta\theta^{S,K}_{ALL}$, was the dependent variable of the regression equation that has received the widest publicity in the infrastructure literature. The infrastructure variable in this equation had an estimated output elasticity of 0.39. Other studies that have used this specification include Otto and Voss (1994), Bajo-Rubio and Sosvilla-Rivero (1993) and Berndt and Hansson (1992). Once again, $\Delta\theta^{S,K}_{ALL}$ and $\Delta\theta^B$ are not closely correlated (the correlation coefficient has a value of only 0.07). The low correlations between the two most widely used measures of TFP in the infrastructure literature ($\Delta\theta^S_{ALL}$ and $\Delta\theta^{S,K}_{ALL}$) and the Basu residual provide an early indication that the relationship between adjusted TFP growth and public infrastructure will be different to that estimated in earlier production function studies. Munnell (1990a) used labour productivity, $\Delta\theta^{S,L}_{ALL}$, as her dependent variable. Again, this variable does not follow the movement of $\Delta\theta^B$ very closely (the correlation coefficient is 0.23). Of course, one would expect a measure of total factor productivity to differ from a measure of capital or labour productivity. However, measures of individual inputs' productivities are obtained by making minor adjustments to the derivations of total measures such as $\Delta\theta^{S}_{ALL}$ and $\Delta\theta^{S}$. For example, labour productivity can be derived by making a simple adjustment to the sources-of-growth equation used to compute the standard Solow residual. Using the assumption of CRS, (5) can be rewritten as

$$\left(\frac{\dot{Q}}{Q}-\frac{\dot{L}}{L}\right)=\frac{\dot{\Theta}}{\Theta}+\left(\left(\Theta\frac{\partial F}{\partial K}\frac{K}{Q}\right)\left(\frac{\dot{K}}{K}-\frac{\dot{L}}{L}\right)\right). \tag{80}$$

This expression shows that labour productivity growth, $\left(\dot{Q}/Q-\dot{L}/L\right)$, equals TFP growth plus the rate of change of capital services per hour, $\left(\dot{K}/K-\dot{L}/L\right)$, multiplied by capital's output elasticity, $\left(\Theta\frac{\partial F}{\partial K}\frac{K}{Q}\right)$. In conclusion, to the extent that the TFP measure that corrects for varying factor utilization is a more accurate measure of efficiency gains than the original Solow residual, conclusions drawn about infrastructure's relationship with TFP are potentially seriously flawed. In the next section causality tests are conducted using the new TFP measure and different infrastructure aggregates. The methodology is identical to that used in Section 3 with $\Delta\theta^{S}$ and so the results are directly comparable.

6. Causality Testing and Estimation of Autoregressive Models – Adjusted Multifactor Productivity

6.1 Introduction

In this section causality tests are conducted using Basu's TFP measure and infrastructure data at different levels of aggregation (total, core and disaggregated). A

Table 18. *The FPEs of Fitting a One-Dimensional Autoregressive Process for the Basu Residual and Infrastructure Investment*

No. lags	$\Delta\theta_t^B$	ΔI_t^C	ΔI_t^T
1	**.0000602***	.002140	.002427
2	.0000634	**.001820***	**.002262***
3	.0000702	.001997	.002396
4	.0000743	.002122	.002442

Note: Asterisks signify minimum FPEs

series of models is also estimated in order to quantify infrastructure's impact on productivity.[38] The results obtained in this section are significantly different to those obtained in Section 4 using the original Solow residual. I also conduct a number of robustness tests, increasing the number of lags on the infrastructure terms to establish whether this affects conclusions drawn about infrastructure's relationship with TFP. Further tests are performed to determine if the specifications chosen by the FPE Criterion are adequate compared with models which exhibit a greater or smaller number of lags.

6.2 . Results – Aggregate Infrastructure

The first step is to determine the appropriate own lag length for the various variables. From Table 18, the lag length that minimises the FPE for the Basu residual, $\Delta\theta_t^B$, is 1. The FPEs for ΔI_t^C and ΔI_t^T are the same as those reported in Table 1. With the appropriate own lag lengths determined, each variable is treated as controlled and the relevant second variable is manipulated. Holding constant the order of the

[38] Once again, adjusted TFP is calculated using $\sigma = 0.7$. See Appendix C for a discussion of the robustness of the results to the use of different values of σ.

Table 19. *FPEs from Inclusion of Optimum Lags on Manipulated Variables*

Controlled Variable [a]	*Manipulated Variable*	*Optimum Lags, Manipulated Variable*	*FPE(m*,n*)* [b]	*FPE(m*)*
Basu Residual				
$\Delta\theta_t^B$ *(1)*	ΔI_t^C	1	**0.000049***	0.0000602
$\Delta\theta_t^B$ *(1)*	ΔI_t^T	1	**0.000051***	0.0000602
Core				
ΔI_t^C *(2)*	$\Delta\theta_t^B$	1	0.001876	0.001820
Total				
ΔI_t^T *(2)*	$\Delta\theta_t^B$	1	0.002409	0.002396

[a] The number in brackets indicates the order of autoregressive operator on the controlled variable, determined in Table 18. [b] The FPEs in the *FPE(m*,n*)* column are the minimum ones obtained from inclusion of different lags on the manipulated variables. Asterisks signify that there is a causal relationship from the manipulated variable to the controlled variable.

autoregressive operator on the controlled variable to the one determined in Table 18, the FPEs of the controlled variables are recalculated by varying the lag orders on the manipulated variables from 1 to 4. The orders which generate the smallest FPEs are presented in Table 19. For example, the FPE for the autoregressive equation with $\Delta\theta_t^B$ as the dependent variable and ΔI_t^T as a regressor is minimised by including one lagged infrastructure term.

Using the results reported in Table 19 it is possible to draw some conclusions about causality. The column *FPE(m*)* contains the minimum FPEs from Table 18. Where these numbers are greater than the FPEs from the equations that include a manipulated variable, *FPE(m*,n*)*, it can be concluded that the manipulated variable causes the controlled variable. For example, for $\Delta\theta_t^B$ and ΔI_t^C, treatment of ΔI_t^C as the input reduces the FPE of the $\Delta\theta_t^B$ equation, implying that $\Delta I_t^C \Rightarrow \Delta\theta_t^B$. We find

Table 20. *Comparison of Lag-Length Selection Criteria*

	$\Delta I_t \Rightarrow \Delta\theta_t^B$			$\Delta\theta_t^B \Rightarrow \Delta I_t^C$		$\Delta\theta_t^B \Rightarrow \Delta I_t^T$	
Criterion	$\Delta\theta^B$	$(\Delta\theta^B, \Delta I^C)$	$(\Delta\theta^B, \Delta I^T)$	ΔI^C	$(\Delta I^C, \Delta\theta^B)$	ΔI^T	$(\Delta I^T, \Delta\theta^B)$
FPE	0.60187(1)	**0.48788(1)***	**0.50890(1)***	0.1820(2)	0.1876(1)	0.2262(2)	0.2409(1)
AIC	0.60178(1)	**0.48761(1)***	**0.50862(1)***	0.1819(2)	0.1873(1)	0.2261(2)	0.2406(1)
HQ	0.62033(1)	**0.51033(1)***	**0.53232(1)***	0.1903(2)	0.1990(1)	0.2365(2)	0.2556(1)
RICE	0.60693(1)	**0.49753(1)***	**0.51897(1)***	0.1859(2)	0.1945(1)	0.2310(2)	0.2498(1)
SBC	0.65951(1)	**0.55944(1)***	**0.58354(1)***	0.2090(2)	0.2250(1)	0.2597(2)	0.2889(1)

Note: Values reported in the first 3 column omit the first four zero decimal places; values reported in the remaining four columns omit the first two zero decimal places. Asterisks signify a causal relationship. Optimal number of lags in parentheses. See Section 3.1 for the sources of the various tests.

the same relationship with total infrastructure, ie $\Delta I_t^T \Rightarrow \Delta\theta_t^B$. However, there is no evidence of reverse causation, regardless of the infrastructure variable used. In other words, $\Delta\theta_t^B \not\Rightarrow \Delta I_t^T$ and $\Delta\theta_t^B \not\Rightarrow \Delta I_t^C$. What's more, these findings are robust to the use of alternative lag-length selection criteria (Table 20).

6.3 Discussion of Results

As with the original Solow residual, the infrastructure growth rates cause the TFP growth rate. Furthermore, productivity's prediction error is reduced more by including core infrastructure investment in the analysis than total infrastructure investment. This is the expected result because the components of the core are hypothesised to be the most productive. However, the two TFP measures generate different results concerning reverse causation. Use of the Basu residual reveals that there is no reverse relationship between productivity and infrastructure. In Section 3 the finding was that the Solow residual causes some types of investment but not others (eg, $\Delta\theta_t^S \Rightarrow \Delta I_t^T$

but $\Delta\theta_t^S \not\Rightarrow \Delta I_t^C$). Thus the new TFP measure overturns the results of the previous section and those obtained by Tatom (1993), who concluded not only that TFP Granger causes infrastructure investment but that infrastructure has no effect on productivity. Whereas the difference between Tatom's results and those of Section 3 can be put down to econometric technique and the use of nonstationary data, the difference between the results contained in Section 3 and those contained in this section can be explained solely by the use of a different measure of TFP.

The results indicate that it is not just the measure of public capital which infrastructure researchers should choose selectively. It is also necessary to ensure that the measure of productivity growth employed resembles closely the true underlying productivity growth rate. The Solow residual follows the business cycle very closely. However, as Basu (1996) argues, a portion of this procyclical behaviour is caused by mismeasurement of input usage (labour and capital) as the economy expands and contracts. Thus, adjusting measured TFP for variations in factor usage allows researchers to determine the true nature of the causal relationship between the variables. The mixed evidence of reverse causation disappears and there is evidence of unidirectional causality from infrastructure investment to multifactor productivity.

This finding does not imply that infrastructure has an income elasticity of zero.[39] First it is worth emphasising that the growth rates of productivity and income

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[39] Empirical estimation of the demand for public goods is a major focus of public finance. The individual's demand for local public goods, for example, can be derived by solving the problem:

$$Max\ U(X, H, G, Z) \quad s.t. Q = X + P_H H + P_G G,$$

where H is units of housing consumed, P_H is the price of a stream of services available from housing, G is the level of public services, P_G is the price of the public good, Q is individual exogenous income, X is private consumption per capita and Z accounts for variations in taste among consumers. Solving the maximisation problem yields the individual's demand function for the public good:

$$G^* = g(Q, P_G, Z).$$

Clearly, one of the factors that determines the demand for public goods is the level of income.

are different variables. Rewriting (66), it is clear that changes in gross income are determined by efficiency gains, changes in factor input and changes in factor input usage:

$$\Delta q_t = \Delta\theta_t + \gamma\left(\alpha_t^{L'}\Delta l_t + \alpha_t^{M'}\Delta m_t + \alpha_t^{K'}\Delta k_t\right) + \gamma\left(\alpha_t^{L'}\Delta c_t + \alpha_t^{K'}\Delta z_t\right). \tag{81}$$

Changes in inputs account for most of the change in income. It is therefore possible that, in certain years, $\Delta\theta_t$ will have the opposite sign to Δq_t. In fact during 11 of the years of the sample period this was the case. Thus while increases in income may increase the demand for infrastructure services, efficiency gains are only one component of increases in income. Second, although demand for infrastructure services may increase with income over time, this relationship may not be apparent in a given sample period. For example, total non-farm private sector income in the U.S. rose by 38 per cent between 1968 and 1992. However, total public investment fell by 30 per cent over this period. Only in 1989 did public investment reach levels seen in the 1960s, by which time national income had risen by a further 31 per cent. Although public investment did not keep up with increases in aggregate income, total government purchases (excluding investment) increased steadily over the period. Between 1968 and 1989 total income grew by 81 per cent; total government purchases grew by 38 per cent.

These trends reflect the fact that during the Ford and Carter Administrations nondefence current expenditures were being driven by commitments to social security and health programmes. According to Stein (1996), both presidents were uncomfortable with large budget deficits and believed that the public shared this attitude.[40] As a consequence nondefence investment suffered during this period. In

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[40] See Stein (1996), pp. 573-582.

contrast, nonmilitary capital expenditures were a priority in the 1960s. Clearly, a number of difficulties not present in standard consumer theory arise in modelling the demand for publicly provided capital. The supply of infrastructure services is determined through a political process. Individuals vote for elected representatives who in turn vote for public budgets. As Stein (1996) notes:

> "Every expenditure program, or almost every one, has behind it a group of supporters in the Congress and in the country who favor expanding it at all times, recession or not. When the recession creates an atmosphere justifying increased expenditure on national income grounds, the supporters of particular programs gain enough allies to push some increases through. There are also always people who want tax reduction, recession or not." (p. 329)

Stein also points out that tension always exists between the aggregate rule being pursued (eg, balancing the budget at high employment) and the "lower-level" decisions (about tax rates and expenditure programmes) needed to conform to them. In conclusion, the finding that TFP does not cause public investment can be explained by the fact that productivity and income are different variables, the relationship between income and public investment may only manifest itself over long periods and the fact that the supply of public infrastructure is determined by the political process.

6.4 Estimating Infrastructure's Impact on Adjusted Productivity

The next step is to quantify infrastructure investment's impact on the adjusted TFP growth rate. The models using core and total investment data are respectively

Table 21. *Autoregressive Estimates of Models Using Basu Residual*

	Core Infrastructure Model		Total Infrastructure Model	
Dependent variable:	$\Delta\theta_t^B$	ΔI_t^C	$\Delta\theta_t^B$	ΔI_t^T
$\Delta\theta_{t-1}^B$	0.148		0.171	
	(1.15)		(1.28)	
ΔI_{t-1}^j	0.080***	0.153	0.065***	0.280*
	(3.26)	(0.76)	(3.58)	(1.74)
ΔI_{t-2}^j		0.449***		0.343**
		(3.12)		(2.15)
Constant	0.020	0.005	0.002	0.006
	(1.51)	(0.79)	(1.48)	(0.77)
R^2	0.279	0.265	0.248	0.276
S.E.	0.0064	0.0387	0.0065	0.0435

Note: j = C (core infrastructure) or T (total infrastructure), depending on the model; t-stats in parentheses and are computed using heteroskedastic-consistent standard errors.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

$$\begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^C \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} \psi_{11}^1(L) & \psi_{12}^1(L) \\ 0 & \psi_{22}^2(L) \end{pmatrix} \begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^C \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \end{pmatrix}, \text{ and} \tag{82}$$

$$\begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^T \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} + \begin{pmatrix} \psi_{11}^1(L) & \psi_{12}^1(L) \\ 0 & \psi_{22}^2(L) \end{pmatrix} \begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^T \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \end{pmatrix}. \tag{83}$$

Note that the second equation contains only lags of the dependent variable because of the absence of reverse causality. Following Erenburg and Wohar (1995), each two-equation system is estimated in a seemingly unrelated regression (SUR) framework to gain efficiency by allowing for the cross-equation correlation of disturbances. The results are reported in Table 21. Again, the coefficient estimates that are of most interest are those which quantify the impact of the growth rates of core and total investment on the productivity growth rate. The impact of infrastructure investment on

Table 22. *Wald Tests for Zero Restrictions*

	Wald Statistic $\sim \chi^2$
Core Infrastructure Model	
$\psi^1_{12}(L) = 0$	10.05(1)***
Total Infrastructure Model	
$\psi^1_{12}(L) = 0$	8.26(1)***

Note: Degrees of freedom in parentheses.
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

TFP is relatively much smaller when the Basu residual is used in place of the Solow residual. The coefficient estimate for core infrastructure falls from 0.114 to 0.080. The estimate for total infrastructure falls from 0.095 to 0.065.

Wald tests provide further evidence that both infrastructure aggregates have a significant effect on the TFP growth rate (Table 22). There may be arguments about whether the causal relationships implied by autoregressive modelling are sensitive to the specification of the order of the autoregressive operator. I checked for this in the two models by increasing the number of lag terms on the infrastructure variables and assuming these specifications were chosen as the maintained hypotheses. The parameter matrix for both models becomes:

$$\begin{pmatrix} \psi^1_{11}(L) & \psi^4_{12}(L) \\ 0 & \psi^2_{22}(L) \end{pmatrix}. \tag{84}$$

For the core infrastructure model, the Wald test of $\psi^4_{12}(L) = 0$ (to test whether $\Delta I^C_t \Rightarrow \Delta\theta^B_t$) has a chi-square value of 15.65 (4 degrees of freedom). For the total infrastructure model the test produces a chi-square value of 12.46 (4 degrees of freedom). Thus, as with the original specifications, the null hypothesis that infrastructure investment does not affect productivity is rejected. As an alternative, the following specification was taken as the maintained hypothesis:

$$\begin{pmatrix} \psi^2_{11}(L) & \psi^2_{12}(L) \\ \psi^2_{21}(L) & \psi^2_{22}(L) \end{pmatrix}. \tag{85}$$

Tests of the restriction $\psi^2_{12}(L) = 0$ produce chi-square values of 9.27 (2 degrees of freedom) for the core infrastructure model and 7.75 (2 degrees of freedom) for the total infrastructure model, leading to rejection of the null hypothesis again.[41]

These tests confirm infrastructure investment's importance in determining TFP. It is also important to determine whether the FPE Criterion performs satisfactorily in identifying the system of equations. Following Hsiao (1981), Ahking and Miller (1985) and Erenburg and Wohar (1995), the adequacy of the models was checked by sequentially overfitting (82) and (83) by adding 1 additional lag and then 2 additional lags to each variable, including those variables that were not significantly different from zero in the final models. For the core infrastructure model the Wald test statistics are respectively 1.73 (4 degrees of freedom) and 7.01 (8 degrees of freedom), indicating that the extra lags are not significantly different from zero. For the total infrastructure model the Wald test statistics are respectively 1.68 (4 degrees of freedom) and 8.97 (8 degrees of freedom). Thus both sets of tests reveal no inadequacy in the models. Next, the models were sequentially underfitted by 1 lag, where possible. For the core infrastructure model, subtracting 1 lag term produces a chi-square value of 8.41 (1 degree of freedom), indicating that the omitted lag is significantly different from zero at the 1 per cent level at least. For the total infrastructure model the relevant chi-square

[41] Identical tests conducted using the standard Solow residual produced chi-square values of 3.89 and 2.39 respectively, implying that the restrictions are accepted (ie. infrastructure investment does not cause productivity).

value is 4.20 (1 degree of freedom) which is significantly different from zero at the 5 per cent level at least.

In conclusion, Wald tests reveal that $\Delta I_t^C \Rightarrow \Delta\theta_t^B$ and $\Delta I_t^T \Rightarrow \Delta\theta_t^B$, even if the number of lagged infrastructure terms differs from that determined by the FPE Criterion. However, the over- and underfitting tests reject in favour of the model identified by the FPE Criterion and it is on these models that I rely when drawing inferences about infrastructure's impact on productivity.

Again a battery of diagnostic tests was performed to confirm the empirical adequacy of the models. Serial correlation in the residuals was tested for as was heteroskedasticity, normality, the specification of the models and their temporal stability. Table 23 contains the results of diagnostic tests applied to individual equations estimated by OLS. Breusch-Godfrey LM tests indicate that there is no serial correlation present. The White heteroskedasticity test and the Jarque-Bera normality test conclude that the errors are homoskedastic and normally distributed. To test for the possible omission of important explanatory variables, all equations were re-estimated employing Ramsey's (1969) RESET procedure. In each test the additional variables were found to be jointly insignificant and so the null hypothesis of no specification error could not be rejected. Chow tests were also employed to check the temporal stability of the models. The results indicate that the productivity equations and infrastructure investment equations have stable parameters over the sample period.

Table 23. *Diagnostic Tests on Individual Equations*

Breusch-Godfrey LM Tests for Serial Correlation $\sim \chi^2$

	Equation (1)	Equation (2)	Equation (3)	Equation (4)
Order: 1	0.55(1)	0.00(1)	0.00(1)	1.14(1)
2	0.67(2)	0.36(2)	0.01(2)	1.19(2)
3	0.98(3)	0.39(3)	0.26(3)	3.21(3)

White Heteroskedasticity Test $\sim \chi^2$

Equation (1)	Equation (2)	Equation (3)	Equation (4)
0.86(5)	1.74(5)	6.38(5)	5.70(5)

Jarque-Bera Normality Test $\sim \chi^2$

Equation (1)	Equation (2)	Equation (3)	Equation (4)
0.98(2)	1.13(2)	1.14(2)	0.15(2)

Ramsey RESET Test of Specification Error (F-Statistics)

	Equation (1)	Equation (2)	Equation (3)	Equation (4)
RESET(2)	1.64(1,24)	0.74(1,24)	0.30(1,24)	0.09(1,24)
RESET(3)	0.85(2,23)	0.76(2,23)	0.27(2,23)	0.05(2,23)
RESET(4)	0.56(3,22)	0.87(3,22)	0.18(3,22)	0.03(3,22)

Chow Test for Structural Change (F-Statistics)

Equation (1)	Equation (2)	Equation (3)	Equation (4)
0.59(3,22)	0.57(3,22)	0.25(3,22)	0.42(3,22)

Equation 1: Basu residual dependent variable; core infrastructure
Equation 2: Basu residual dependent variable; total infrastructure
Equation 3: Core investment dependent variable
Equation 4: Total investment dependent variable
* Rejection of the relevant null hypothesis (serial independence, homoskedasticity, normality, no specification error, no structural break) at the 5% level at least. Degrees of freedom in parentheses.

6.5 Discussion of Results

The estimates obtained using the different productivity measures differ significantly in relative magnitude. The coefficient on core investment falls by 35 per cent and the coefficient on total investment falls by 38 per cent. The estimates obtained in the models which use the Basu residual are also more significant than those obtained in the Solow models. In particular, the coefficient on total infrastructure investment is significant at the 1 per cent level whereas in the Solow model the estimate was only significant at the 10 per cent level. The Wald tests also reject the hypothesis that the off-diagonal terms equal zero at higher levels of significance.

Equally interesting are the absolute magnitudes of the coefficient estimates obtained using the adjusted TFP measure. A 1 percentage point increase in the growth rate of core infrastructure in period t leads to an increase of 0.08 in the growth rate of TFP in period $t + 1$. For total infrastructure, the increase in the TFP growth rate is only 0.065. These estimates imply that, while infrastructure has an effect upon productivity growth, the impact is very small. Thus the decline in infrastructure investment from the late 1960s contributed to the productivity growth slowdown but was not the only factor responsible.

6.6 Causality Tests – Disaggregated Infrastructure Data

In this section Akaike's FPE Criterion is applied to determine whether the different types of core infrastructure (roads, water structures, sewer structures and other structures) cause or are caused by Basu's TFP measure. Table 24 is similar to Table 19 in the sense that it reports the minimum FPEs calculated using each variable's own lags, $FPE(m^*)$, and the minimum FPE obtained by also including another variable $FPE(m^*,n^*)$. If $FPE(m^*,n^*) < FPE(m^*)$ then there is a causal relationship between the

Table 24. *Optimum Lags of Manipulated Variable and the FPE of the Controlled Variable (Disaggregated Infrastructure Data)*

Controlled Variable [a]	*Manipulated Variable*	*Optimum Lags, Manipulated Variable*	*FPE(m*,n*)* [b]	*FPE(m*)*
Basu				
$\Delta\theta_t^B(1)$	ΔI_t^H	1	**0.0000444***	0.0000602
$\Delta\theta_t^B(1)$	ΔI_t^W	1	0.0000606	0.0000602
$\Delta\theta_t^B(1)$	ΔI_t^S	1	0.0000610	0.0000602
$\Delta\theta_t^B(1)$	ΔI_t^O	3	**0.0000564***	0.0000602
Reverse Causality				
$\Delta I_t^H(2)$	$\Delta\theta_t^B$	2	0.002462	0.002270
$\Delta I_t^W(1)$	$\Delta\theta_t^B$	1	0.019030	0.017957
$\Delta I_t^S(1)$	$\Delta\theta_t^B$	1	0.022800	0.021565
$\Delta I_t^O(1)$	$\Delta\theta_t^B$	1	0.020086	0.018863

[a] The number in brackets indicates the order of autoregressive operator on the controlled variable.
[b] The FPEs in the *FPE(m*,n*)* column are the minimum ones obtained from inclusion of different lags on the manipulated variables. Asterisks signify that there is a causal relationship from the manipulated variable to the controlled variable. ΔI_t^H is the growth rate of highways and streets, ΔI_t^W is the growth rate of water structures, ΔI_t^S is the growth rate of sewer structures and ΔI_t^O is the growth rate of other structures.

variables. The first set of FPEs tests whether there is a causal relationship from infrastructure investment to TFP. The minimum FPEs imply that, as with the Solow residual, highway and street investment affect the Basu residual. However, inclusion of electric and gas facilities and mass transit (the "other structures" component) also minimises the FPE. In summary, $\Delta I^H \Rightarrow \Delta\theta_t^B$, $\Delta I^O \Rightarrow \Delta\theta_t^B$, $\Delta I^W \not\Rightarrow \Delta\theta_t^B$ and $\Delta I^S \not\Rightarrow \Delta\theta_t^B$. Turning to the tests for reverse causality reported in Table 24, it is apparent again that the different TFP measures generate different results. While growth in the Solow residual causes investment in highways and streets and water and sewer systems, the adjusted TFP measure again provides no evidence of reverse causation. In summary, $\Delta I^H \not\Leftarrow \Delta\theta_t^B$, $\Delta I^O \not\Leftarrow \Delta\theta_t^B$, $\Delta I^W \not\Leftarrow \Delta\theta_t^B$ and $\Delta I^S \not\Leftarrow \Delta\theta_t^B$.

6.7 Discussion of Results

Thus the results for the Basu measure reported in Section 6.2 using aggregate public investment data are robust to the use of data for different types of public investment. This is an interesting finding because some researchers (for example, Morrison and Schwarz, 1997) only include highways and water and sewer systems in their measure of core infrastructure and ignore the other structures component. The authors ignored these types of infrastructure because Munnell (1990b) found "other infrastructure" to be insignificant in her production function studies.[42] However, Munnell's variable included not only other structures but also an assortment of buildings (hospitals, courthouses, fire stations etc.) which arguably do not have a direct effect upon private productivity.[43] However, the results reported in Table 24 imply that one component of "other infrastructure" – the structures component – is one of the most productive types of infrastructure. Highway investment has the biggest impact on private productivity, however. Inclusion of this variable leads to the greatest reduction in the prediction error of $\Delta\theta_t^B$.

6.8 Estimating Infrastructure's Impact on Productivity – Disaggregated Infrastructure Data

The next step is to quantify the impact of investment in roads and other structures on

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[42] The results from this study are discussed in Chapter 1.

[43] Munnell's data is given particular attention because it has been used by a number of other researchers, eg Eisner (1991).

the TFP growth rate, as was done in Section 6.4. However, this time the Basu model contains three variables ($\Delta\theta_t^B$, ΔI_t^H and ΔI_t^O). In determining the optimum number of lags for each variable it has to be decided in which order they are added to the equation. For example, the equation in which $\Delta\theta_t^B$ is the dependent variable will consist of 1 own lag term, $\Delta\theta_{t-1}^B$, and lags of ΔI_t^H and ΔI_t^O. Employing the specific gravity criterion, the variable that generated the smallest FPE when included as a manipulated variable is included first. In this case we know from Table 24 that the FPE for road investment is less than that for other structures (0.0000444 < 0.0000564), so roads are included first. It is also known that a lag order of 1 for ΔI_t^H minimises the FPE of $\Delta\theta_t^B$.

In the next stage, ΔI_t^O is added 1 lag at a time (up to 4) and the FPE is recalculated. The lag length that generates the smallest FPE enters the estimating model. The outcomes of this stepwise procedure are summarised in Table 25. Using the information contained in Table 25 the following model is obtained

$$\begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^H \\ \Delta I_t^O \end{pmatrix} = \begin{pmatrix} a \\ b \\ c \end{pmatrix} + \begin{pmatrix} \psi_{11}^1 & \psi_{12}^1 & \psi_{13}^1 \\ 0 & \psi_{22}^2 & 0 \\ 0 & 0 & \psi_{33}^1 \end{pmatrix} \begin{pmatrix} \Delta\theta_t^B \\ \Delta I_t^H \\ \Delta I_t^O \end{pmatrix} + \begin{pmatrix} \upsilon_t \\ \nu_t \\ \varepsilon_t \end{pmatrix}. \tag{86}$$

The results from estimating the model using SUR are reported in Table 26. The R^2s in the $\Delta\theta_t^B$ and ΔI_t^H equations are reasonably high for models that use differenced data. The estimate on ΔI_t^H is significant at the one per cent level at least. It is not just road investment that affects TFP in the Basu model; ΔI_t^O also has a small effect. This variable is significant at the 5 per cent level at least. Wald tests also confirm that each

Table 25. *Construction of Basu Model, Disaggregated Infrastructure Data*

(1)
Dependent Variable, $\Delta\theta_t^B$

Controlled Variables	Manipulated Variable	$FPE(m^*,n^*,p^*)^a$	$FPE(m^*,n^*)$
$\Delta\theta_t^B(1), \Delta I_t^H(1)$	$\Delta I_t^O(1)$	**0.0000441***[b]	0.0000444

(2)
Dependent Variable, ΔI_t^H

Controlled Variable	Manipulated Variable	$FPE(m^*,n^*)$	$FPE(m^*)$
$\Delta I_t^H(2)$	$\Delta\theta_t^B(2)$	0.0024619	0.0022703

(3)
Dependent Variable, ΔI_t^O

Controlled Variable	Manipulated Variable	$FPE(m^*,n^*)$	$FPE(m^*)$
$\Delta I_t^O(1)$	$\Delta I_t^H(1)$	0.019724	0.018863

Notes: [a] p^* **is the optimum lag for variable 3;**[b] Asterisks signify causality.

1. Equation (1) contains ΔI_t^H and ΔI_t^O because the bivariate FPEs (0.0000444 and 0.0000564 respectively) are lower than the univariate one (0.0000602). The variable with the lower FPE (ΔI_t^H) is included first and lags of ΔI_t^O are added one at a time. The minimum FPE (0.0000441) is obtained from using one lag.
2. Equations (2) and (3) contain only own-lag terms. Even the minimum bivariate FPEs (for $\Delta\theta_t^B$ in the ΔI_t^H equation and ΔI_t^H in the ΔI_t^O equation) exceed the univariate FPEs (ie, 0.0024619 > 0.0022703 and 0.019724 > 0.018863). The equations are included in the model as each of the dependent variables may be subject to the same stochastic shocks.

type of infrastructure investment Granger causes the TFP growth rate (Table 27). However, it is only possible to reject the hypothesis $\psi_{13}^{1} = 0$ at the 10 per cent level. Again, there may be arguments about whether the causal relationships implied by autoregressive modelling are sensitive to the specification of the order of the autoregressive operator. I checked for this by individually increasing the number of lag terms on ΔI_t^H and ΔI_t^O and assuming these specifications were chosen as the

Table 26. *Estimation Results, Disaggregated Infrastructure Data*

Dependent Variable:	$\Delta\theta^B_t$	ΔI^H_t	ΔI^O_t
$\Delta\theta^B_{t-1}$	0.082		
	(0.68)		
ΔI^H_{t-1}	0.078***	0.436***	
	(3.05)	(3.19)	
ΔI^H_{t-2}		0.275**	
		(2.30)	
ΔI^O_{t-1}	0.014**		-0.383**
	(2.31)		(2.52)
Constant	0.003	0.001	0.043*
	(2.07)**	(0.09)	(1.73)
R^2	0.397	0.385	0.139
S.E.	0.006	0.043	0.130

Note: *H* and *O* denote highways and streets and other structures respectively; t-stats in parentheses and are computed using heteroskedastic-consistent standard errors.
*** Significantly different from zero at less than the 1% level.
** Significantly different from zero at less than the 5% level.
* Significantly different from zero at less than the 10% level.

Table 27. *Wald Tests for Zero Restrictions*

Equation:		*Wald Statistic* $\sim\chi^2$
$\Delta\theta^B_t$	$\psi^1_{12}=0$	15.95(1)***
	$\psi^1_{13}=0$	3.21(1)*
	$\psi^1_{12}=\psi^1_{13}=0$	21.43(2)***

Note: Degrees of freedom in parentheses
*** Significantly different from zero at less than the 1 % level.
** Significantly different from zero at less than the 5 % level.
* Significantly different from zero at less than the 10 % level.

maintained hypotheses. For tests on the growth rate of road investment the matrix of lagged coefficients was assumed to be

$$\begin{pmatrix} \psi^{1}_{11} & \psi^{2}_{12} & \psi^{1}_{13} \\ 0 & \psi^{2}_{22} & 0 \\ 0 & 0 & \psi^{1}_{33} \end{pmatrix}, \begin{pmatrix} \psi^{1}_{11} & \psi^{4}_{12} & \psi^{1}_{13} \\ 0 & \psi^{2}_{22} & 0 \\ 0 & 0 & \psi^{1}_{33} \end{pmatrix} \text{ and } \begin{pmatrix} \psi^{2}_{11} & \psi^{2}_{12} & \psi^{2}_{13} \\ \psi^{2}_{21} & \psi^{2}_{22} & \psi^{2}_{23} \\ \psi^{2}_{31} & \psi^{2}_{32} & \psi^{2}_{33} \end{pmatrix}. \tag{87}$$

The chi-square values from testing the hypotheses $\psi^{2}_{12} = 0, \psi^{4}_{12} = 0$ and $\psi^{2}_{12} = 0$, are 19.68 (2 degrees of freedom), 19.71 (4 degrees of freedom) and 12.27 (2 degrees of freedom). Thus, as in the original specification, the null hypothesis that road investment does not affect productivity is rejected. For tests on the growth rate of investment in other structures the matrix of lagged coefficients was assumed to be

$$\begin{pmatrix} \psi^{1}_{11} & \psi^{1}_{12} & \psi^{2}_{13} \\ 0 & \psi^{2}_{22} & 0 \\ 0 & 0 & \psi^{1}_{33} \end{pmatrix}, \begin{pmatrix} \psi^{1}_{11} & \psi^{1}_{12} & \psi^{4}_{13} \\ 0 & \psi^{2}_{22} & 0 \\ 0 & 0 & \psi^{1}_{33} \end{pmatrix} \text{ and } \begin{pmatrix} \psi^{2}_{11} & \psi^{2}_{12} & \psi^{2}_{13} \\ \psi^{2}_{21} & \psi^{2}_{22} & \psi^{2}_{23} \\ \psi^{2}_{31} & \psi^{2}_{32} & \psi^{2}_{33} \end{pmatrix}. \tag{88}$$

The chi-square values for testing the hypotheses $\psi^{2}_{13} = 0, \psi^{4}_{13} = 0$ and $\psi^{2}_{13} = 0$ are respectively 2.60 (2 degree of freedom), 4.30 (4 degrees of freedom) and 2.20 (2 degrees of freedom). Thus, unlike the original specification, the null hypothesis that other structures investment does not affect productivity cannot be rejected. These tests confirm road investment's importance in determining TFP but show that the results obtained using other structures investment are sensitive to the choice of lag specification. To determine whether the FPE Criterion performs satisfactorily in identifying the system of equations, the adequacy of the original models was checked by sequentially overfitting (86) by adding 1, 2, 3 and 4 additional lags to each variable, including those variables that were not significantly different from zero in the final model. The respective Wald test statistics are 6.89 (9 degrees of freedom), 19.30 (18 degrees of freedom), 29.53 (27 degrees of freedom) and 60.29 (36 degrees of freedom), all indicating that the extra lags are not significantly different from zero and that there is no inadequacy in the models chosen by the FPE Criterion.

In conclusion, Wald tests reveal that $\Delta I_t^H \Rightarrow \Delta\theta_t^B$, even if the number of lagged infrastructure terms differs from that determined by the FPE Criterion. The results for ΔI_t^O are quite sensitive to the specification of the lag operator. However, the overfitting tests reject in favour of the model identified by the FPE Criterion and it is on this model that I rely when drawing inferences about the impact of other structures' investment on the TFP growth rate.

As before, a number of diagnostic tests were conducted on the equations in the final model. The test statistics reported in Table 28 imply that the model does not suffer from serial correlation, heteroskedasticity, non-normality, misspecification problems or structural breaks.

6.9 Discussion of Results

Again the two TFP measures generate coefficient estimates that differ significantly in relative magnitude. For example, the coefficient on lagged roads investment in the Basu model is almost 40 per cent smaller than that estimated using the Solow residual. The adjusted TFP estimate implies that if the growth rate of highway and street investment increases from, say, 2 per cent to 3 per cent, the TFP growth rate will increase from, say, 2 per cent to 2.078 per cent in the following period. The estimate on ΔI_t^O implies that if the growth rate of investment in utilities and mass transit increases by 1 percentage point in period t, the TFP growth rate will increase from, say, 2 per cent to 2.014 in period $t + 1$. This does not imply that additional road investment is 5.6 times (0.078/0.014) as productive as investment in other structures.

Table 28. *Diagnostic Tests on Individual Equations*

Breusch-Godfrey LM Tests for Serial Correlation $\sim \chi^2$

	Dependent Variable		
	$\Delta\theta_t^B$	ΔI_t^H	ΔI_t^O
Order: 1	0.18(1)	1.53(1)	0.00(1)
2	0.26(2)	2.68(2)	3.65(2)
3	2.34(3)	4.12(3)	3.79(3)

White Heteroskedasticity Test $\sim \chi^2$

Dependent Variable		
$\Delta\theta_t^B$	ΔI_t^H	ΔI_t^O
13.9(9)	8.31(5)	0.61(1)

Jarque-Bera Normality Test$\sim \chi^2$

Dependent Variable		
$\Delta\theta_t^B$	ΔI_t^H	ΔI_t^O
0.66(2)	1.62(2)	0.45(2)

Ramsey RESET Test of Specification Error (F-Statistics)

	Dependent Variable		
	$\Delta\theta_t^B$	ΔI_t^H	ΔI_t^O
RESET(2)	0.25(1,23)	0.44(1,24)	2.14(1,25)
RESET(3)	0.44(2,22)	3.25(2,23)	2.80(2,24)
RESET(4)	0.31(3,21)	2.10(3,22)	1.89(3,23)

Chow Test for Structural Change (F-Statistics)

Dependent Variable		
$\Delta\theta_t^B$	ΔI_t^H	ΔI_t^O
0.23(4,20)	1.63(3,22)	0.63(2,24)

* Rejection of the relevant null hypothesis (serial independence, homoskedasticity, normality, no specification error, no structural break) at the 5% level. Degrees of freedom in parentheses.

Road investment is by far the largest component of total investment. It also accounts for most of the core infrastructure investment that took place over the sample period (exactly 60 per cent). On average over the sample period the level of road investment was 4 ½ times higher than investment in other structures. Thus identical growth rates represent very different levels of investment. It is known from the FPEs reported in Table 24 that roads are more productive than other structures but not by the kind of multiple that an uncritical comparison of the coefficient estimates would imply.

That roads are the most productive type of public investment is a new finding in the distinct body of research exploring the possible relationship between public capital and factor productivity.[44] However, this result would come as no surprise to those researchers who specialise in the analysis of the economic effects of transportation capital. For example, a report by the Federal Highway Administration (1992) argues that:

> "Productivity in virtually every sector of the economy is affected by the performance of the nation's highways, because this affects the efficiency with which commodities and industry personnel are carried by motor vehicles." (p. 15)

A study by the Congressional Budget Office (1991) noted that:

> "The limited available evidence shows that returns to public investments vary widely for different types of infrastructure. Cost benefit analysis finds substantial returns to some increases in federal spending for highways... carefully selected highway projects would yield high rates of return."[45]

Fisher (1997) reviews 15 studies that analyse the relationship between various

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[44] In fact, some authors such as Evans and Karras (1994) have found that the highway capital stock and/or highway investment is insignificant.

[45] Quoted by the Federal Highway Administration (1992), p. 15.

transportation measures, such as per capita highway spending, on economic development, as measured by changes in foreign investment, employment, income or the number of firms and concludes that:

> "Of all the public services examined for an influence on economic development, transportation services, and highway facilities especially, show the most substantial evidence of a relationship. Of the 15 studies reviewed, a positive effect of highway facilities or spending on economic development is reported in 10 (or nearly 70 per cent), with that effect being statistically significant in eight of the cases." (p. 54)

Although road investment is the most productive type of public investment, it is clear from the size of the coefficient estimate reported in Table 26 that it is only one of several contributing factors. Many other factors may have affected TFP growth over the period, including workers' years of schooling[46], the level of unionization[47], agglomeration and scale effects. If it is assumed that the depreciation rate of highways and streets remained constant over the sample period, from Chapter 2 it is known that the growth rate of investment is broadly equivalent to the growth rate of the capital stock. Thus the coefficient estimates reported in Table 26 can be compared with estimates of public capital's output elasticity obtained in production function studies. Clearly the estimates reported in Table 26 are significantly lower than those reported in the literature review in Chapter 1.

It is also necessary to comment on the finding that infrastructure investment affects productivity growth with a lag of only one year. It is to be expected that some

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[46] See Moomaw and Williams (1991).
[47] See Kendrick and Grossman (1980).

infrastructure spending will only affect productivity with a considerable lag because of the time between the allocation of funds and completion of the project. However, the finding of a short time lag for aggregate core infrastructure can possibly be explained by the fact that spending on highways and streets is the largest component of core infrastructure spending (60 per cent during the sample period) and, as the FPEs and coefficient estimates make clear, has the most significant effect on productivity growth. Much of the spending on highways and streets is in the form of current maintenance and upgrading of sections that do not meet minimum standards. There is a relatively short time lag between allocations being made and these tasks being completed. According to the Congressional Budget Office (1991) the expected rate of return from keeping highways in their current condition is between 30 and 40 per cent; the return on selected new urban construction is between 10 and 20 per cent and the return from upgrading roads that do not meet minimum service or safety standards is between 3 and 7 per cent.

7. Disaggregated TFP

In Section 3.8 and Section 6.6 the public investment data was disaggregated so that the most productive types of infrastructure spending could be identified. However, all tests and estimations have so far been performed using manufacturing data at the aggregate level only. The U.S. manufacturing sector is made up of a medley of industries, producing goods as diverse as shoes and computers, and car tyres and cigarettes. It is important for policymakers to identify which industries are affected most by infrastructure spending as that may help explain the mixed fortunes of the manufacturing sector in the post-war period. For example, average output growth was 5.9 per cent per year in the chemicals industry in the period up to 1973, the highest among all manufacturing industries. After 1973 average annual growth fell to 1.7 per cent per year.

The question that may be asked is whether this slowdown was influenced by the infrastructure slowdown that took place at approximately the same time, or whether it was caused by other industry-specific factors. In this section, data at the two-digit SIC level is used to determine, by the FPE Criterion, which industries are the major beneficiaries of infrastructure investment. For comparative purposes two sets of TFP measures are calculated:

$$\Delta\theta_t^{S,i} \quad i = 20,\ldots,39\text{, and}$$

$$\Delta\theta_t^{B,i} \quad i = 20,\ldots,39\,. \tag{89}$$

The first set consists of industry-specific Solow residuals, the second set consists of individual industry Basu residuals. Although $\Delta\theta_t^{B,i}$ is my preferred productivity measure, Solow residuals are calculated for comparative purposes and to determine whether the results obtained in Section 4 are robust at different levels of industry aggregation. Calculating these measures is a straightforward procedure based on (21).

Estimating individual industry Basu residuals is slightly more involved. First, estimates of the returns to scale parameter $\gamma_i, i = 20,\ldots,39$ have to be obtained using IV techniques. The estimates are reported in Appendix C. Once returns to scale have been estimated, TFP growth rates for each of the 20 industries are obtained using the following variation of (78)

$$\Delta\theta_t^{B,i} + \upsilon_t^i = \Delta q_t^i - \hat{\gamma}^i\left(\Delta m_t^i - \sigma\left(\overline{\alpha}_t^{L',i} + \overline{\alpha}_t^{K',i}\right)\left(\Delta p_t^{v,i} - \Delta p_t^{m,i}\right)\right) \quad i = 20,\ldots,39\,. \tag{90}$$

Differences between the industries are immediately apparent. Apart from the wide divergence in estimates of the returns to scale parameter (these range from 0.83 to 1.44) the correlation matrix reveals that correlation between the TFP measures is very low.[48]

The next step is to test for causality. First, using each industry's productivity growth rate (both $\Delta\theta_t^{S,i}$ and $\Delta\theta_t^{B,i}$) the appropriate "own" lag length, m^*, is determined by minimising the FPE of the univariate autoregressive process. This is then compared with the minimum FPE of the bivariate equation, $FPE(m^*,n^*)$, obtained by including the growth rate of core infrastructure investment. The results are summarised in Table 29. The tests carried out using Solow residuals are generally disappointing. When aggregate manufacturing data was used in Section 3 the conclusion was that the growth rate of core infrastructure investment causes the growth rate of multifactor productivity. However, when the manufacturing data is disaggregated, evidence of a causal relationship largely disappears. Only seven of the 20 industries are affected by public investment. Thus evidence of causality obtained using Solow's (1957) measure of TFP is not robust to the use of either disaggregated infrastructure or productivity data. Turning to the results presented in the second column of Table 29, use of the adjusted TFP measure provides evidence that core infrastructure investment affects productivity in only 40 per cent of nondurable goods industries but 70 per cent of durable manufacturing industries. It is interesting to note that Nadiri and Mamuneas (1991) obtained a similar result using a completely

[48] I am not alone in finding diverse TFP growth rates among industries. Using Solow residuals, Fernald (1997) obtained average TFP growth rates ranging from -0.8 per cent per year to 3.8 per cent per year for the period 1953-89. Jorgenson, Gollop and Fraumeni (1987) also found that TFP growth rates vary widely among industries.

Table 29. *Results of Individual Industry Causality Tests*

	-------- $\Delta\theta_t^{S,i}$ --------		--------- $\Delta\theta_t^{B,i}$ ---------	
	FPE(m,n*)*	*FPE(m*)*	*FPE(m*,n*)*	*FPE(m*)*
Durable Goods Industries				
sic24 Lumber & wood	**.00065(1,1)***	.00073(1)	**.00027(1,1)***	.00033(1)
sic25 Furniture & fixtures	.00054(2,1)	.00050(2)	**.00025(1,1)***	.00026(1)
sic32 Stone, clay & glass	**.00046(2,1)***	.00056(2)	**.00010(1,3)***	.00014(1)
sic33 Primary metals	**.00092(1,1)***	.00099(1)	**.00021(2,1)***	.00030(2)
sic34 Fabricated metals	**.00037(2,1)***	.00041(2)	.00029(3,1)	.00027(3)
sic35 Industrial machinery & equip.	**.00076(1,1)***	.00078(1)	**.00031(1,1)***	.00032(1)
sic36 Electronic & electric equip.	.00045(2,1)	.00044(2)	.00054(4,1)	.00050(4)
sic37 Transportation equipment	.00067(1,1)	.00066(1)	**.00018(1,2)***	.00020(1)
sic38 Instruments and related	.00050(2,2)	.00049(2)	**.00114(1,4)***	.00117(1)
sic39 Miscellaneous manufacturing	.00136(1,1)	.00133(1)	.00096(1,1)	.00092(1)
Nondurable Goods Industries				
sic20 Food and kindred products	.00014(1,1)	.00013(1)	.00026(1,1)	.00024(1)
sic21 Tobacco products	.00116(1,1)	.00109(1)	.00147(1,1)	.00138(1)
sic22 Textile mill products	.00047(3,1)	.00044(3)	**.00035(1,1)***	.00035(1)
sic23 Apparel and other textile	.00025(1,1)	.00024(1)	.00025(1,1)	.00024(1)
sic26 Paper and allied	.00053(3,1)	.00051(3)	.00015(2,1)	.00014(2)
sic27 Printing and publishing	.00051(1,1)	.00048(1)	**.00016(1,1)***	.00017(1)
sic28 Chemicals and allied	**.00097(2,1)***	.00104(2)	**.00101(1,1)***	.00105(1)
sic29 Petroleum and coal products	**.00173(1,3)***	.00197(1)	**.00220(1,3)***	.00240(1)
sic30 Rubber & misc. plastics	.00067(1,1)	.00065(1)	.00069(1,1)	.00067(1)
sic31 Leather and leather products	.00093(1,1)	.00089(1)	.00126(3,1)	.00119(3)

Note: Asterisks signify a causal relationship.

different econometric approach. Estimating a translog cost function for U.S. manufacturing from 1956-86, it was found that infrastructure cost elasticities vary considerably across two-digit industries. The authors conclude that

> "There is no discernible pattern except that the magnitude of the elasticities tend to be higher in durable manufacturing sectors." (p.17)

The interesting question is why infrastructure affects durable manufacturers' productivity more than that of nondurable producers. There are a number of differences between the two types of industries. From Table 32 in Appendix C it can be seen that estimates of the returns to scale parameter are considerably higher for nondurable goods industries than for durable producers. The average estimates of γ are

Table 30. *Descriptive Statistics of Industries (mean values 1958-91)*

	$\overline{\alpha}_t^{L'}$	$\overline{\alpha}_t^{M'}$	$\overline{\alpha}_t^{K'}$	Δq_t	Δl_t	Δm_t	Δk_t
Durable							
sic 24*	0.236	0.650	0.113	0.021	-0.001	0.021	0.015
sic 25*	0.335	0.592	0.073	0.023	0.007	0.022	0.032
sic 32*	0.285	0.533	0.182	0.011	-0.005	0.008	0.014
sic 33*	0.199	0.644	0.156	0.002	-0.015	0.002	0.007
sic 34	0.304	0.597	0.099	0.016	0.004	0.015	0.030
sic 35*.	0.334	0.564	0.103	0.029	0.006	0.029	0.040
sic 36	0.346	0.557	0.097	0.046	0.019	0.036	0.051
sic 37*	0.234	0.674	0.092	0.021	-0.003	0.019	0.020
sic 38*	0.389	0.502	0.110	0.047	0.014	0.042	0.051
sic 39	0.315	0.599	0.086	0.020	-0.001	0.018	0.028
Average	**0.298**	**0.591**	**0.111**	**0.024**	**0.003**	**0.021**	**0.029**
Nondurable							
sic 20	0.124	0.800	0.076	0.019	-0.005	0.014	0.021
sic 21	0.125	0.789	0.086	0.001	-0.022	-0.006	0.043
sic 22*	0.225	0.658	0.117	0.019	-0.013	0.018	0.012
sic 23	0.306	0.651	0.043	0.014	-0.089	0.011	0.026
sic 26	0.210	0.633	0.157	0.026	0.003	0.023	0.039
sic 27*	0.409	0.482	0.109	0.021	0.015	0.023	0.031
sic 28*	0.182	0.641	0.177	0.036	0.005	0.030	0.028
sic 29*	0.045	0.868	0.087	0.021	-0.010	0.024	0.014
sic 30	0.274	0.593	0.134	0.046	0.023	0.038	0.044
sic 31	0.314	0.632	0.054	-0.020	-0.037	-0.019	-0.001
Average	**0.221**	**0.675**	**0.104**	**0.018**	**-0.013**	**0.016**	**0.026**

Note:

$\overline{\alpha}_t^{L'}$ = cost share of labour

$\overline{\alpha}_t^{M'}$ = cost share of materials

$\overline{\alpha}_t^{K'}$ = cost share of capital

Δq_t = growth rate of output

Δl_t = growth rate of labour

Δm_t = growth rate of materials

Δk_t = growth rate of capital

* Industries that exhibit a causal relationship with infrastructure investment using $\Delta\theta_t^{B,i}$

1.14 and 1.0 respectively. However, estimates of γ obtained using aggregate durable and nondurable data are far more uniform (see Table 15), indicating that the difference in estimates of returns to scale can be put down to econometric issues rather than inter-industry differences.[49] There are, however, a number of structural differences

[49] Causality tests were also conducted using TFP measures calculated using the estimates of γ obtained using aggregate durable and nondurable data. There is no difference in the results obtained using the different estimates.

between the industries. Table 30 provides a summary of some of the key descriptive statistics of the 20 manufacturing sub-sectors. The table contains summary information on the cost shares of labour, materials and private capital and the average annual growth rates of gross output, labour, materials and capital. The main difference between the cost bills of the two industry groupings is that materials account for a greater share in nondurable industries than in durable industries. Wages account for a greater share of total costs in durable industries. It is also clear that output grew considerably faster in industries that produce durable goods (2.4 per cent per year compared with 1.8 per cent in nondurable industries). Although materials make up a greater share of the cost bill in nondurable industries, growth in this input was higher in durable industries. Labour input grew by only 0.3 per cent per year in durable-producing industries and actually shrank in nondurable industries. The capital stocks grew at approximately the same rate. Ignoring the durable-nondurable division, more important differences are revealed by comparing industries in which $\Delta I^C \Rightarrow \Delta\theta^B$ with industries in which $\Delta I^C \not\Rightarrow \Delta\theta^B$. The first major difference is that output growth in the former was higher than the latter in the period 1959-73[50], when infrastructure investment was high; output growth was lower in the former than the latter in the period 1974-91, when infrastructure investment was lower.[51] The second major difference is that industries in which $\Delta I^C \Rightarrow \Delta\theta^B$ are significantly more capital intensive than industries in which $\Delta I^C \not\Rightarrow \Delta\theta^B$. The average share of capital in costs is 26 per cent higher in industries which show evidence of a causal relationship. The reason infrastructure affects productivity in industries that employ more capital may be

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[50] 3.6 % per year versus 3.3 % per year.
[51] 11.7 % per year compared with 15.3 % per year.

because public and private capital are complements.[52] Thus if increased public investment enhances the marginal productivity of private capital, capital intensive industries will enjoy the largest productivity gains.

Further evidence that public and private capital are complements can be found by analyzing a specific component of the private capital stock, more specifically motor vehicle shares. It is to be expected that the most vehicle-intensive industries are the ones that benefit most from core infrastructure investment. This is because investment in streets and highways makes up the greater proportion of total core investment and, as Fernald (1997) points out, if roads are productive then industries that use roads intensively should benefit more. There are no direct measures of industry road use. However, given the complementarity between roads and vehicles, vehicle use provides an indirect measure of road usage. Table 31 ranks the industries by average vehicle share and there is some evidence that the most vehicle-intensive industries are the ones that benefit most from infrastructure investment. Among the 10 most vehicle-intensive industries, there is evidence of a causal relationship between infrastructure and productivity in seven. Among the 10 least vehicle-intensive industries, there is evidence of a causal relationship between infrastructure and productivity in only four. This result is not surprising in light of the evidence in Section 6 that roads are the most productive type of public capital. Although some explanations have been given as to why infrastructure affects TFP more in some industries than others, any findings obtained using disaggregated productivity data should be treated with caution. This is because the more disaggregated the manufacturing data the more difficult it is to identify a relationship with an aggregate national measure such as public investment. For example, even if a reverse relationship exists between infrastructure investment and

[52] Studies that uncovered a complementary relationship are listed in Chapter 1.

Table 31. *Comparison of Causality Test Results and Average Vehicle Shares by Industry*

Industry		Average Vehicle Share	Causality
sic 32	Stone, clay and glass	2.8	$\Delta I^{C} \Rightarrow \Delta\theta^{B,32}$
sic 24	Lumber and wood	1.7	$\Delta I^{C} \Rightarrow \Delta\theta^{B,24}$
sic 20	Food and kindred	1.3	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,20}$
sic 29	Petroleum and coal	1.0	$\Delta I^{C} \Rightarrow \Delta\theta^{B,29}$
sic 26	Paper and allied	0.9	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,26}$
sic 28	Chemicals and allied	0.7	$\Delta I^{C} \Rightarrow \Delta\theta^{B,28}$
sic 33	Primary metals	0.6	$\Delta I^{C} \Rightarrow \Delta\theta^{B,33}$
sic 25	Furniture and fixtures	0.6	$\Delta I^{C} \Rightarrow \Delta\theta^{B,25}$
sic 27	Printing and publishing	0.6	$\Delta I^{C} \Rightarrow \Delta\theta^{B,27}$
sic 21	Tobacco products	0.5	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,21}$
sic 34	Fabricated metals	0.5	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,34}$
sic 36	Electronic and electric	0.5	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,36}$
sic 38	Instruments and related	0.4	$\Delta I^{C} \Rightarrow \Delta\theta^{B,38}$
sic 39	Miscellaneous	0.4	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,39}$
sic 35	Industrial machinery	0.3	$\Delta I^{C} \Rightarrow \Delta\theta^{B,35}$
sic 37	Transportation equip.	0.3	$\Delta I^{C} \Rightarrow \Delta\theta^{B,37}$
sic 22	Textile mill products	0.3	$\Delta I^{C} \Rightarrow \Delta\theta^{B,22}$
sic 23	Apparel & textile	0.3	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,23}$
sic 30	Rubber and misc.	0.2	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,30}$
sic 31	Leather products	0.2	$\Delta I^{C} \not\Rightarrow \Delta\theta^{B,31}$

Note: Industries ranked according to vehicle shares taken from Fernald (1997).[53]

productivity, it would be very difficult to detect using disaggregated manufacturing data. A change in the printing and publishing industry's productivity, holding constant productivity in all other industries, is unlikely to have a noticeable effect on the accumulation of capital by the public sector.

Nevertheless, the above test results are an interesting adjunct to the findings obtained using aggregate manufacturing data. To date no research using disaggregated data for the private business sector has shown any consistent pattern among industries

[53] Vehicle shares are calculated following Hall and Jorgenson (1967) and Hall (1990), multiplying the current value of the stock of vehicles by an estimate of the user cost of capital.

with respect to the role of public capital.[54] However, the results reported in this section suggest that the services provided by core infrastructure may have a varying impact on TFP growth rates because of differences in private factor intensities within industries.

8. Conclusion

The aim of this chapter has been to establish whether public investment Granger causes productivity growth or whether causation runs in the opposite direction. By carrying out a wide variety of tests and estimations using aggregate and disaggregated TFP and public investment data, I have also attempted to identify the most productive types of infrastructure and whether infrastructure investment accounts for a substantial portion of the variation in the productivity growth rate. Another important issue which this chapter attempts to shed light on is the extent to which some manufacturing industries benefit more than others from infrastructure spending. The results indicate that infrastructure is a policy variable with important supply-side effects. However, policymakers have to be selective in their spending – only a few types of public capital are directly productive and not all industries will benefit.

Two different measures of multifactor productivity were employed in the analysis. Using the standard Solow residual the following results were obtained:

1. Core infrastructure investment and total investment Granger cause the productivity growth rate. Evidence of reverse causation is ambiguous, however. Productivity causes

[54] Studies that analyse the role of public capital on different industries and sectors include Dalenberg and Partridge (1995), Luce (1994) and Papke (1991). Apart from using different econometric approaches, the authors examine infrastructure's effect on employment and investment rather than direct measures of factor productivity.

total investment but not core investment. The results are not sensitive to the use of alternative lag-length selection criteria.

2. Using disaggregated infrastructure data the finding is that only investment in roads determines the productivity growth rate. Again the evidence of reverse causation does not make economic sense. In particular, tests on sums of coefficients reveal that the Solow residual has both a negative and positive effect on some types of investment.

Although the Solow residual is used widely in the infrastructure literature it is arguably not the best measure of TFP growth available to researchers. If the "true" productivity growth rate is less cyclical and has lower variance, the Solow residual may distort the true relationship between infrastructure and productivity. Basu (1996) has shown that a productivity measure can be calculated that takes account of increasing returns to scale and variable factor utilisation over the cycle. The following are the major findings obtained using this measure:

1. Increasing returns to scale are not a major cause of mismeasurement of TFP. Adjusting for the intensity of labour and capital usage makes a substantial difference, however. The correlation between the Basu residual and the manufacturing Solow residual and Solow residuals used in previous infrastructure research is very low.

2. The adjusted TFP growth rate is caused by core and total investment. Core investment is more productive than total investment. When the infrastructure data is disaggregated, the finding is that both investment in roads and other structures Granger causes the Basu residual.

3. There is no evidence of reverse causation using any of the infrastructure measures. This does not imply that infrastructure is not a normal good. TFP growth is only one component of income growth and the results may be sensitive to the particular sample period.

4. When the manufacturing data is disaggregated it is found that public investment determines the productivity growth rate in some industries but not others. The most capital-intensive industries, in particular those with the highest vehicle shares, are the biggest beneficiaries of infrastructure investment.

5. Quantitative evidence of infrastructure's impact on the TFP growth rate was also obtained. The different infrastructure aggregates have a small but significant effect on the TFP growth rate. Core infrastructure investment has a more significant effect than total investment; road investment is the most productive component of the core. However, the estimates are very small compared with others obtained in previous infrastructure research. Thus I would not agree with, for example, Aschauer (1993) that up to a quarter of the productivity growth slowdown can be explained by the fall in infrastructure investment. Nor, however, would I agree with Tatom (1993) or Hulten and Schwab (1991a) and Jorgenson (1991) that the relationship between the variables runs in the opposite direction or is purely spurious. It is likely that infrastructure investment has a positive effect on private productivity but this effect is quite small, smaller even than that implied by the regional production function and cost function studies discussed in Chapter 1.

Overall, the results show that researchers must not only take care choosing which measure of infrastructure to include in the analysis (total, core, or disaggregated) but must also choose the "secondary variable" with care. Although many of the different results obtained by infrastructure researchers (for example, those of Tatom, 1993, compared with those of Section 3) can be attributed to differences in infrastructure data and econometric technique, the differences between the results obtained in Section 3 and Section 6 can be attributed solely to the use of different TFP measures.

In conclusion, it is worth highlighting some of the weaknesses of the approach used in this chapter and some possible avenues for future research. First, although the methodology allows for dynamic effects of infrastructure investment on productivity, it is not possible to identify any long-run relationship between the variables. This would require formal economic modelling of the productivity effects of infrastructure. A general equilibrium framework would allow recognition of the fact that increases in infrastructure investment may lead to alterations in the allocation of resources and alter factor prices.

Second, the focus in this chapter is only on the importance of the manufacturing sector, whose share of total U.S. output has been on the decline since at least the 1970s[1], whereas infrastructure is likely to affect production possibilities in many other sectors as well. However, because the data is in differences (growth rates) there is no danger of underestimating infrastructure's importance simply because the manufacturing sector is only one component of the private business sector. However, to the extent that different factors determine productivity growth in the manufacturing and non-manufacturing economy, the results are of less use to policymakers wishing to measure the total supply-side effects of infrastructure investment.

Finally, although it is an improvement on traditional measures of technical progress, in its residual form Basu's measure is still what Abramovitz (1993) describes as a "grab-bag" – a cover for other sources of growth (both tangible and intangible) besides technological advance. He argues that such residuals provide "some sort of measure of our ignorance" upon which researchers should focus their attention. For

[1] According to the *Survey of Current Business* (1996), real GDP in the U.S. increased at an average annual rate of 2.6 per cent from 1977-94. The gross product of all major sectors increased over this period, with growth rates ranging from 4.9 per cent for wholesale trade to 0.9 per cent for mining. Manufacturing output increased 2.3 per cent per year, 0.3 per cent per year less than the total.

example, in future work the labour and capital cost share terms in Basu's measure could be adjusted, thereby altering the size of the residual, to take account of improvements in the quality of capital and labour. Other sources of growth are not as simple to harness.

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Appendix A

Data Sources

Manufacturing Data

The following data for each industry are from the NBER Manufacturing Productivity Database (see Bartelsman and Gray (1996) and http://www.nber.org/productivity.html):

L	Total employment (1,000s)
P_L	Total compensation of employees (millions, \$current)
Hp	Hours of production workers (millions of hours)
M	Real cost of materials inputs (millions, \$1987)
K	Real capital stock (beginning of year, millions, \$1987)
Q	Real shipments (millions, \$1987)
P_Q	Price deflator for value of shipments (1987=1)
P_M	Price deflator for value of materials (1987=1)

User Cost of Capital

The rental price of private capital is similar to the measure constructed in Chapter 3:

$$P_{K,i} = q_i(r+\delta_i)\left[\frac{1-\iota-uz}{1-u}\right].$$

The only difference is that z, the present value of capital consumption allowances, contains an extra term, ω:

$$z = \frac{\rho(1-\omega\cdot\iota)}{(r+\rho)},$$

where ω is a dummy variable that takes the value of 0.5 in 1962-63 and 0 elsewhere. Under the Long Amendment (1962-63) firms were required to reduce the depreciable base of their assets by half the amount of the investment tax credit (see Nadiri and Mamuneas, 1994).

The subscript i denotes either industries 20-39 or the three manufacturing aggregates (total, durable and nondurable), depending on which measure of TFP is being calculated.

The physical capital deflator, q_i, is calculated by dividing the current capital stock by the constant (\$1987) capital stock. This data was obtained from the BEA diskettes, *Fixed Reproducible Tangible Wealth in the United States, 1925-1994*. The individual industry or aggregate economic depreciation rates, δ_i, were constructed using data from the same source.

The remaining variables: ι, the investment tax credit; u, the corporate income tax rate; and ρ, the capital consumption allowance rate are identical to those used in Chapter 3.

Instruments

Defence Spending (billions, chained \$1992) from 1959 is taken from the February 1997 *Economic Report of the President*, Table B2 p. 303. Based on quantity indices (1992=100) provided by the Department of Commerce, movements in the quantity index series were spliced to the billions of chained 1992 dollar series to obtain the 1958 value.

The oil price (spot US\$/barrel) from 1965 onwards is taken from the 1995 *International Financial Statistics Yearbook*. This measure is calculated as the average of the prices of UK Brent (light), Dubai (medium) and Alaska North Slope (heavy), equally weighted. Pre-1965 oil prices were calculated from the 1983 *International Financial Statistics Yearbook* as the average of the following blends: Saudi Arabian (Ras Tanura); Libyan (Es Sidra) from 1961; and Venezuelan (Tia Juana), equally weighted.

The Political Party of the President was obtained from the *Encyclopaedia Britannica*, 1992.

Public Capital Data

All public capital data was obtained from the Bureau of Economic Analysis *Fixed Reproducible Tangible Wealth* diskettes. All data is measured in millions of \$1987. Core infrastructure investment data is the sum of state and federal spending on highways and streets, water and sewer systems and "other structures" (electric and gas facilities and mass transit). Total infrastructure investment is the sum of state and federal non-military spending on equipment and structures, excluding spending on residential structures and conservation and development.

Appendix B

Model Stability Tests

Following Lütkepohl (1991)[56], to ensure that the various estimated systems are stationary I computed the roots of the characteristic polynomials and checked whether the moduli lie outside the unit circle. In each case the stability condition was satisfied. Consider (86), the three-dimensional VAR (2) model for $\Delta\theta_t^B$ and disaggregated infrastructure data:

$$\begin{bmatrix} \Delta\theta_t^B \\ \Delta I_t^H \\ \Delta I_t^O \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} + \begin{bmatrix} \psi_{11}^1 & \psi_{12}^1 & \psi_{13}^1 \\ 0 & \psi_{22}^1 & 0 \\ 0 & 0 & \psi_{33}^1 \end{bmatrix} \begin{bmatrix} \Delta\theta_{t-1}^B \\ \Delta I_{t-1}^H \\ \Delta I_{t-1}^O \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & \psi_{22}^2 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\theta_{t-2}^B \\ \Delta I_{t-2}^H \\ \Delta I_{t-2}^O \end{bmatrix} + \begin{bmatrix} \upsilon_t \\ v_t \\ \varepsilon_t \end{bmatrix}.$$

The reverse characteristic polynomial is

$$\det\left[\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} \psi_{11}^1 & \psi_{12}^1 & \psi_{13}^1 \\ 0 & \psi_{22}^1 & 0 \\ 0 & 0 & \psi_{33}^1 \end{bmatrix}\lambda - \begin{bmatrix} 0 & 0 & 0 \\ 0 & \psi_{22}^2 & 0 \\ 0 & 0 & 0 \end{bmatrix}\lambda^2\right],$$

which, after substituting the relevant parameter estimates, is found to be:

$$1 - 0.135\lambda - 0.0399\lambda^2 - 0.1017\lambda^3 + 0.0086\lambda^4.$$

The roots of this polynomial are

$$\lambda_1 = 1.91,\ \lambda_2 = 12.25,\ \lambda_3 = -1.17 - 1.90i, \lambda_4 = -1.17 + 1.90i.$$

The modulus of λ_3 and λ_4 is $|\lambda_3| = |\lambda_4| = \sqrt{1.17^2 + 1.90^2} = 2.23$. Since all roots lie outside the unit circle the model satisfies the stability condition:

$$\det\left[\boldsymbol{I} - \boldsymbol{\Psi}_1\lambda - \boldsymbol{\Psi}_2\lambda^2\right] \neq 0,$$

where $\boldsymbol{I}$ is the 3 x 3 identity matrix and $\boldsymbol{\Psi}_1$ and $\boldsymbol{\Psi}_2$ are the 3 x 3 parameter matrices for order 1 and order 2 variables respectively. It can therefore be concluded that the three series fluctuate around constant means and their variance does not change. The same test was conducted on each of the remaining models. For example, for the aggregate infrastructure model of focus, the bivariate model with $\Delta\theta_t^B$ and ΔI_t^C, the roots are -1.67, 1.33 and 6.75, which are all greater than 1 in absolute value.

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[56] See pages 9-13.

Appendix C

Results from IV Estimation – Disaggregated TFP Data

Table 32 contains individual estimates of the returns to scale parameter for the 20 manufacturing industries. Wald tests were conducted to test whether the $\hat{\gamma}$s are significantly different from unity. Except for SIC 26 and 37, none of the estimates was found to be significantly different from unity. This finding may be because each of the estimations in Table 32 contains far fewer degrees of freedom than the 3SLS estimations performed using aggregate data.

Table 32. *Estimates of Returns to Scale, SIC 20-39*

Durable Goods Industries	**σ=0.0**	**0.3**	**0.5**	**0.7**	**1.0**
sic24 Lumber and wood	0.97	0.98	0.98	0.99	1.00
sic25 Furniture and fixtures	1.00	1.02	1.02	1.03	1.04
sic32 Stone, clay and glass	0.90	0.92	0.93	0.94	0.96
sic33 Primary metals	0.99	0.98	0.96	0.95	0.94
sic34 Fabricated metals	1.12	1.12	1.12	1.12	1.13
sic35 Industrial machinery and equipment	0.96	0.95	0.94	0.94	0.93
sic36 Electronic and other electric equipment	1.18	1.16	1.15	1.13	1.11
sic37 Transportation equipment	0.83	0.84	0.85	0.86	0.87
sic38 Instruments and related products	1.12	1.10	1.08	1.07	1.05
sic39 Miscellaneous manufacturing industries	1.03	1.04	1.04	1.05	1.06
Nondurable Goods Industries					
sic20 Food and kindred products	1.20	1.20	1.21	1.21	1.22
sic21 Tobacco products	1.44	1.41	1.39	1.37	1.34
sic22 Textile mill products	1.08	1.09	1.09	1.09	1.09
sic23 Apparel and other textile	0.91	0.93	0.94	0.95	0.96
sic26 Paper and allied	1.21	1.19	1.17	1.16	1.14
sic27 Printing and publishing	0.85	0.89	0.91	0.95	1.00
sic28 Chemicals and allied	1.25	1.22	1.20	1.18	1.15
sic29 Petroleum and coal products	1.11	1.10	1.09	1.08	1.06
sic30 Rubber and misc. plastics products	1.11	1.11	1.11	1.11	1.10
sic31 Leather and leather products	1.33	1.32	1.32	1.32	1.31

Note: Based on standard t-tests all of the estimates of γ are significantly different from zero at less than the 1% level, except SIC21.

Appendix D

Comparison of Elasticities of Substitution

In Section 6 a value of 0.7 was used for σ, the (local) elasticity of substitution between value-added and materials. To check the robustness of the causality tests, further tests were conducted using $\sigma = 0.3$ (see Bruno, 1984) and $\sigma = 0.5$ (see Malley *et al.*, 1998). As the results reported in Table 33 make clear, there is very little difference between the different variables. The FPEs are of a similar magnitude to those reported in Table 19 and the same lag order is chosen for each of the variables. In other words the results imply that causation is still unidirectional, ie $\Delta I^C \Rightarrow \Delta\theta^B$.

Table 33. *Optimum Lags of Manipulated Variable and FPE of Controlled Variable.*

Controlled Variable [a]	*Manipulated Variable*	*Optimum Lag, Manipulated Variable*	*FPE(m*,n*)* [b]	*FPE(m*)*
$\sigma = 0.3$				
$\Delta\theta_t^B$ *(1)*	ΔI_t^C	1	**0.000046***	0.000057
ΔI_t^C *(2)*	$\Delta\theta_t^B$	1	0.001877	0.001820
$\sigma = 0.5$				
$\Delta\theta_t^B$ *(1)*	ΔI_t^C	1	**0.000047***	0.000058
ΔI_t^C *(2)*	$\Delta\theta_t^B$	1	0.001874	0.001820

[a] The number in brackets indicates the order of autoregressive operator on the controlled variable, determined in Table 19. [b] The FPEs in the *FPE(m*,n*)* column are the minimum ones obtained from inclusion of different lags on the manipulated variables. Asterisks signify that there is a causal relationship from the manipulated variable to the controlled variable.

Appendix E

Comparison of Model-Building Techniques

The method used to construct the estimating models is based primarily on Hsiao (1981). Ahking and Miller (1985) and Erenburg and Wohar (1995) used a slightly different model-building method, including variables even if this did not lead to a lowering of the final prediction error. Thus the models were deliberately overfitted initially. Diagnostic checks (F-tests and Wald tests respectively) were then used to arrive at the final models and draw conclusions about causality. In comparison, in Section 3 and Section 6 variables are only included in the autoregressive models if they lower the prediction error. To ensure that the choice of model-building technique does not affect conclusions drawn about causality, the total and core infrastructure models, (82) and (83), were re-estimated after including variables that lead to increases in prediction error. Thus using information contained in Table 19 the initial matrices of lag operators for the two models are given respectively by

$$\begin{pmatrix} \psi_{11}^{1}(L) & \psi_{12}^{1}(L) \\ \psi_{21}^{1}(L) & \psi_{22}^{2}(L) \end{pmatrix}, \text{ and}$$

$$\begin{pmatrix} \psi_{11}^{1}(L) & \psi_{12}^{1}(L) \\ \psi_{21}^{1}(L) & \psi_{22}^{2}(L) \end{pmatrix}. \tag{91}$$

Wald tests of the hypothesis $\psi_{21}^{1}(L) = 0$ with 1 degree of freedom produce chi-square values of 0.78 for the core infrastructure model and 0.32 for the total infrastructure model. Hence the restrictions are accepted, confirming the adequacy of the final models and the conclusion $\Delta\theta_t^B \not\Rightarrow \Delta I_t^C$ and $\Delta\theta_t^B \not\Rightarrow \Delta I_t^T$.

Conclusion:

Summary of Findings, Comparison of Empirical Approaches, and Avenues for Future Research

1. Introduction

The aim of this thesis has been to analyse the role of public capital in private production in the United States, in particular the roles of the different types of infrastructure. Two different empirical approaches were used to answer a number of questions, in particular the questions of causality and optimality. Does infrastructure cause total factor productivity? Did the cost savings enjoyed by firms warrant additional investment in roads, water and sewer systems and other structures over the sample period. On the question of optimality, one of the most important insights is that, even if the public sector decides to cut infrastructure investment, a shortage of this type of capital may not develop if there are changes to other variables that influence the decision-making process of private producers. Another important insight obtained from the cost function study is that, regardless of whether there is a surplus or shortage of total infrastructure, the optimal/actual ratios of the different types of capital may be moving in opposite directions. On the question of causality, one of the most important insights is that infrastructure causes the productivity growth rate but some types of investment (roads in particular) are more productive than others. The study in Chapter 4 also reveals that conclusions drawn about infrastructure's relationship with total factor productivity depend on the assumptions underlying the derivation of the latter measure. In the sections that follow the approaches and results of each of the two major studies are summarised and discussed. Some of the weaknesses inherent in each are also considered and opportunities for further research are mentioned.

2. Summary of Empirical Approaches and Results

Chapter 3: Calculating Optimal Public Capital Stocks

The cost function approach is utilised because of the advantages it has over the production function approach and because it provides a convenient framework for the calculation of optimal capital stocks. Data for the total private business sector is used to take account of the fact that there are a number of sectors that are likely to benefit from the infrastructure stock. Use of a short-run cost function allows the optimal infrastructure stock to be calculated simultaneously with the optimal private capital stock. The motivation for calculating the optimal quantity of each type of infrastructure is that if there is, for example, a shortage of core infrastructure, this does not justify a general increase in public investment. Some of the individual infrastructure stocks may be in surplus while others are in shortage. Furthermore, some types of infrastructure may be moving towards a state of underprovision while others are moving towards a state of overprovision.

Apart from calculating the stocks of total and disaggregated infrastructure that are optimal to the U.S. private business sector, this chapter contributes the following to the already well-established cost function literature: an analysis of the responsiveness of the optimal capital stocks to pre-tax and tax-adjusted factor prices; use of the wealth of depreciation data available from the BEA; and calculation of Divisia indexes for private and public capital in the United States. The latter reveal that the average quality of private capital increased over the sample period because of the relative increase in equipment investment but the quality of public capital remained unchanged.

Using the Generalised Leontief specification, two cost function models were estimated, one using aggregate infrastructure data, the other using disaggregated data. Each model was estimated using both the pre-tax and tax-adjusted price of labour. The estimation results and diagnostic tests are satisfactory, with most estimates significant at the 1 per cent level at least. Wald tests reject in favour of including the various infrastructure variables in the models. Estimating the disaggregated infrastructure model consumes a large number of degrees of freedom and there is some evidence of multicollinearity. While this affects the efficiency of the parameter estimates, they remain unbiased and the pattern of the optimal/actual ratios, which is one of the main focuses of the analysis, is largely unaffected.

The estimates from the cost function models are inserted into the optimal capital stock equations, along with data on the level of output and factor input prices. Optimal infrastructure elasticities are also calculated using these parameter estimates and variables. The elasticities illustrate the responsiveness of the optimal quantity of infrastructure to changes in factor input prices (labour and private capital). The finding is that infrastructure and labour are substitutes and infrastructure and private capital are complements. A similar finding is obtained using the individual road, water and sewer and other structures stocks. The output elasticities of the different infrastructure aggregates (evaluated at the optimum) were also estimated. These reveal that, although infrastructure has a positive effect on output, its role is much smaller than that which the vast majority of aggregate production function studies attribute to it. Highways and streets have the highest output elasticity followed by water and sewer systems and other structures.

When the optimal capital stocks are calculated the finding is that, in spite of the infrastructure slowdown from the early 1970s, there was never a shortage of core infrastructure during the sample period. In fact, on average, there was a small surplus of this type of capital. The user cost of private capital increased substantially from the early 1970s and, because G and K are complements, this led to a fall in the desired quantity of public capital, G^*. When the core is disaggregated, the finding is that each of the individual stocks was never undersupplied over the sample period. The average optimal/actual ratio for roads was 0.96; the average ratio for water and sewers was 0.92 and the average ratio for other structures was 0.86.

Without attributing too much importance to the levels of the ratios, it is also clear from Figure 12 in Chapter 3 that the ratios were moving in different directions at different times during the sample period. Furthermore, comparison of the period when the public capital stocks were growing rapidly (1959-72) with the period of slower growth (1973-94), reveals that the infrastructure slowdown caused only a small movement in the optimal/actual ratios for water & sewers and other structures towards a state of underprovision. Roads became more oversupplied over this period.

It was also illustrated that the different ways of treating the input prices of public and private capital and labour for tax purposes have an effect on the results but not a very substantial one. This does not, however, detract from the importance of analysing the direction of taxation effects. Although the results obtained in Chapter 3 make a contribution to the already well-established body of cost function research there are a number of issues that have to be addressed in future research, especially with respect to the use of value-added data, the construction of the user cost of public capital and the time lag between public outlays and responses by producers. It may also be argued that more experimentation is required with alternative functional forms.

Chapter 4: Using Adjusted Measures of Productivity to Resolve the Causality Issue

This chapter attempts to contribute to the infrastructure literature by using a framework that has not received much attention in the infrastructure literature: the construction of autoregressive models that introduce dynamic effects from infrastructure investment. A variety of statistical techniques are employed in the chapter to test for causality between total factor productivity and public investment. Furthermore, the focus moves to the productivity literature and the derivation and estimation of a TFP measure that incorporates possible increasing returns to scale and, by making use of manufacturing materials usage data, adjusts for variable labour and capital utilisation over the cycle. Once again use is made of disaggregated public investment data

Although manufacturing is only one sector that is likely to derive benefits from the public capital stock, the effect of public capital is not underestimated per se using the causality testing approach, because data in differences (growth rates) is used. To the extent that manufacturing and total private TFP differ, extrapolation of the results is not justified. Interesting insights are gleaned, however, by comparing the results obtained using the original Solow residual and adjusted TFP and because manufacturing is arguably one of the sectors that benefits most from infrastructure investment.

In constructing the adjusted TFP measure, instrumental variable techniques are employed to obtain an estimate of the returns to scale parameter. The finding is that returns to scale are increasing when Hall's modified residual (which uses cost shares instead of revenue shares to take account of market power) is estimated, but close to constant when variable factor utilisation is also incorporated. The correlation between the adjusted TFP measure and the business cycle is very low, as is its relative variance.

The new TFP measure is then used to analyse the relationship between the growth rates of public investment and TFP. The FPE Criterion is used to determine the appropriate number of lags and the model-building technique allows each variable to enter the model with a different number of lags. A selection of other lag-length selection criteria, that usually choose larger or smaller numbers of lags than the FPE Criterion, are also used to test the sensitivity of the results. Two causality testing procedures are used. The first compares the minimum FPEs from adding infrastructure variables to lags of TFP. The second takes the form of Wald tests carried out on the off-diagonal terms in the autoregressive models. An examination of the parameter estimates from the autoregressive models also allows the *direction* of causation to be determined and provides quantitative evidence of infrastructure effects. The SUR estimation results are subjected to a battery of diagnostic tests, including under and overfitting tests that determine the adequacy of the models chosen by the FPE Criterion and tests that establish the sensitivity of the causality results to increases in the number of lagged infrastructure terms. Using adjusted TFP the finding throughout is that an increase in the investment growth rate causes an increase in the productivity growth rate. Roads are the most productive type of infrastructure investment, followed by investment in other structures. Water and sewer systems are found to have no effect on TFP. Contrary to the stated view of a number of infrastructure researchers, there is no evidence of reverse causation. The quantitative evidence points to a small but statistically significant role for infrastructure in determining the productivity growth rate. When the TFP data is disaggregated the finding is that some industries benefit more from infrastructure investment than others, especially those that are capital intensive and use roads most intensively.

As the philosophical literature on causality makes clear, it is important not to accept the results of causality testing procedures uncritically. The results obtained using the adjusted TFP measure do conform to certain researchers' expectations, however. The core is found to reduce prediction error more than the total measure, roads affect productivity more than the other types of public investment and the results obtained using individual industry data seem to be explained by differences in industry structure.

Tests and estimations were also carried out using the original Solow residual to provide comparative evidence. Although this is arguably an imprecise measure of TFP growth, it is still used in much empirical work in the infrastructure literature. Differences between the results I obtain using the Solow residual and other researchers' results can be attributed to differences in econometric technique. However, any differences in the results I obtain using the Solow residual and the adjusted TFP measure can be attributed solely to the choice of productivity measure.

Using the original Solow residual there is some evidence that infrastructure causes TFP but the results are not as statistically significant as those obtained using the new measure. There is also some evidence of reverse causality but it is not robust to the use of disaggregated infrastructure data. Sums of coefficient tests also indicate that TFP has both a positive and negative effect on certain types of infrastructure investment. These results lead me to question the appropriateness of the Solow residual as a measure of factor productivity. Infrastructure's quantitative effect, though not as statistically significant, is larger than that of the adjusted measure. A battery of diagnostic tests was carried out to ensure that the difference in results can be attributed solely to the use of different estimates of total factor productivity.

Although I conclude that there is no evidence that productivity Granger causes infrastructure, in the long run it is to be expected that increases in income will lead to increases in the stock of public capital. The fact that such an effect could not be found can be explained by the finding that the residual and income were moving in different directions in certain years of the sample period and possibly by the fact that the supply of infrastructure is determined by a political process. In the 1970s the "Great Society" welfare programmes took precedence over the enhancement of future public services.

Although increases in infrastructure investment may have only a short-term effect on the productivity growth rate, a possible drawback of the approach followed in this chapter is that it ignores any long-run relationship between the variables. Although beyond the scope of this thesis, there has not been adequate analysis of infrastructure effects within a general equilibrium framework.

3. Similarities and Differences

The different empirical approaches followed in this thesis each facilitate the answering of a number of questions. It is also worthwhile investigating how the results obtained from the different approaches vary. The cost function study in Chapter 3 uses a formal specification of the determination of firms' costs. As the dual to the production function, the cost function reflects technology, incorporates the optimising behaviour of firms and represents the dependence of costs on the level of output. It also makes available a wide variety of analytical statistics that reveal how changes in private sector variables affect optimal capital measures. The autoregressive framework used in Chapter 4 incorporates dynamic effects and treats each variable as endogenous within a multivariate framework. There is no specification of the relationship between infrastructure and TFP. Nevertheless, within this framework meaningful economic hypotheses can be tested.

In the literature survey in Chapter 1 it was mentioned that the assumption that public capital enters the production function as a fixed unpaid factor of production has important implications for the calculation of total factor productivity measures. An example was provided of how the Solow residual would have to be stripped of infrastructure to derive a more accurate measure of TFP. In Chapter 3 the cost function embodies the assumption that public capital enters the production function as a fixed unpaid factor of production. However, the manufacturing production function, from which the various TFP measures are derived in Chapter 4, makes no such assumption. Gross output depends on labour, materials and private capital only. It is easy enough to derive many of the alternative productivity measures with G included as a production factor, although empirical implementation is somewhat more complicated. It appears, therefore, that there is scope for further research into the transmission mechanism, ie, how public capital affects the private production process, and using growth accounting techniques.

Another difference between the studies is that Chapter 3 uses capital stock measures; Chapter 4 uses investment measures. Investment measures were used to prevent some of the problems that arise when causality tests are conducted using non-stationary variables. The difference between stock and flow growth rates can be attributed mainly to composition effects (changes in the depreciation rate caused by changes in the asset mix). However, this difference is not as significant when use is made of disaggregated infrastructure data, the analysis of which forms the backbone of this thesis.

One difference between the disaggregated infrastructure results of chapters 3 and 4 is the finding that investment in water and sewer systems is a significant variable in the cost function models but does not have a significant effect on TFP. There is a possibility that these types of capital have a significant effect on non-manufacturing production only, but this does not seem realistic. The water and sewer variables used in the two analyses also differ in certain respects. A joint measure was used in the cost function analysis to preserve degrees of freedom, individual measures were used in Chapter 4. This, however, was not the reason for the difference in the results. It may be that the average effect of water and sewer capital is positive but that the marginal effect is zero, which becomes apparent in an analysis that makes use of variables' growth rates.

Despite the differences in the approaches there are a number of similarities in the results. The general finding is that infrastructure matters. It is a significant variable in the cost function models and it causes the growth rate of total factor productivity.

Each study urges caution from policymakers in certain respects, however. Infrastructure may be a significant variable in the cost function models but even the prolonged decline in public investment from 1968-82 had little affect on the optimality of the public capital stock. Furthermore, infrastructure is found to have a positive and highly statistically significant effect on the growth rate of TFP. However, the quantitative effect is very small. This finding would probably come as no surprise to many productivity researchers, who attribute the productivity growth slowdown to a variety of factors.