Essays on dynamic macroeconomics

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Part II

Public Capital and Economic Growth

Chapter 5

Public Capital and economic growth: A Survey

5.1 Introduction

Public capital, and especially infrastructure, is central to the activities of households and firms. According to the World Bank (1994), public capital represents the 'wheels' – if not the engine – of economic activity. Input-output tables show, for example, that telecommunications, electricity, and water are used in the production process of nearly every sector, while transport is an input for every commodity. However, the World Bank (1994, p. 19) also concludes that 'infrastructure investment is not sufficient on its own to generate sustained increases in economic growth'.

In recent years, a substantial research effort focused on estimating the contribution of public capital to the productivity of private factors of production and to economic growth. This research was motivated by two factors (Aschauer, 2000). First, for many years the ratio of public capital investment to gross domestic product (GDP) declined in the OECD area. Figure 5.1 shows average government investment spending as a percentage of GDP for 22 OECD countries over the period 1963–2001 (left-hand side scale) and its standard deviation (right-hand side scale). The data relate to consolidated general government and are based on the Standardised National Accounts compiled and published by the OECD. Figure 5.1 shows

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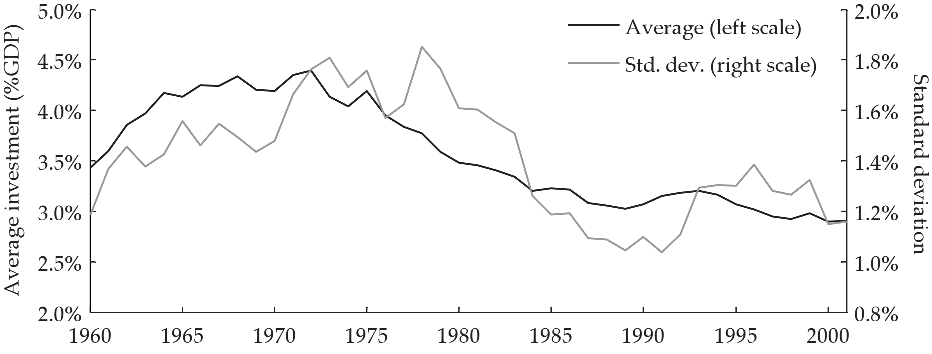
Figure 5.1. Government investment in 22 OECD countries, 1961–2001, average (%GDP) and standard deviation



Source: Kamps (2006)

that public capital spending as a share of GDP declined between 1971 and 1990 and slightly recovered afterwards.[1] Another conclusion that can be drawn from Figure 5.1 is that government investment spending varies considerably across countries. As Table 5.1 in the Annex shows, in 2000–01, government capital spending ranged between 1.6 percent of GDP in the United Kingdom and 6.9 percent in Japan.

Second, various authors claim that the decline in public non-military capital spending in the United States contributed to the productivity slowdown of the 1970s and 1980s. The early empirical work in this area, conducted largely at the national level, reported a significant and large impact of public capital on productivity. For instance, using a production-function approach for the US between 1949 and 1985, Aschauer (1989) found that a 10-percent rise in the public capital stock would raise multifactor productivity by almost 4 percent. Other studies using aggregate data also reported large effects of public capital spending. At a time when the slowdown in productivity growth was a widespread concern, these findings suggested that a decline in the rate of public capital accumulation was 'a potential new culprit' (Munnell, 1990b, p. 3).

However, several economists questioned Aschauer's estimates on the grounds that they were implausibly high (see, for instance, Gramlich, 1994). Furthermore, the early studies were fraught with methodological and econometric difficulties.

[1] According to Oxley and Martin (1991, p.161) the decline of government investment reflected 'the political reality that it is easier to cut-back or post-pone investment spending than it is to cut current expenditures.' de Haan et al. (1996) report evidence that during large scale fiscal contractions government capital spending is indeed reduced more than other categories of government spending

Issues ranking high on the list of potential problems include reverse causation from productivity to public capital and a spurious correlation due to non-stationarity of the data.

Perhaps the most important concern is the direction of causality between public capital and aggregate output: while public capital may affect productivity and output, economic growth can also shape the demand and supply of public capital services, which is likely to cause an upward bias in the estimated returns to public capital if endogeneity is not addressed.[2] The recent literature on the economic growth effects of public capital suggests various ways of solving this problem.

Some of the earlier studies have also been criticised for not taking the stationarity of the data properly into account (see, for instance, Sturm and de Haan, 1995). Unit root tests often suggest that output and public capital contain a unit root. However, it is well known that unit root tests have low power to discriminate between unit root and near unit root processes. This problem is especially pronounced for small samples. One way to alleviate the small-sample problem that has become popular in recent research is to make use of the cross-sectional dimension of the data and to apply panel data techniques.

In some of the earlier studies unit roots in GDP and capital stock were removed by taking first differences. But this may ignore evidence of a long-run relationship in the data if the series are cointegrated (Munnell, 1992). Indeed, various recent studies report evidence for such a cointegrating relationship between public capital (or infrastructure) and output. By exploiting this cointegrating relationship, these studies estimate the long-run effect of public capital (or infrastructure) on GDP per capita. However, the existence of a cointegrating relationship in itself does not necessarily imply that causality runs from infrastructure to long-run growth (Canning and Pedroni, 1999).

In their survey of the earlier literature, Sturm et al. (1998) show that the literature contained a relatively wide range of estimates, with a marginal product of public capital that is much higher than that of private capital (e.g., Aschauer, 1989), roughly equal to that of private capital (e.g., Munnell, 1990a), well below that of private capital (e.g., Eberts, 1986) and, in some cases, even negative (e.g., Hulten and Schwab, 1991). The wide range of estimates makes the results of these older

[2] The problem not only occurs in studies like that of Aschauer (1989), but also in studies based on panel data, like Munnell (1990a), who found positive elasticities of output to public capital using panel data at the US state level. According to Holtz-Eakin (1994, p. 13), '[b]ecause more prosperous states are likely to spend more on public capital, there will be a positive correlation between the state-specific effects and public sector capital. This should not be confused, however, with the notion that greater public capital leads a state to be more productive'.

studies almost useless from a policy perspective.

However, more recent studies generally suggest that public capital may, under specific circumstances, raise income per capita. The purpose of this chapter is to review this literature, thereby providing an update of the survey of Sturm et al. (1998). We focus on two important questions. First, does an increase in public capital spur economic growth? Second, to what extent do conclusions on the effect of more infrastructure change once it is taken into account that infrastructure construction diverts resources from other uses?

The remainder of the chapter is organised as follows. Before we start reviewing the literature in some detail, Section 5.2 zooms in on our central questions and some other general considerations. Section 5.3 reviews studies belonging to the production-function approach in which the public capital stock is considered as an additional input factor in a production function. The next sections review three other approaches that have been applied to assess the impact of public capital on economic growth: the cost-function approach (Section 5.4), vector autoregressions (Section 5.5), and cross-country models (Section 5.6). In Section 5.7, we discuss the issue of the optimal capital stock. Section 8 offers some concluding comments.

5.2 Key questions concerning the link between public capital and economic growth

5.2.1 What do we want to know?

Empirical research on the relationship between public capital and growth should provide answers to two important questions. First, does an increase in the public capital stock foster economic growth?[3] Second, the policy relevant question for infrastructure investment is not what is the effect of extra infrastructure, holding everything else constant, but what is the net effect of more infrastructure given that infrastructure construction diverts resources from other uses (Canning and Pedroni, 1999). In other words, is the existing stock of capital optimal?

Of course, the possibility of a long-run impact of infrastructure on income very much depends on whether the data are generated by a neoclassical exogenous growth model or an endogenous growth model. In the exogenous growth model,

[3] The impact of public investment on economic growth is also relevant from a regional policy perspective. Governments can influence the rate at which regions accumulate various productive factors, particularly infrastructure. If these factors affect productivity and the location of mobile private production factors, there will be room for supply-side policies to influence the regional dispersion of income (de la Fuente and Vives, 1995).

in which technical progress drives long-run growth, shocks to the infrastructure stock can only have transitory effects. In an endogenous growth model, shocks to infrastructure can raise the steady-state income per capita. For instance, in the endogenous growth model with constant returns to aggregate capital of Canning and Pedroni (1999), positive shocks to infrastructure stocks raise long-run income per capita when the economy is below the efficient infrastructure level.

Apart from the growth model selected, the existing capital stock matters for the marginal productivity of public capital. This is clear from a network perspective: a new network may yield a one-time increase in productivity rather than a continuing path to prosperity (Fernald, 1999). Furthermore, according to the law of diminishing returns, an increment to the public capital stock would have a small (large) output effect if the capital stock in the previous period was large (small). There is evidence that countries with a small public capital stock have the highest marginal productivity of public capital (Demetriades and Mamuneas, 2000). Many empirical studies focus on the average, as opposed to the marginal, productivity of public capital and can therefore not be used to assess whether the existing capital stock is optimal. Kamps (2005) adopts the methodology proposed by Aschauer (2000) in order to investigate whether there is a lack of public capital in European Union countries.

In addressing the second question, it comes natural to take a government budget perspective and to look at how additional public investment is financed. The effect of public investment on growth is likely to depend on how the increased spending is financed. Increases in taxes are widely considered to reduce the rate of economic growth. An increase in public capital stimulates economic growth only if the productivity impact of public capital exceeds the adverse impact of higher taxes. If cutting other government spending finances an increase in capital spending, there is still no guarantee that growth will be enhanced. Hulten (1996) argues, for instance, that new infrastructure construction may have a perverse effect if it draws scarce government resources away from maintenance and operation of the existing capital stock.

Sections 5.3 to 5.6 will focus on the growth-enhancing effects of public capital spending while Section 5.7 will turn to the issue of the optimality of the public capital stock. But first we review why public capital may affect growth and how the stock of public capital can be measured.

5.2.2 Why does public capital matter for economic growth?

How does public capital affect economic growth? This issue has received only scant attention in the literature on the relationship between public capital spending and economic growth. As Holtz-Eakin and Lovely (1996, p.106) note, 'A somewhat surprising feature of this literature is the noticeable absence of formal economic models of the productivity effects of infrastructure'.

In the earlier literature it is generally assumed that public capital forms an element in the aggregate production function. The stock of public capital (G_t) may enter the production function in two ways: directly, as a third input, or it may influence multifactor productivity (A)

$$Q_t = A(G_t)f(K_t, L_t, G_t), \tag{5.1}$$

where Q_t is real aggregate output of the private sector, L_t is (aggregate hours worked by) the labour force and K_t is the aggregate non-residential stock of private fixed capital.

Although is it pretty common to model the growth effects on government capital by adding a third factor in the production function, on second thoughts it is questionable whether it makes much sense. After all, government roads as such do not produce anything. Implicitly, it is assumed that the services of public capital are a pure, non-rival public good, with services proportional to the stock of capital. However, as pointed out by the World Bank (1994), many infrastructure services are almost (although not perfectly) private goods. Private goods can be defined as both rival (i.e., consumption by one user reduces available supply to others) and excludable (i.e., a user can be prevented from consuming them).

Furthermore, public capital is treated symmetric to labour and private capital. According to Duggal et al. (1999), this goes against standard marginal productivity theory in assuming that a market determined per unit cost of infrastructure is known to the individual firms and can be used in calculating total cost. However, since public investment is financed through general tax revenues or government debt, per unit costs of public capital are not market determined. Moreover, there is no guarantee that the total cost of infrastructure to the firm is related to the amount it uses. Aaron (1990) argues that this absence of a market test, coupled with possible government pricing inefficiencies, makes it impossible to assume that public capital as a factor input would be remunerated in line with its marginal product.

An alternative would be to incorporate public capital into the production function as part of the technological constraint that determines total factor productivity (see Duggal et al., 1999). Rather than acting as a discretionary factor input, public investment increases total productivity by lowering production costs. By increasing the technological index, additional public capital shifts the production function upward, and thus enhances the marginal products of the factor inputs. However, as pointed out by Sturm et al. (1998), in a Cobb-Douglas function (estimated in log levels) it does not make any difference whether public capital is treated as a third production factor or as influencing output through the factor representing technology. Both ways of modelling the influence of public capital yield similar equations to be estimated, so that the direct and indirect impact of public capital cannot be disentangled.

A better way to model the growth effect of public capital is by focusing explicitly on the services provided by the assets. For instance, Fernald (1999) assumes that for each industry i, production depends, apart from L_i and K_i, on transport services (T_i) produced within that particular sector. These services, in turn, depend upon the flow of services provided by the aggregated stock of government capital (roads) G and the stock of vehicles in the sector V_i. Output also depends on the Hicks neutral level of technology U_i. This yields

$$Q_t = U_i F^i\big(K_i, L_i, T(V_i, G)\big). \tag{5.2}$$

This way of modelling the growth effects of public capital also makes it possible to introduce the effects of congestion and network externalities. Many services provided by the stock of public capital may be subject to congestion: more vehicles on a road lower the productivity of this road. More roads will reduce congestion, and therefore, improve productivity. Above a certain threshold, however, marginal increments will no longer affect output since they no longer cause a decline in congestion (Sanchez-Robles, 1998). So congestion will give rise to non-linearities in the relationship between public capital and economic growth.

Public capital, notably infrastructure, is often distinguished from other types of capital because several market imperfections make accumulating and operating those assets prone to extensive government interventions and give rise to a special role for institutional characteristics. Economies of scale due to network externalities are a widely recognised imperfection in infrastructure services (World Bank, 1994). An important characteristic of modern infrastructure is the supply of services through a networked delivery system designed to serve a multitude of users. This interconnectedness means that the benefits from investment at one point in the network will generally depend on capacities at other points. The network character also has important consequences for the relationship between public capital and economic growth. Once the basic parts of a network are established, opportunities for highly productive investment diminish. In line with this argument, Fernald (1999) reports that once the highway system in the US was roughly completed, after 1973, the hypothesis that the marginal productivity of roads is zero cannot be rejected. In other words, road building gave a boost to productivity growth in the years before 1973, but post-1973 investment did not yield the same benefits at the margin.

There is broad consensus among economists and politicians that public infrastructure investment is an important aspect of a competitive location policy.[4] Often it is argued that infrastructure lowers fixed costs, attracting companies and factors of production and, thereby, raising production (see e.g., Haughwout, 2002 and Egger and Falkinger, 2003). This does not necessarily imply higher growth at the national level, however, since production in other regions might go down. A common result in this type of models is that, under certain assumptions, the resulting stock of capital without coordination between regions or countries is sub-optimal. Since more infrastructure in the 'home' region attracts production factors out of the 'foreign' region, there is a risk of the infrastructure being too high in both regions compared to the situation in which they coordinate their actions. That said, spillover effects of infrastructure could lead to the opposite outcome: because the investing region only gets part of the benefits, both regions end up with too little infrastructure.

The size of spillover effects will depend on the size of the country or region concerned and its openness. One simple way to model these spillovers has been suggested by Cohen and Morrison Paul (2004). Their model for a cost function of the manufacturing sectors in US states not only includes the public capital stock in the state concerned, but also the public capital stock in geographically connected states.[5] In a similar way, the public capital stock of a neighbouring state (G_j) can be included in a production function, which gives

$$Q_i = A_i K_i^{\alpha} L_i^{\beta} G_i^{\gamma} G_j^{\eta}. \tag{5.3}$$

A somewhat different reason why public capital may affect economic growth is suggested by the new economic geography (e.g., Krugman, 1991, Holtz-Eakin and

[4] The member countries of the European Union, for example, agreed upon a benchmark method to determine the competitiveness of the EU economies in which infrastructure plays a prominent role.

[5] Also Holtz-Eakin and Schwartz (1995) consider interstate spillovers.

Lovely, 1996, Fujita et al., 1999), which considers transport costs to be a central determinant of the location and scale of economic activity and of the pattern of trade. More transport infrastructure has a profound impact on the size of the market, so producers can cluster together in one central region. This clustering of activities leads to specialisation and economies of scale. In these theoretical models it is common to model transport costs as 'iceberg costs' (Krugman, 1991, Bougheas et al., 1999). The producer of a particular good sells a certain quantity and during transport a fraction of the shipped quantity 'melts' away. The longer the distance, the larger the fraction that melts and the higher are the transport costs. The buyer has to pay for more goods than he actually receives. This bypasses the need to model the transport sector separately. However, the concept of iceberg costs implicitly assumes that the transport sector's production function is equal to the production function of transported products, which is a rather strong assumption.

De la Fuente and Vives (1995) offer another nice and simple way to model transportation costs. They assume that final output Q in region i depends positively on intermediate production Y_i and negatively on transportation costs C_i. Transportation costs rise with the land area S of the region (as a proxy for distance) and decrease with the region's public capital stock G. de la Fuente and Vives further assume that Q_i exhibits constant returns to scale with respect to Y and C and that there is perfect private capital mobility across regions (so: $Q_i = Y_i^c G_i^\gamma S_i^{1-c-\gamma}$ where $c < 1 < c + \gamma$ so that transportation costs increase with land area). For intermediate production they assume a Cobb-Douglas production function with private capital and labour. Substitution results in

$$Q_i = A_i K_i^\alpha L_i^\beta G_i^\gamma S_i^{1-\alpha-\beta-\gamma}. \tag{5.4}$$

Even though the theoretical reasoning is different, the specification of de la Fuente and Vives is remarkably similar to Equation (5.1), suggesting observational equivalence.

Finally, the effects of government capital spending on growth will also crucially depend on the extent to which private and public capital are substitutes. The literature generally assumes that public and private capital spending are complements. However, public investment might also be a substitute for private investment. For instance, firms might build a road on their own, thereby allowing the government to withhold from this investment.

5.2.3 How to define public capital?

Most people probably think about roads and other infrastructure – such as electricity generating plants and water and sewage systems – when they refer to the public capital stock. However, it is important to point out that this does not fully correspond to the concept of public sector investment expenditure as defined in national accounts statistics, which are typically used to construct data on public capital stock. First, only spending by various government sectors is included. That implies that spending by the private sector (including public utility firms concerned with electricity generation, gas distribution, and water supply) is excluded. Secondly, public investment includes spending on various items (public buildings and swimming pools, for instance), which may not add anything to the productive capacity of an economy.

In calculating the stock of public capital on the basis of investment flow data, researchers typically use the sum of past investments, adjusted for depreciation. In applying the so-called perpetual inventory method, the researcher has to make certain assumptions about the assets' lifespan and depreciation. Furthermore, one needs an initial level for the capital stock. Especially with infrastructure these assumptions are far from trivial. There is a huge variation in the economic lifespan of different types of infrastructure; the lifespan of a railway bridge cannot be compared with the lifespan of an electricity transmission line. Usually, the initial stock is calculated by assuming that the real investments were constant at the level of the first observed investment level and that the capital stock was at its steady state at the start of the observed time series. With very low depreciation rates, the rate of convergence towards the steady-state level is very low, which requires a very long time of constant investment.

To calculate the public capital stock one needs long-term time-series data on public investment. Long-term national account time-series data on government investment spending are available for most OECD countries. However, for many developing countries the availability of long-term data is more of a problem, so that the public capital stock cannot be constructed for these countries. Therefore various studies use government investment or some physical measure of infrastructure instead of the government capital stock. A drawback of the use of government investment spending (as share of GDP) as regressor – which is a fairly common approach in studies based on cross-country growth regressions and in some vector autoregression studies – is the implicit assumption that the effects of public investment are independent of the level of the corresponding capital stock. Economic theory suggests that this assumption is dubious (Kamps, 2006). Also the use of some physical measure of infrastructure, like the number of kilometres of paved roads, has certain advantages and disadvantages (see below).

Pritchett (1996) points to some serious problems with using monetary values to calculate the stock of public capital. Prices for infrastructure capital vary widely across countries. Furthermore, the level of expenditure may say little about the efficiency in implementing the investment project. Especially if the investment project is carried out by the public sector, actual and economic costs (defined as the minimum of possible costs given available technology) may deviate. So, monetary investment in infrastructure may be a poor guide to the amount of infrastructure capital produced because government investment may be very inefficient. According to Pritchett (1996), this is probably true, in particular, in developing countries. He estimates that only slightly more than half the money invested in investment projects will have a positive impact on the public capital stock.[6] This implies that public capital stock series constructed on the basis of investment series will tend to be overvalued.

Also from a network perspective, the monetary value as obtained by the perpetual inventory method of measuring capital stock is not appropriate. In particular, the internal composition of the stock matters since the marginal productivity of one link depends on the capacity and configuration of all links in the network. Using measures of the total stock may thus allow estimating the average marginal product of, say, roads in the past, but these estimates may not be appropriate for considering the marginal product of additional roads today (Fernald, 1999).

Given these problems, many recent studies have employed some physical measure of infrastructure in analysing its impact on economic growth. Studies have used, in particular, the number of kilometres of paved roads, kilowatts of electricity generating capacity, and the number of telephones (see, for instance, Canning and Pedroni, 1999, Sanchez-Robles, 1998, and Esfahani and Ramíres, 2003).[7] As these physical measures are available for many countries for long time spans, they are ideal for estimating panel models. An advantage of using physical measures of infrastructure is that they do not rely on the concept of public investment as em-

[6] How the project is financed may affect these figures; the stronger the incentives for the government to minimise costs, the higher the contribution to the public capital stock of an investment project.

[7] Canning (1998) describes an annual database of physical infrastructure stocks for 152 countries for 1950-95. The database contains six measures: kilometres of roads, kilometres of paved roads, kilometres of railway lines, number of telephones, number of telephone main lines, and kilowatts of electricity generating capacity.

ployed in the national accounts. For instance, by whom electricity is generated does not matter. However, simple physical measures do not correct for quality. Furthermore, some of the measures do not necessarily refer to (the results of) government spending.

Initially research on the impact of public capital on economic growth focused on the United States. Only few of the earlier studies investigated the productivity of government capital for a group of OECD countries (see, for instance, Ford and Poret, 1991 and Evans and Karras, 1994). These authors drew their data from the OECD that assembled capital stock series for 12 countries over the period 1970–1996, provided directly by the national authorities. However, these data were not internationally comparable because estimation methods differed widely across countries. This was one of the reasons why the OECD suspended the publication of the capital stock series after 1997. Recently, Kamps (2006) has provided internationally comparable annual capital stock estimates for 22 OECD countries for the period 1960–2001.

Whereas Aschauer (1989) and many subsequent studies employed national data for the United States, other studies used regional data again with mixed findings (see Sturm et al., 1998). For the US, data at the state level are only available after 1970. Also for some European countries (Spain, France, Germany, and Italy) regional public capital stock data are available. Using regional data increases data variation, which may make the estimates more reliable.

To summarise, this section has set out the main research questions addressed by the literature on the relationship between public capital and growth, explained the meaning of public capital and its link to infrastructure, and sketched theoretical insights about the role of public capital for economic growth. The following sections elaborate on alternative empirical research strategies used to learn more about the role of public capital for economic growth.

5.3 Production function approach

Let us start with a description of the theoretical framework underlying the empirical studies that follow the production-function approach. In this type of analysis, the production function as given in equation (5.1) is generally written as an aggregated Cobb-Douglas production function in which the public capital stock (or the monetary value of the stock of infrastructure),G_t, is added as an additional input factor,

$$Q_t = A_t K_t^{\alpha} L_t^{\beta} G_t^{\gamma}. \tag{5.5}$$

Writing Equation (5.5) in per capita terms, taking the natural logarithm, and assuming constant returns to scale across all inputs ($\alpha + \beta + \gamma = 1$), gives

$$\ln \frac{Q_t}{L_t} = \ln A_t + \beta \ln \frac{K_t}{L_t} + \gamma \ln \frac{G_t}{L_t}. \tag{5.6}$$

The parameter γ gives the elasticity of infrastructure. To assess γ, a straightforward procedure is to estimate the production function in log-level or, alternatively, in first-difference or growth. This is indeed common practice in the initial attempts at measuring the role of infrastructure. Aschauer (1989) introduces a constant and a trend variable as a proxy for $\ln A_t$. The capacity utilization rate is added to control for the influence of the business cycle. Many subsequent papers have used this or a similar specification.[8] A drawback of the estimated production functions is that labour and capital are exogenous; it is implicitly assumed that both factors are paid according to their marginal productivity. Some studies have used a translog function, which is more general than the Cobb-Douglas function (e.g. Canning and Bennathan, 2000, Albala-Bertrand and Mamatzakis, 2004, Everaert and Heylen, 2004, and Charlot and Schmitt, 1999).

A major problem in estimating a production function is the potential for reverse causation. If capital investments ($I_t = \Delta K_t$) depend on income (for example, through a savings function S_t) we can write

$$\Delta K_t = sY_t - \delta K_t, \tag{5.7}$$

[8] Various authors have taken issue with the specification of Aschauer's model. Tatom (1991), for instance, uses another specification with energy prices included and capacity utilization entered multiplicatively to both the private and public capital stock and finds little evidence that the public capital stock raises productivity. However, Duggal et al. (1999) criticize Tatom's approach arguing that the relative price of energy is a market cost factor that would be included in the firm's cost function and therefore also in the factor input demand functions.

where Y_t is total income and δ is the depreciation rate. This gives the steady state relationship

$$K_t = \frac{sY_t}{\delta}. \tag{5.8}$$

This implies a feedback from income to the capital stock, making it difficult to identify the results of regressions such as equation (5.6) as a production function relationship. There is also a potential feedback from income to a demand for infrastructure. Dealing with this problem has been at the heart of the controversy over the infrastructure-growth relationship.

Various approaches have been followed in the literature to deal with the problem of causality. One is to derive an appropriate test in such a way that it is clear how the causality runs. Other approaches that have been followed are: estimating panel models, estimating simultaneous equation models, and using instrumental variables.

Fernald (1999) is a good example of the first approach. Using data for 29 sectors in the US economy for the years 1953-89, he finds that changes in road growth are associated with larger changes in productivity growth in industries that are more vehicle intensive. Fernald argues that if roads were endogenous, one would not expect any particular relationship between an industry's vehicle intensity and its relative productivity performance when road growth changes. According to Fernald, his results suggest that the massive road building in the US of the 1950s and 1960s offered a one-time boast to the level of productivity. His results have important policy implications: building an interstate highway network may be very productive, but building a second network may not.

Another highly relevant study that belongs to the first approach is Canning and Pedroni (1999). They derive a reduced form of a model in which public and private capital are financed out of available savings so that there is a growth-maximising level of public capital. The nature of the long-run relationship and the short-run dynamics may vary across countries. Since they find that in each country the physical stock of infrastructure and per capita income are individually non-stationary but cointegrated, they can represent the series in the form of a dynamic error-correction model. By testing restrictions in this model, they can decide on the direction of causality. It appears that causality runs in both directions. For balanced panels of different countries they find that, on average, telephones and paved roads are supplied at around the growth-maximising level, but some countries have too few, others too many. Canning and Pedroni also find that long-run effects of investment in electricity generating capacity are positive in many countries, with negative effects being found in only a few.

Canning and Bennathan (2000) argue that the causality problem may be solved by using a panel data approach. If the cointegrating Equation (5.4) in a panel setting is a homogeneous relationship, while Equation (5.5) differs across countries, pooling the data across countries allows identifying the long-run production-function relationship. For two infrastructure stock variables (electricity generating capacity and the length of paved roads) they find higher rates of returns than for other types of capital, although there is some heterogeneity in their sample.

The most intuitive way to solve the causality problem is to develop a simultaneous-equations model, consisting of two equations. The first equation links production to public capital, the second equation links public capital to production. The main question is the functional form for the second equation. Demetriades and Mamuneas (2000) estimate a system of equations that is derived from an intertemporal profit maximisation framework.[9] The estimates refer to a pooled model for 12 OECD countries over 1972-91. In the short run, the output effect of public capital varies from 0.36 percent in the UK to 2.06 percent in Norway. Also for the intermediate to long run, Demetriades and Mamuneas find diverging rates of return across countries. In their theoretical model, producers take at each point in time the publicly provided inputs as given and maximise the present value of future profits to determine their output, variable inputs, and quasi-fixed factor demands. In the first stage, firms decide on the optimal output and variable input demands, conditional on the private and public capital stocks. In the second stage, firms choose the optimal sequence of capital inputs. The authors claim that 'by taking into account the optimising behaviour of firms we avoid the simultaneity problem typical of the production-function approach' (pp. 688-89). Although this may be true for the private capital stock, it is not true for the public capital stock, which is simply assumed to be exogenous.

A better attempt to estimate a simultaneous-equations model is the cross-country growth study by Esfahani and Ramíres (2003), who develop a structural growth model that helps discern the reciprocal effects of infrastructure and the rest of the economy. The model specifies the ways in which country characteristics and policies enter the infrastructure GDP interactions and lead to heterogeneity of outcomes across situations. The authors distinguish heterogeneity in the steady state and in the rate of convergence towards a steady state. They derive the infrastruc-

[9] This paper belongs to the cost-function approach as discussed in the next section, but is taken up here since it is a good example of the simultaneous equations approach.

ture-output interactions as a recursive system that can be estimated simultaneously while solving the identification problem. The relationships between infrastructure and income are formulated as error-correction processes to account for the simultaneous effects of infrastructure innovations and responses to deviations from the steady state. Esfahani and Ramíres find that the contribution of infrastructure services to GDP is substantial and, in general, exceeds the cost of providing these services. The findings of Esfahani and Ramíres also shed light on the factors that shape a country's response to its infrastructure needs. An interesting result in this respect is that private ownership of infrastructure and government credibility (low risk of contract repudiation) matter for infrastructure growth, but mainly in speeding up the rate of adjustment rather than the steady-state infrastructure-income ratios

Cadot et al. (2002) also endogenise public capital formation by focusing on the decision making process of public capital spending. The policy equation explicitly models the political decision process, including lobbying from different regions. Estimating the model for 21 regions in France over the period 1985–91, Cadot et al. (2002) find an elasticity of output with respect to public capital of 0.101 for France as a whole. This is very close to their simple single equation OLS estimates of 0.099, which suggests that the simultaneous-equation bias is only moderate. Interestingly, they find evidence that roads and railways are not built to reduce traffic jams: they are built essentially to get politicians re-elected. The number of large companies in a region seems to be an important determinant in explaining the total public investment allocated to that region.

Kemmerling and Stephan (2002) also focus on the political decision-making process on public investment. Using panel data for 87 German cities for the years 1980, 1986, and 1988 in a simultaneous equations model, they estimate the relationship between infrastructure investments, investment grants, local manufacturing output, policy and lobbying variables. Their main findings are that political affiliation, measured by the coincidence of party colour between state and local government, is decisive in explaining the distribution of investment grants across cities, and that cities with 'marginal voters' neither spend more on public infrastructure nor receive more investment grants from higher-tier governments. Interestingly, they also conclude that efficiency considerations do not seem to determine the observed intergovernmental grant allocation across cities.[10]

[10] These studies point to an interesting area for future research, i.e. the explanation of differences in public investment spending across regions/countries and over time. So far, most of the theoretical literature assumes that desicion-making on public capital spending is only based on efficiency considerations; the evidence presented by Cadot et al. (2002) and Kemmerling and Stephan (2002) suggest that this assumption is highly unrealistic.

Finally, some instrumental variable approach may be used. Some of the older studies already applied the Generalized Method of Moments (GMM) estimator, which resembles an instrumental-variables procedure and therefore avoids the possible reverse-causation bias (Finn, 1993; Ai and Cassou, 1995).[11] A more recent study is Calderón and Servén (2002). They chose for the instrumental variable method since this is easier to carry out than the simultaneous-equations model. These authors estimate a per capita Cobb-Douglas production function (in log-levels) for a panel of 101 countries for the period 1960–97. To solve the causality problem they use lagged values of the explanatory variables. Because of non-stationary data, they estimate a per capita Cobb-Douglas production function in first differences. Allowing for country-specific effects by a 'within' estimator they find an average elasticity of 0.16 for different types of infrastructure.

Table 5.2 summarises key features and results of the papers reviewed above and other studies based on the production-function approach. The table is an update of Table 1 in the survey of Sturm et al. (1998) and has a similar set-up. The first column presents the study, the second to fourth columns show the aggregation level, the sample, the specification, and the way public capital has been measured, respectively, while the final column summarises the study's main findings. Although not all studies find a growth-enhancing impact of public capital, it is worth noting that – compared to the results surveyed by Sturm et al. (1998) – there is more consensus that public capital furthers economic growth. Another interesting result is that the impact as reported in recent studies is substantially less than suggested in earlier studies.

5.4 The cost function approach

A key shortcoming of the production-function approach is that it violates standard marginal productivity theory. Some studies have tried to get around the violation by focusing on the cost function and assuming that public capital is externally provided by the government as a free input. These studies specify a cost function for the private sector, with firms being assumed to aim at producing a given level of output at minimum private cost (C). Because the input prices (p_i) are exogenously determined, the instruments of the firm are the quantities of the private inputs (q_i). Alternatively, firms are assumed to maximize their profits (Π) given the output (p^Q)

[11] Finn (1993) reports a significant elasticity of the stock of public highways in the US of 0.16. The elasticity estimates of Ai and Cassou (1995) for the total stock of public capital in the US range between 0.15 and 0.26.

and input prices.

$$C\left(p_t^i, q_t^i, A_t, G_t\right) = \min \sum p_t^i q_t^i \qquad \text{s.t.} \quad Q_t = f(q_t^i, A_t, G_t) \tag{5.9}$$

$$\Pi\left(p_t^Q, p_t^i, q_t^i, A_t, G_t\right) = \max p_t^Q Q_t - \sum p_t^i q_t^i \qquad \text{s.t.} \quad Q_t = f(q_t^i, A_t, G_t) \tag{5.10}$$

When firms optimise, they take into account the environment in which they operate. One of these environmental variables is the state of technical knowledge (A). Another is the amount of public infrastructure capital available (G). The public capital stock enters the cost or profit function as an unpaid fixed input. Although the stock of infrastructure is considered externally given in the cost-function approach, each individual firm must still decide the amount it wants to use. This implies that a firm's use of the infrastructure is part of its optimisation problem, which, in turn, leads to the need of a demand function for infrastructure that must satisfy the conditions of standard marginal productivity theory (Duggal et al., 1999). To make this approach comparable with the production-function approach, various authors (e.g., Demetriades and Mamuneas, 2000) use Hotelling's Lemma to obtain supply functions, which can be used to calculate output elasticities of public capital.

Sturm et al. (1998) note that many authors estimating a cost or profit function adjust the stock of public capital by an index, such as the capacity utilisation rate, to reflect its use by the private sector. Two reasons have been advocated for adjusting the stock of public capital. First, public capital is a collective input that a firm must share with the rest of the economy. However, since most types of public capital are subject to congestion, the amount of public capital that one firm may employ will be less than the amount supplied. Moreover, the extent to which a capacity utilisation index measures congestion is dubious. Second, firms might have some control over the use of the existing public capital stock. For example, a firm may have no influence on the highways provided by the government, but can vary its use of existing highways by choosing routes. Therefore, there are significant swings in the intensity with which public capital is used.

As pointed out by Sturm et al. (1998), an important advantage of the cost-function approach is that it is less restrictive than the production-function approach. The use of a flexible functional form hardly enforces any restrictions on the production structure. For example, *a priori* restrictions placed on the substitutability of production factors, as in the production-function approach, do not apply. Apart from the focus on the direct effects in the production-function approach, public capital might also have indirect effects. Firms might adjust their demand for private inputs if public capital is a substitute or a complement to these other production factors. It seems very plausible that, for instance, a larger stock of infrastructure raises the quantity of private capital used and therefore indirectly raises production.

By using a flexible functional form, the influence of public capital through private inputs can be determined. A flexible function not only consists of many parameters that need to be estimated, but also of many second-order terms which are cross products of the inputs. These second-order variables can create multicollinearity problems. Therefore, the data set not only has to be relatively large, but must also contain enough variability so that multicollinearity can be dealt with. In other words, the most appealing feature of the cost-function approach also induces the biggest problem, i.e., the flexibility of the functional form requires considerable information to be included in the data. Most cost-function studies therefore use panel data, which combine a time dimension with either a regional dimension or a sectoral dimension.

Interestingly, whereas Sturm et al. (1998) found that the cost-function approach was used in many studies they reviewed, we have found only a few studies that rest on the cost-function approach. Table 5.3 summarizes these studies, thereby updating Table 2 of Sturm et al. (1998). We discuss two of these studies – probably the most interesting – in some detail.

Moreno et al. (2003) estimated cost functions for 12 manufacturing sectors in Spanish regions during the period 1980–91. They conclude that the average cost elasticity of public capital is only -0.022. However, there is wide variety in the effect across regions and industries; in fact, the range of values (-0.062 to 0.033) is wide enough to suggest the possibility that some regions and sectors did not benefit from public capital in some years. Costs in industries such as electric machinery, food and drinks, and textiles seem to have been most sensitive to a rise in infrastructure, while the opposite applies to sectors such as metallic and non-metallic minerals and chemistry. Among the regions with higher-than-average cost-infrastructure sensitivities are some of the least and most developed regions in Spain.

Cohen and Morrison Paul (2004) estimated a cost-function model by maximum likelihood techniques; they used data for 48 US states on prices and quantities of aggregate manufacturing output and inputs (specifically: capital, production and non-production labour, and materials) and on public highway infrastructure; their analysis covers the period 1982–96. They assume that manufacturing firms minimise short-run costs by choosing a combination of inputs for a given level of input prices, demand (output), and capacity (capital) and for given (external) technological and environmental conditions. The model also distinguishes between intra- and interstate effects of public infrastructure and accounts for interaction between the two. More specifically, for a given state, the model includes not only the public infrastructure of that state but also the infrastructure in neighbouring states. Cohen and Morrison Paul find a significant contribution of public infrastructure investment to lowering manufacturing cost - an effect enhanced by spillover effects across states. If the stock of infrastructure of a neighbouring state is not included, as in most of this literature, the elasticity is around -0.15, which is comparable to those found in other studies. However, taking spillovers into account raises the average elasticity to -0.23. So recognising spatial linkages increases the estimated effects of intrastate infrastructure investment. They also find that the intra- and interstate effects of public capital increase over time.[12]

In conclusion, the results of the cost-function studies reviewed in this section are broadly in line with those of studies using the production-function approach: public capital reduces cost, but there is much heterogeneity across regions and/or industries.

5.5 Vector autoregression models

Various recent studies use vector autoregression (VAR) models, which – unlike the production function and cost-function approaches – do not impose causal links among the variables under investigation.[13] In a VAR model, all variables are jointly determined with no a priori assumptions about causality. So VAR models allow to test whether the causal relationship assumed in other approaches is valid or whether there are feedback effects from output to public capital. Furthermore, the VAR approach allows testing for indirect effects between the variables of the model. An unrestricted VAR model can be simply estimated by standard ordinary least squares (OLS). OLS will yield consistent and asymptotically normally distributed estimates, even if variables are integrated and possibly cointegrated (Sims et al., 1990).

However, even in a simple VAR model some choices with respect to the spe-

[12] The results of Cohen and Morrison Paul are also interesting from the viewpoint of the causality issue. To test for the potential endogeneity of infrastructure, they conducted a Hausman test and found that they could not reject the null hypothesis of infrastructure exogeneity, which they argue is 'consistent with our a priori conjectures that manufacturing sector activity is unlikely to drive policy decisions across states (or even within a state), due to the small share of manufacturing production in states' overall GSP' (p. 555).

[13] This section heavily draws on Kamps (2004).

cification of the model have to be made, and all of them may affect the estimated responses and, thus, alter the conclusions about the link between public investment and economic growth. For instance, to simulate the cumulative response functions, restrictions with regard to ordering are imposed. These restrictions are rationalised by invoking assumptions of exogeneity and/or pre-determinedness, both of which can only be derived from theoretical considerations. In the absence of ordering assumptions, the non-structural VAR model can be used to characterise the data, but it cannot be used to spell out causation. Furthermore, Phillips (1998) shows that impulse responses and forecast error variance decompositions based on unrestricted VAR models are inconsistent at long-run horizons in the presence of non-stationary data. In contrast, Vector Error Correction Models (VECMs) yield consistent estimates of impulse responses and of forecast error decompositions if the number of cointegrating relationships is estimated consistently.

Table 5.4 summarizes VAR studies, updating Table 3 of Sturm et al. (1998). The following conclusions can be drawn. First, only few studies (for example Mittnik and Neumann, 2001, and Kamps, 2004) refer to a group of OECD countries; the rest focuses on one or two countries only. Second, most studies consist of a four variables VAR with output, employment, private capital, and public capital. Third, there is a wide variety of model specifications. Some studies specify VAR models in first differences, without testing for cointegration, while others explicitly test for cointegration. Some studies specify VAR models in levels, following the argument of Sims et al. (1990) that OLS estimates of VAR coefficients are consistent even if the variables are non-stationary and possibly cointegrated. Fourth, in the majority of studies the long-run response of output to public capital shock is positive.[14] However, as pointed out by Kamps (2004), most studies fail to provide any measure of uncertainty surrounding the impulse response estimates so that it is impossible to judge the statistical significance of the results. Kamps (2004) employs bootstrapping techniques to provide confidence intervals. Fifth, many VAR studies report evidence for reverse causality, i.e. feedback from output to public capital. Finally, some studies (e.g. Everaert, 2003) report that public capital has less impact on economic growth than reported by Aschauer (1989).

[14] Voss (2002) gives no conclusions regarding output effects of infrastructure as he focuses on possible crowding in effects found by Aschauer (1989). These 'crowding in' effects enforce the positive effects of public investment, but using cointegrating techniques to correct for non-stationarity in the data, Voss does not find evidence for these effects in both the US and Canada. Only Ghali (1998) finds negative effects on growth, but these can easily be explained by the very structure of the Tunisian economy where 'highly subsidized and inefficient state owned enterprises [] have often reduced the possibilities for private investment'.

5.6 Cross-section studies

Since the mid-1980s, the study of economic growth and its policy implications has vigorously re-entered the research agenda. Various studies tried to explain, theoretically and empirically, why differences in income over time and across countries did not disappear as the neoclassical models of growth predicted. The idea that emerged from this literature is that economic growth is endogenous. That is, economic growth is influenced by decisions of economic agents, and is not merely the outcome of an exogenous process. Endogenous growth theory assigns a central role to capital formation, where capital is not just confined to physical capital, but includes human capital, infrastructure and knowledge capital.

Initially, the econometric work on growth was dominated by cross-country regressions, in which growth of real per capita GDP is estimated by a catch-up variable, human capital, investment, and population factors like fertility. Some of these studies add government investment as an explanatory variable. The equations estimated in various studies can be summarised as

$$\Delta \ln \left(\frac{Y}{L}\right)_{0,T} = \alpha + \beta \left(\frac{Y}{L}\right)_{0} + \gamma \left(\frac{I^G}{L}\right)_{0,T} + \delta, \tag{5.11}$$

where $(Y/L)_{0,T}$ is the average per capita GDP over a period $[0,T]$, $(Y/L)_0$ is the initial level of real per capita GDP, and $(I^G/Y)_{0,T}$ is the average rate of public investment (as percentage of GDP) over a period $[0,T]$. The variable δ captures a set of conditional variables such as private investment (as percentage of GDP) and primary and/or secondary enrolment (as a proxy for human capital). The parameter γ measures the effect of public investment on growth and is not the same as the marginal productivity of public capital.

Unfortunately, most empirical economic growth studies do not distinguish between public and private investment, instead relying on an aggregate measure of total investment. However, the services from public investment projects are likely to differ from those of private investment projects for a number of reasons, and this suggests that an aggregate investment measure is inappropriate (Milbourne et al., 2003). Table 5.5 at the end of this chapter, which updates Table 4 in Sturm et al. (1998), provides a summary of cross-country growth models that include public investment.

Probably the first study that included public capital in an empirical growth model is Easterly and Rebelo (1993), who ran pooled regressions (using decade averages for the 1960s, 1970s and 1980s) of per capita growth on (sectoral) public investment and conditional variables (see Sturm et al. (1998) for a summary). They found that the share of public investment in transport and communication infrastructure is correlated with growth. Likewise, Gwartney et al. (2006) find a significant positive effect of public investment, although its coefficient is always smaller than that of private investment.

However, other studies using the public investment share of GDP as regressor report different results. For instance, Sanchez-Robles (1998) finds a negative growth impact of infrastructure expenditure in a sample of 76 countries. Devarajan et al. (2000) report evidence for 43 developing countries, indicating that the share of total government expenditure (consumption plus investment) has no significant effect on economic growth. However, the authors find an important composition effect of government expenditure: increases in the share of consumption expenditure have a significant positive impact on economic growth whereas increases in the share of public investment expenditure have a significant negative effect. Devarajan et al. attribute their results to the fact that excessive amounts of transport and communication expenditures in those countries make them unproductive. Pritchett (1996) suggested another explanation, arguing that public investment in developing countries is often used for unproductive projects. As a consequence, the share of public investment in GDP can be a poor measure of the actual increase in economically productive public capital.

Milbourne et al. (2003) report that for the steady-state model, there is no significant effect from public investment on the level of output per worker. Using standard ordinary least squares (OLS) methods for the transition model, they find that public investment has a significant effect on economic growth. However, when instrumental variables methods are used, the associated standard errors are much larger and the contribution of public investment is statistically insignificant.

The only study in this category that we are aware of that has used physical indicators of infrastructure instead of public investment spending is Sanchez-Robles (1998). When she includes indicators of physical units of infrastructure, she finds they are positively and significantly correlated with growth in a sample of 76 countries.

There are two important general problems in the cross-country growth regressions: one is model uncertainty and the other is outliers and parameter heterogeneity (Temple, 2000; Sturm and de Haan, 2005). Model uncertainty has been discussed extensively in the literature. The main issue here is that several models may all seem reasonable given the data, but yield different conclusions about the parameters of interest. In these circumstances, presenting only the results of the model preferred by the author can be misleading (Temple, 2000). Unfortunately, economic theory does not provide enough guidance to properly specify the empirical model. For instance, Sala-i-Martin (1997) identifies around 60 variables supposedly correlated with economic growth. The so-called extreme bound analysis (EBA) of Leamer (1983) and Levine and Renelt (1992) is therefore often used to examine how 'robust' the economic growth effect of a certain variable is. The key idea of EBA is to report an upper and lower bound for parameter estimates, thereby indicating the sensitivity to the choice of model specification. The upper and lower bounds are based on a set of regressions using different subsets of the set of explanatory variables. If the upper and lower bounds have a different sign, the relation is not robust.

The second problem – the role of outliers and parameter heterogeneity – has been largely ignored by the empirical growth literature . Although economists engaged in estimating cross-country growth models often test the residuals of their regressions for heteroskedasticity and structural change, they hardly ever test for unusual observations. Still, their data sets may frequently contain unusual observations. In particular, less developed countries tend to have a lot of measurement error in national accounts and other data. This may have affected the conclusions of cross-country growth models.

Unfortunately, none of the studies reviewed in this section takes the issues of model uncertainty and outliers and parameter heterogeneity seriously into account, which casts considerable doubt on their findings. With this somewhat sober remark we finish the review of different empirical strategies to estimate the link between public capital and economic growth, and we move on to a brief discussion of what could constitute an optimal capital stock.

5.7 Optimal capital stock

In estimating the optimal stock of public capital, the assumption on the public good character of infrastructure is crucial. For pure public goods, one could define total marginal benefits of public capital as the sum of the shadow values over all firms plus the sum of corresponding marginal benefits over all final consumers, yielding what might be called the social or total marginal benefit of public capital. Alternatively, if there is no congestion in the consumption of public goods, the total marginal benefit could be the largest benefit accruing to any one or set of consumers and producers rather than the sum over all consumers and producers. The simplest rule to determine the optimal provision of public capital is to calculate the amount of infrastructure for which social marginal benefits just equal marginal costs.

The difficulty in the empirical implementation of this rule lies in approximating the marginal costs of public capital. Sturm et al. (1998) found only a few studies that estimated the optimal amount of public capital and compared it with the actual stock of public capital. These studies use some measure for the cost of borrowing, such as the government bond yield, to approximate the marginal costs of public capital. Adopting this approach, Berndt and Hansson (2004), for instance, report excess public capital in the United States, which has declined over time, however. Alternatively, Conrad and Seitz (1994) interpret the case in which the social marginal benefit of public capital is greater than the price of private capital as a shortage of public capital, whereas the reverse indicates over-investment in public capital. These authors find that during 1961-79 the social marginal benefit of public capital in Germany was larger than the user cost of private capital, whereas in the 1980–88 period the opposite was true.

The more recent literature has taken other ways of modelling the optimal public capital stock. Canning and Pedroni (1999) develop a model in which public investment spending lowers investment in other types of capital because they all need to be financed out of savings. In this approach, there is a certain level of public capital that maximises economic growth, and if there is too much infrastructure, it diverts investment away from other productive uses to the point where income growth falls. In this setting, the effect of an increase in public investment on economic growth depends on the relative marginal productivity of private versus public capital. In other words, we need to know not only whether public capital is productive but also whether it is productive enough to boost economic growth. An interesting finding of this study is that the assumption of parameter homogeneity can clearly be rejected. In other words, there is much heterogeneity among countries with regard to the optimal level of public capital.

Aschauer (2000) has developed a non-linear theoretical relationship between public capital and economic growth in order to obtain estimates of the growth-maximising ratio of public to private capital. Permanent increases in the public capital ratio bring forth permanent increases in growth – but only if the marginal product of public capital exceeds the after-tax marginal product of private capital. Using data for 48 US states over the period 1970–90, Aschauer finds that for most of the United States the actual levels of public capital were below the growth-maximising level. Kamps (2005) is the first study to use the methodology of Aschauer (2000) in the European context to assess the gap between actual and optimal public capital stocks. The empirical results suggest that there currently is no lack of public capital in most 'old' EU countries. However, current fiscal policies imply that in the long run the public capital to GDP ratio will be significantly lower than its growth-maximizing level in 4 out of 14 EU countries considered if the government investment to GDP ratio in these countries is not raised.

5.8 Concluding comments

Our review of recent studies that examine the relationship between public capital and economic growth suggests the following main results. First, although not all studies find a growth-enhancing effect of public capital, there is more consensus in the recent literature than in the older literature as summarised by Sturm et al. (1998). Second, according to most studies, the impact is much lower than found by Aschauer (1989), which is generally considered to be the starting point of this line of research. Third, many studies report that there is heterogeneity: the effect of public investment differs across countries, regions, and sectors. This is perhaps not a surprising result. After all, the effects of new investment spending will depend on the quantity and quality of the capital stock in place. In general, the larger the stock and the better its quality, the lower will be the impact of additions to this stock. The network character of public capital, notably infrastructure, causes non-linearities. The effect of new capital will crucially depend on the extent to which investment spending aims at alleviating bottlenecks in the existing network. Some studies also suggest that the effect of public investment spending may also depend on institutional and policy factors.

In concluding, we would like to mention a few issues we believe have not been well researched. First, attempts at explaining existing differences in capital stocks are only in their infancy. Second, only a few of the enormous bulk of studies on the output effects of infrastructure base their estimates on solid theoretical models. But to understand non-linearities and heterogeneity, we must understand the channels through which infrastructure affects economic growth. After all, government roads as such do not produce anything, and to include infrastructure or public capital as a separate input in a production function neglects the usually complex links. Third, most of the literature has focused on the importance of additional public investment spending, while maintenance of the existing stock is as important, if not more important, as additions to the stock. As pointed out by the World Bank (1994), inadequate maintenance imposes large and recurrent capital costs. For instance, paved roads will deteriorate fast without regular maintenance. Likewise, insufficient maintenance of a railway system will lower its reliability, causing delays for travellers when parts of the system break down. Unfortunately, policy makers have a perverse incentive: given their higher visibility, new public investment projects are politically more attractive than economically crucial, but politically less rewarding spending on infrastructure maintenance.

Table 5.1. Government investment in 22 OECD countries as percentage of GDP, 1960-2001

Country	1960–69	1970–79	1980–89	1990–99	2000–01
Australia	3.77	3.61	2.59	2.56	2.76
Austria	5.03	5.50	3.74	2.72	1.37
Belgium	2.06	3.44	3.15	1.74	1.62
Canada	3.40	2.65	2.36	2.59	2.48
Denmark	5.15	4.42	2.07	1.74	1.86
Finland	2.82	3.40	3.34	3.11	2.49
France	4.02[1]	3.55	2.97	3.23	2.99
Germany	4.05	3.86	2.61	2.37	1.95
Greece	3.90	3.34	2.78	3.12	3.86
Iceland	4.21	4.29	3.23	3.48	3.48
Ireland	5.65	6.24	4.56	2.29	3.01
Italy	3.31	2.88	3.15	2.58	2.39
Japan	7.50	9.32	7.47	7.68	6.91
Netherlands	6.21	4.88	3.18	2.96	3.27
New Zealand	5.65[2]	6.42	5.37	3.21	3.02
Norway	3.31	4.13	3.25	3.48	3.13
Portugal	2.37	2.08	2.60	3.69	3.92
Spain	2.82	2.54	2.98	3.86	3.14
Sweden	2.72	2.65	2.15	2.63	2.19
Switzerland	2.55	3.29	2.90	3.17	2.99
United Kingdom	3.96	3.52	1.85	1.99	1.57
United States	4.51	2.99	3.14	3.37	3.41

[1] 1963–1969, [2] 1962–1969
Source: Kamps (2006)

Table 5.2. Studies using some kind of production function approach

Study	Countries	Sample	Specification	Public capital variable	Conclusion
Albala-Bertrand & Mamatzakis (2004)	Chile	1960–98	Translog PF	Infrastructure capital stock (transportation, communication, general purpose)	Infrastructure capital growth appears to reduce productivity slightly up to 1971. From 1972 onwards, the reverse seems true
Albala-Bertrand (2004)	Chile and Mexico, regions	1950-2000	Gap approach using a Leontief PF (with private and public capital as inputs)	Infrastructure capital stock (transportation, communication, general purpose)	In Chile potential output is mostly constrained by shortages of normal capital, in Mexico infrastructure is the binding factor
Batina (1999)	U.S.	1948–1993	Cobb-Douglas production function with public capital as separate factor	Various proxies for state level public capital	The productivity of public capital depends on the proxies used for private and public capital
Bonaglia et al. (2000)	Italy, regions	1970-94	Cobb-Douglas PF with public capital as separate factor	Public capital stock	Elasticity is 0.05 (insignificant) for Italy as a whole, large variation between regions
Cadot et al. (2002)	France, regions	1985-92	Cobb-Douglas PF combined with policy equation for transport infrastructure	Infrastructure capital stock (transportation)	Elasticity is 0.08
Calderón & Servén (2002)	101 countries	1960-97	Cobb-Douglas PF with different types of infrastructure as separate factor	Infrastructure capital stock (transportation, communication, general purpose)	Elasticity is 0.16
Canning (1999)	57 countries	1960-90	Cobb-Douglas PF with different types of infrastructure as separate factor	Number of telephones, electricity generating capacity and kilometres of paved roads and railways	Electricity and transportation routes have normal capitals rate of return, telephone above normal
Canning & Pedroni (1999)	Panel of countries, different length	1950-92	Tests whether infrastructure has long-run effect on growth based on dynamic error-correction model	Number of telephones, electricity generating capacity and kilometres of paved roads and railways	Evidence of long-run effects running from infrastructure to growth, but results differ across countries and type of infrastructure

table continues on next page. . .

Table 5.2. (continued)

Study	Countries	Sample	Specification	Public capital variable	Conclusion
Canning & Bennathan (2000)	62 countries	1960-90	Cobb-Douglas and translog PF with different types of infrastructure as separate factor	Number of telephones, electricity generating capacity and kilometres of paved roads and railroads	On average, only the low- and middle-income countries benefit from more infrastructure
Charlot & Schmitt (1999)	France, regions	1982-93	Cobb-Douglas and translog PF with public capital as separate factor	Public capital stock	Elasticity is 0.3 (Cobb-Douglas), 0.4 (translog), but very sensitive to region and period
Delgado Rodriguez & Álvarez Ayuso (2000)	Spain, regions	1980-95	Cobb-Douglas Productive capital stock (Factor model)	Km of roads, km of railway, no. of telephone lines lines, and so on	The results indicate that productive infrastructure encourages private investment and can be considered to be essential for economic growth.
Duggal et al. (1999)	USA, national	1960-89	PF, technology index is non-linear function of infrastructure and time trend	Public capital stock	Elasticity for infrastructure is 0.27
Everaert & Heylen (2004)	Belgian regions	1965-96	Translog PF. Using a general equilibrium model, they analyse labour market effects of public investment. As a by-product they estimate the output elasticity.	Public investments	Elasticity is 0.31
La Ferrara & Marcellino (2000)	Italy, regions	1970-94	Cobb-Douglas PF with physical capital stocks as separate input	Public capital stock	
Holtz-Eakin & Schwartz (1995)	US states	1971-86	Neo-classical growth model that separates adjustment effects from steady state effects	Infrastructure capital (transportation and communications) and public capital stock	Infrastructure has a negligible effect on output nowadays
Kamps (2006)	22 OECD countries	1960-2001	Aschauer (1989) model for individual countries and panel	Public capital stock	Elasticity is 0.22 in panel, but much higher in time-series models

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Table 5.2. (continued)

Study	Countries	Sample	Specification	Public capital variable	Conclusion
Kemmerling & Stephan (2002)	87 large German cities	1980, 1986 and 1988	Cobb-Douglas PF combined with policy equation for transport infrastructure and investment function for private capital		Rate of return on infrastructure is 16%. Political colour is important determinant for receiving grants
Ligthart (2002)	Portugal	1965-95	Cobb-Douglas PF, with and without CRS	Public capital stock	Positive and significant output effects of public capital
Seung & Kraybill (2001)	Ohio	Calibrated on 1990	Computable general equilibrium model with congestion adjusted infrastructure as third factor in Cobb-Douglas PF	Public capital stock	Welfare effects of infrastructure are non-linear
Shioji (2001)	US states and Japanese regions	US: 1963-93 & Japan: 1955-95, 5 year interval	Computable general equilibrium model with public capital in the technology term of a Cobb-Douglas PF	Public capital stock	Elasticity between 0.10 and 0.15
Stephan (2000)	W-German and French regions	Germany: 1970-95, France: 1978-92	Cobb-Douglas PF with public capital as separate factor and translog PF	Infrastructure capital stock (transportation)	Cobb Douglas gives elasticity of 0.11. Translog specification runs into multicolinearity problems.
Stephan (2003)	West-German regions (11)	1970-96	Cobb-Douglas PF with public capital as separate factor	Infrastructure capital (transportation and communications)	Elasticity between 0.38 (first differences) and 0.65 (loglevels)
Vijverberg et al. (1997)	US, time series	1958-89	Cobb-Douglas and semi-translog	Net stock of non-military equipment in the hands of the government	

Table 5.3. Studies using some kind of cost/profit function approach

Study	Countries	Sample	Specification	Public capital variable	Conclusion
Bonaglia et al. (2000)	Italy, regions	1970-94	Cobb-Douglass variable cost function	Public capital stock	Inconclusive, no good measure of the social user cost of public capital available
Boscá et al. (2000)	Spain, regions	1980-93	Generalized Leontief	Infrastructure capital stock (transportation, communication, general purpose)	Elasticity is 0.08
Canaleta et al. (2002)	Spain, regions	1964-91	Flexible cost function	Infrastructure capital (transportation) and public capital stock	Public capital reduces private production costs, public and private capital factors are complementary. Spillovers exist in Spain
Cohen & Morrison Paul (2004)	US, States	1982-96	Generalized Leontief	Public highway stock constructed using perpetual inventory method	Infrastructure investment reduces own costs and increases cost reducing effect of adjacent states
Demetriades & Mamuneas (2000)	12 OECD countries	1972-91	Quadratic cost function	Public capital stock	Output elasticity varies from 2.06 (Norway) to 0.36 (UK)
La Ferrara & Marcellino (2000)	Italy, regions	1970-94	Cobb-Douglas and generalized Leontief with physical capital stocks as separate input	Public capital stock	
Mamatzakis (1999a)	Two digit Greek industries (20)	1959-90	Translog cost function	Infrastructure capital stock (transportation, communication)	Cost saving impact of public infrastructure ranges from 0.02% in food manufacturing to 0.78% in wood and cork
Moreno et al. (2003)	Spain, regions and sectors	1980-91	Translog cost function	Infrastructure capital stock (transportation, communication, general purpose)	Public and private investments increase efficiency
Vijverberg et al. (1997)	US	1958-89	Translog cost and profit functions	Net stock of non-military equipment in the hands of the government	

Table 5.4. Summary of VAR/VECM studies

Study	Countries	Sample[1]	Specification	Variables[2]	Public capital variable	Conclusion
Agénor et al. (2005)	Egypt, Jordan, Tunesia	1965–2002(A)	VAR	I^G/Y, I^K/Y, growth Y, private sector credit/Y, growth r, G	Public capital stocks	There is a weak effect, short-lived and usually insignificant effect of public capital on private capital
Batina (1998)	US	1948–93 (A)	VAR and VECM	Y, L, different types of G and K	Public capital stock	Public capital has long-lasting effects on output and vice-versa
Belloc & Vertova (2006)	7 highly indebted countries	1970–99, some sub–sample (A)	VECM	Y, I^G, I^K	Public investment	In 6 of the 7 cases there is a positive effect of public investment on output
Crowder & Himarios (1997)	US	1947–89 (A)	VECM	Y, K, G, L, E	Public capital stock	Public capital is at the margin slightly more productive or as productive as private capital
Everaert (2003)	Belgian regions	1953–96 (A)	VECM	Y, K, G	Public capital stock	Output elasticity of public capital is 0.14, which is only a fraction (0.4) of output elasticity of private capital
Flores de Frutos et al. (1998)	Spain	1964–92 (A)	VARMA (first dif's log levels)	Y,K,G,L	Infrastructure capital (transport and communications)	Transitory increase of public capital growth implies a permanent increase of output, private capital and employment
Ghali (1998)	Tunesia	1963–93	VECM	Y, I^G, I^K	Public investment	Public investment has a negative effect on growth
Kamps (2004)	22 OECD countries	1960–2001 (A)	VECM	Y, K, G, L	Public capital stock	For majority of countries there is a positive and significant effect on growth
Ligthart (2002)	Portugal	1965–95 (A)	VAR, log levels	Y, K, G, L	Public capital stock	Positive output effects of public capital

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Table 5.4. (continued)

Study	Countries	Sample	Specification	Variables	Public capital variable	Conclusion
Mamatzakis (1999b)	Greece	1959–93	VECM	Y, K, G, L	Public capital stock	Positive effect of public capital on productivity, no reverse effect
Mittnik & Neumann (2001)	Canada, France, UK, Japan, Netherlands, and Germany	Different periods per country (Q)	VECM	Y, I^G, C^G, I^K	Public investment	Weak positive output effect of infrastructure, public investment induces private investment; no reverse causation from GDP to public capital
Pereira (2000)	US	1956–97 (A)	VAR, first dif's log levels	Y, I^G, I^P, L	Public investment (different types)	Positive effect through crowding in of private investment
Pereira (2001)	US	1956–97 (A)	VAR, first dif's log levels	Y, I^G, I^P, L	Public investment (different types)	All types of public investment are productive, but core infrastructure displays the highest rate of return
Pereira & Andraz (2003)	US (sectoral and national)	1956–97 (A)	VAR, first dif's log levels	Y, I^G, I^P, L	Public investment	Public investment positively affects private investment, employment and output
Pereira & Flores de Frutos (1999)	US	1956–89 (A)	VAR, first dif's log levels	Y, K, G, L	Public capital stock	Public capital is productive, but substantially less than suggested by Aschauer (1989)
Pereira & Roca-Sagales (1999)	Spain (regional and national)	1970–89 (A)	VAR, first dif's log levels	Y, K, G, L	Infrastructure capital (transport and communications)	Positive and significant long-run effects on output, employment and private capital
Pereira & Roca-Sagales (2001)	Spain (sectoral and national)	1970–93 (A)	VAR, first dif's log levels	Y, K, G, L	Infrastructure capital (transport and communications)	Positive and significant long-run effects on output, employment and private capital
Pereira & Roca-Sagales (2003)	Spain (regional and national)	1970–95 (A)	VAR, first dif's log levels	Y, K, G, L	Infrastructure capital (transport and communications)	Positive and significant long-run effects on output, employment and private capital

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Table 5.4. (continued)

Study	Countries	Sample	Specification	Variables	Public capital variable	Conclusion
Pina & St. Aubyn (2005)	Portugal	1960–2001 (A)	VAR, first dif's log levels	Y, K, G, H	Public capital stock	Without feedback effects, the rates of return on public investment are higher then on private investment
(Pina and St. Aubyn, 2006)	US	1956–2001 (A)	VAR, first dif's log levels	Y, K, G, L	Public capital stock	Taking crowding out of private investment into account lowers rate of return on public investment from 7.3% to 4%
Sturm et al. (1999)	Netherlands	1853–1913	VAR, levels	Y, I^G, I^K	Public investment	Positive and significant short-run effect; no long-run effect
Voss (2002)	US and Canada	US: 1947–88 (Q) Canada: 1947–96 (Q)	VAR, 11 lags first dif's	$Y, p^G, p^K, r, I^G/Q, I^K/Q$	Public investment as share of output	Public investment tends to crowd out private investment

[1] A = Annual, Q = Quarterly.

[2] Y = real GDP (output), K = private capital stock, G = public capital stock, L = number of employed persons, p^G = relative price of public investment, p^K = relative price of private investment, r = real interest rate, I^G = public investment, I^K = private investment, C^G = public consumption, E = energy price.

Table 5.5. Summary of cross section studies

Study	Countries	Sample	Public capital variable	Conclusion
Devarajan et al. (2000)	43 LDCs		Transportation and communication expenditure	Significant negative effect
Esfahani & Ramíres (2003)	75 countries	1965–95 (three decades)	Growth rates of telephones and power production per capita	Significant positive impact
Gwartney et al. (2006)	86 countries of which 66 LDCs	1980–2000	Public investment/GDP	Significant positive effect, but coefficient is less than coefficient of private investment
Milbourne et al. (2003)	74 countries	1960–85	Public investment as share of GDP, total and disaggregated into 6 sectors	Not significantly different from zero in steady state model; in transition model with IV also not significantly different from zero
Miller & Tsoukis (2001)	Varying per decade from 30 to 91	1960–89 (three decades)	Public investment/GDP	Government investment appears to be an important factor in growth
Sanchez-Robles (1998)	57 countries and 19 Latin American countries	1970–85 and 1980–92 (large sample); 1970–85 (small sample)	Index of physical units of infrastructure at beginning of the sample	Significant positive effect