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An Empirical Approach to Public Capital, Infrastructure, and Economic Activity: A Critical Review

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ABSTRACT

The economic literature recognises the importance of public capital -commonly associated to infrastructure- as an additional factor in the production process, along with labour and private capital. This paper presents a critical review of the latest research assessing the link between public capital and national income from different perspectives. It is shown that empirical studies have been relatively successful in evidencing the importance of public capital on economic activity. However, more research in this field is needed, as there are still important caveats to be looked into.

Key words: public capital, infrastructure, national income, national product

JEL codes: E22, E23, H54

1 INTRODUCTION

The economic literature recognises the importance of public capital -commonly associated to infrastructure- as an additional factor in the production process, along with labour and private capital. From this perspective, public capital has a direct contribution to the economy, since it increases its productive capacity. Public capital makes it possible to provide public services that are necessary in the production process. According to public finance theory, the rationality for public provision of some services lies in the fact that they are partially or purely public goods (*i.e.* they are non-rival and non-excludable goods at least up to a certain degree). Another reason for public provision of services is the presence of economies of scale in production. In that case, a central and coordinated provision of a service might be more efficient than a decentralised and uncoordinated supply by private agents (Aschauer 1989).

Despite the importance of the problem, there has been a general lack of interest in research on the topic, which is surprising. It was not until the late 1980s when the first studies using formal analysis to measure the effect of public capital on economic activity started to be conducted. This paper reviews a series of works that tackle this topic, starting with the seminal paper by David Aschauer (1989), which started a new wave of research in public capital.

This review is organised as follows: the second section presents some theoretical foundations about the importance of public capital into economic activity from a neoclassical growth theory point of view. The third section discusses early empirical studies that attempt to estimate the aggregate production function. The fourth section discusses an alternative approach, consisting of the empirical estimation of cost-functions. Section five presents two examples in recent literature that tackle the analysis of public capital from an equilibrium location perspective. Section six discusses a vector autoregressive approach. Finally, Section seven concludes with some final remarks.

2 PUBLIC CAPITAL IN THE NEOCLASSICAL FRAMEWORK

From a macroeconomic perspective, the link between public capital and economic activity can be modelled within a standard neoclassical framework, considering public capital stock as an argument in the production function as shown in Equation 1, where Y represents aggregate production, K private capital stock, L labour, G aggregate public capital stock, and A is a technological parameter. Sub-index t gives the period of time, usually a year.

Equation 1 $$Y_t = f(K_t, L_t, G_t, A_t)$$

Depending on the functional form of the production function, public capital can have different short and long-term effects on production. In particular, under a Cobb-Douglas specification constant returns to scale implies that neither private nor public capital generates long run per capita growth. In this case, the effects of a variation in public capital are given by the partial derivative of Y with respect to G. Under the assumption that public capital is productive, this derivate is positive, and its effect in the long run is reflected in an increased production level, with negligible effects on economic growth.

However, in theory public capital may also have effects on economic growth, as long as it leads to a more efficient use of inputs. Another possibility is that public capital -in particular, transport infrastructure- may have a positive effect on the technological growth process, facilitating the transit and access to technological innovations. In that case, an expansion of public capital may affect the technological parameter A in Equation 1 positively. Following this case, public capital can be interpreted as part of the technological constraints of factor productivity (Dugall *et al.* 1999).

From an empirical perspective, it is necessary to propose a succinct definition of public capital in order to carry out any econometric assessment. Most of the empirical studies presented in this review use a broad definition of public capital, which includes public capital stock of roads (motorways and streets), water and sewer systems, schools, hospitals, conservation, and development structures. A seminal paper, which defines the concept of public capital empirically, is that by Munell (1990), who uses data from the US Bureau of Economic Analysis' (BEA) publication *Fixed Reproducible Tangible Wealth* to build a dataset of public capital stock for the US. This dataset has commonly been used in subsequent research. Besides this broad definition of public capital, Aschauer (1989) proposes the use of the concept of core infrastructure, trying to conceptually identify those variables with the greatest effects on economic activity. Core infrastructure is often defined as the stock of streets, motorways, airports, energy facilities, mass transit, water system, and sewers.

The estimation of the value of public capital entails some methodological difficulties, since no market value for public structure and equipment is available. The BEA uses a perpetual inventory methodology to assess the value of public capital in the US. Alternative measures of public capital use time-series of government expenditure on public investment, assuming an explicit depreciation rate to public capital.

The most important problem when using a pecuniary value of public capital for studying its link with economic activity is that this methodology may not be appropriate to study spatially interconnected networks. In fact, the internal composition of the stock matters, since the marginal productivity of any link depends on the capacity and configuration of all the links in all the networks. An aggregate monetary measure of public capital fails to capture these effects, allowing only the estimation of the average marginal product of the network in the past (Fenald 1999). This problem is of particular interest since most of the public capital stock is associated with networks, such as roads, water systems, sewers, and electric grids, among others.

3 PRODUCTION FUNCTION APPROACH

3.1 Early research

David Aschauer's paper (1989) started an important debate in the economic literature about the effect of public capital on economic activity. The main motivation behind this seminal paper is to empirically test the existence of a relationship between public capital and production. The empirical strategy that the author follows consists of estimating an aggregate production function of the US economy. He defines public infrastructure as federal, state, and local capital stock of non-military equipment and structures. The paper finds that non-military public capital has positive and significant effects on aggregate output. His empirical exercise estimates the elasticity of production with respect to public capital at 0.35. Core infrastructure -defined as motorways, airports, energy facilities, and water systems- accounts for 55 percent of the effect of public capital on productivity. In addition to that, he finds evidence of a positive effect of public capital on total factor productivity and of increasing returns to scale in the production function. These results suggest that public expenditure is in fact productive when it is invested in public capital.

The empirical strategy followed by Aschauer (1989) is now a common methodology in the economic literature to the point of being known as the 'production function approach'. His results raised several questions leading to a boom in the study of the effects of public infrastructure on the economy. Although, from a theoretical point of view, few authors would question that infrastructure has impacts on production, the magnitude of the estimated effect in that paper, has been questioned. An elasticity of 0.35 implies a return rate of public infrastructure considerably higher than the associated returns to private capital. This result also implies a severe shortage of public capital in the US. Actually, the paper suggests that the reduction in infrastructure investment can be identified as the main cause of the productivity slowdown that the US experienced in the 1970s and early 1980s.

Another critique to Aschauer's study is that the aggregate correlation that he finds does not imply any causal relationship between production and infrastructure. Actually, Garcia-Mila (1996), and Karras *et al.* (1994) suggest that if these variables are non-stationary, this relationship might be reflecting only a spurious correlation. A more severe critique lies in the actual causal direction of this correlation. The issue is whether public capital increments actually cause economic growth, or whether the causality operates in the opposite direction.

3.2 Panel Data Analysis

Serious attempts to review Aschauer's (1989) work focus on the estimation of aggregate production functions at state level, such as Evans *et al.* (1994), Garcia-Mila (1996), Hotz-Eakin (1994), and Kelejian *et al.* (1997). Conceptually, these papers follow the same empirical strategy and in most cases use the same definition of public capital. The main advantage of this panel data approach, in comparison to time series, is that state level samples are large enough to produce reliable estimates. The most important problem is the lack of primary data on public capital stock at state level; hence, these studies have to use estimated figures for this variable. In general, the estimated magnitude of the effect of public capital on production tends to be considerably smaller or even negligible under this approach.

Hotz-Eakin (1994) replicates Aschauer's (1989) analysis using state level data for the 48 contiguous states, and finds results that contradict Aschauer's original estimates. The empirical results of the paper fail to show evidence of a positive relationship between public capital stock and production both at absolute levels and growth rates. This result is robust under different econometric specifications, aggregation levels of the infrastructure variable, and estimation techniques. Garcia-Mila *et al.* (1996) repeat this study using essentially the same econometric approach and dataset. The contribution of this paper is the consideration of alternative measures and desegregation levels of public capital, confirming that at state level, the effects of public capital stock are negligible on absolute production levels. This paper also performs formal tests that fail to reject the hypothesis of endogeneity of public capital.

The empirical estimates in Evans (1994) imply that public capital has negative productivity. He studies the relationship between production and public capital both at absolute levels and growth rates. The explanation he offers is linked to an oversupply of public infrastructure in the US. He argues that this is not the case for current government expenditure, since education spending has a positive effect on output. His results are based on the estimation of a state-level production function that assumes fixed state effects and autocorrelation in the error term. He suggests that the assumption of non-correlated errors in previous studies is the origin of biased estimates of the effect of public capital on production.

In Hotz-Eakin *et al.* (1995), a slightly different methodology is followed to analyse the effects of public capital on economic growth. Rather than estimating output elasticity, this paper develops a neoclassical growth model, which incorporates infrastructure capital. Using the Seemingly Unrelated Regression (SUR) technique to estimate a set of simultaneous equations, Hotz-Eakin *et al.* (1995) conclude that public capital does not have an important quantitative role in explaining growth patterns across states in the US.

The use of panel data answers some of the critiques to Aschauer's paper. However, it also raises a puzzle: under some empirical strategies, the results not only estimate smaller returns to public capital, but also contradict the idea of public capital as a productive input. Kelejian *et al.* (1997) exemplify the extension of the lack of robustness of this approach. They use data for the US 48 contiguous states to estimate under several econometric specifications, state level production functions. They conclude that the estimated elasticities are not consistent, since the estimated effect varies its sign, magnitude, and significance level depending on the chosen econometric specification and estimation technique. Moreover, it appears that the robustness problem is not related to the quality of data, since more disaggregated definitions of public capital do not generate consistent estimators.

One possible answer to this puzzle lies in a clarified reading of the results. Hotz-Eakin (1994) suggests that although state-level data and region-level data yield an ‘elasticity of private output or productivity with respect to state and local government capital’ of zero, that does not mean that ‘the large stock of public capital provides no benefits’ and it would not be sensible ‘to argue that there are not important direct impacts from the provision of road networks, bridges, water supply systems, sewerage facilities, and the host of other infrastructure services’ (Hotz-Eakin 1994, p.20). He concludes that the results from using aggregate data do not support the hypothesis of government capital spillovers being the source of variations in private productivity but there are probably instances when the productivity effects are positive (Hotz-Eakin 1994, p.20).

Following the same lines Garcia-Mila *et al.* (1996) find that there is no evidence of a positive link between public capital and private output when studied within the aggregate production function framework. Their results however are assessed within a very narrow framework (the estimation of state-level Cobb-Douglas production functions), which does not exhaust all possible methods for examining the link between public capital and productivity. Thus, they argue, they do not demonstrate that public infrastructure is unproductive, but rather, that ‘within the aggregate production function framework, there is no evidence of a positive linkage between public capital and private output' (Garcia-Mila *et al.*, 1996, p.180).

3.3 Inter-industry Analysis

The most promising strategy that can be explored to solve these puzzling results is the analysis of industry level data. If the effects of public capital were unevenly distributed across industry sectors, this approach would allow the identification of industry specific effects not captured at the aggregate level. Moreover, the analysis would give some insights about the mechanism through which public capital impacts economic activity.

Following these research lines, Fernald (1999) presents an industry level empirical analysis on the effects of public infrastructure on economic activity. He focuses on road infrastructure, arguing that production depends on transport services as an additional input factor to labour and private capital. In his model, he proposes that transport services depend upon the flow of services provided by the aggregate stock of public roads, as well as the stock of vehicles of the industry. This theoretical framework presents an interesting feature that can be applied to the study of public capital on economic activity. In particular, it implies that positive variations in road stock should be associated with more-than-proportional changes in productivity growth of vehicle-intensive industries. According to the model, if roads have neutral effects on productivity, changes in road infrastructure should not imply any particular relationship between vehicle intensity and relative productivity performance.

The empirical estimation of Fernald's (1999) model reveals a positive output elasticity with respect to road stock of 0.35, quite similar to Aschauer's (1989) original estimate. However, the return rate that this elasticity implies is implausible, raising again the original critique to

Aschauer's work on the magnitude of this effect. On the other hand, the paper goes further and analyses the stability of the estimated elasticity, finding that although the extensive road investment of the 1950s and 1960s had a very high marginal productivity, the productivity of roads is statistically significantly smaller after 1973. Quantitatively, the paper suggests that between 1953 and 1973, the average contribution of road infrastructure to GDP was 1.4 percent per year, dropping to 0.4 percent after 1973.

The empirical analysis also makes it clear that the estimated effect of road infrastructure on productivity is smaller in the non vehicle-intensive industries, pointing out the direct causality of this effect. The author argues that the construction of the interstate motorway system between the late 1950s and early 1970s substantially boosted US productivity. However, these findings should not be read in the sense that similar levels of investment in road infrastructure would have the same marginal returns today. In plain words, he concludes that it is unlikely that the high returns of the interstate motorway system could be replicated by building a second network.

An interesting implication of Fernald (1999) is that the traditional Cobb-Douglas production function specification might not be the most accurate way to model the actual behaviour of public capital. If marginal productivity of public capital presents extra normal returns at low levels of accumulation and diminishing returns at higher levels, it makes sense to model public capital using a standard neoclassical S-shape production function. In Duggal *et al.* (1999), time-series data for the US is successfully fitted using this specification. In this paper, the authors find that at the 1999 levels of private capital stock and employment, the elasticity of infrastructure with respect to output was 0.27. This effect is comparable to that found by Aschauer (1989) when he separates out the effect of core infrastructure. The fitted model suggests that at the 1999 level of infrastructure and capital, the US economy was close to a production plateau with respect to labour input.

An attractive feature of the paper by Duggal *et al.* (1999) is that it models public capital explicitly as part of the constraining technological parameter A in equation (1) - rather than as a discretionary factor. This specification allows identifying the existence of positive non-linear effects of the other productive factors on the growth rate of output. Indeed, the model shows that infrastructure increases as it interacts with higher levels of technological innovations.

3.4 Convergence Analysis

An interesting extension of the production function approach is found in Shioji (2001). Based on an open economy growth model, the paper derives an empirical application that allows estimating the parameters of a production function. The peculiarity of this approach is that it assumes that the economy is out of its long-run equilibrium. It also allows analysing the dynamics of the effect of public capital, and determining the convergence rate of the economy, conditional on infrastructure stock. This methodology is commonly referred to in the economic literature as the convergence approach. In this paper, it is applied to the analysis of US states data and Japanese prefectures.

The estimates in in Shioji (2001) evince that the effects of public infrastructure in the US and Japan are similar. The empirical analysis supports the hypothesis of convergence across regions for both Japan and the US. However, the convergence rate for the US is higher, possibly corroborating the presence of larger idiosyncratic differences across states. The long run equilibrium elasticity of infrastructure is estimated to be between 0.09 and 0.143 for the US, and 0.10 and 0.169 for Japan. These values are considerably lower than the short run elasticities estimated in previous literature, suggesting that the contribution of public capital to economic growth is small, but not negligible.

The estimated marginal product of infrastructure is larger than that of private capital in both countries, suggesting a shortage of public investment in both countries; however, a growth accounting exercise proves that the contribution of public infrastructure in the post-war period has been modest.

3.5 Public Infrastructure and Spillovers

From a theoretical point of view, the expansion of public capital stock in one region can cause spillover effects in neighbouring regions. The direction and magnitude of these effects in general depend on the mobility of input factors. Under assumptions of perfect mobility of production factors, a positive variation of public infrastructure in any location increases the marginal product of private input factors -labour and capital- in all regions. This increment is reflected in higher wages and higher private capital return rates, as well as in labour and capital migration to the region with more public capital.

On the other hand, under the assumption of imperfect mobility of production factors, an unbalanced expansion of public capital investment across regions can originate a worsening in the payment of the non-mobile factor in the region with less public capital stock. At local level, this effect can be interpreted as negative spillovers of public capital. An interesting extension of this argument is that the effect of an expansion of public capital at aggregate levels is ambiguous, since it depends on the relative magnitude of the negative spillover, and the relative size of the local economies that are affected. In Boarnet (1998) these arguments are formalised in a two-city location model.

Boarnet (1996) presents an empirical extension of the two-city location model to analyse the spillover effects of public capital at local level. Using disaggregated information at county level for California, the author estimates a production function and finds that public infrastructure has a positive and significant effect on output. Due to the availability of data, the author narrows his investigation, to a definition of public infrastructure that only includes street and highway capital in urban areas. Depending on the econometric methodology, this value is estimated to be between 0.16 and 0.22, considerably smaller than the estimates obtained with national aggregate data. The paper finds evidence of negative spillover effects: under different specifications, public investment in infrastructure in neighbouring counties appears to have a negative and significant impact. The implications at aggregate level are ambiguous: as long as the direct positive effect of public capital exceeds its negative spillovers, the aggregate value of infrastructure might be positive.

Boarnet (1996) assumes that spillover effects can only be transmitted across geographically contiguous locations. In an extension of this paper -Boarnet (1998) - the author considers alternative transmission mechanisms recognising that it is more likely to find spillover effects in locations with similar industry and economic features. In this paper, the author extends the results of his first study, finding that public infrastructure negative spillovers are stronger across locations with similar urbanisation level. As in Boarnet (1996), the paper finds evidence of positive direct effects of infrastructure capital; however, they are smaller than in earlier literature. Finally, the paper suggests that the most important gains of public infrastructure are found at local level, and that these gains have important distribution effects across locations.

3.6 Assessment

The production-function approach analysis started in the late 1980s with the seminal paper by Aschauer (1989). The paper highlights the importance of public capital on economic activity. Early estimates of the effects of public capital on economic activity seem to overstate the magnitude of the effect. Moreover, the econometric methodology that they use is subject to severe critics. Studies based upon state level information, tends to generate smaller estimates, and solve some of the econometric problems found in the earlier literature. However, in general they fail to estimate robust results in the sense that they are significantly sensitive to the econometric specification and estimation technique.

Recent work on this topic has incorporated a richer structure, analysing specific effects across industry sectors and their interaction, spillover impacts at local level, and the implications of convergence in growth rates. These studies exhibit complex features of this topic often underestimated in the early literature. The central issue of the production function approach is that it imposes a minimal structure on the data. If sufficient structure is not imposed, the estimated parameters of the underlying production function structure are likely to be biased and will not be robust. The main problem from a conceptual point of view is that the production function is viewed as a purely technological relationship and firms' behaviour is not considered explicitly. A more comprehensive approach should consider marginal productivity conditions as well as the production function, independently of whether the subject of analysis is national, regional, or local level aggregate data (Nadiri and Mamuneas 1998).

4 COST FUNCTION APPROACH

4.1 Theoretical Framework

Despite providing useful information on the link between public capital and production, the production function approach is unable to capture behavioural responses of firms to variations in public capital (Nadiri and Mamuneas 1998). In particular, most of the early literature does not take advantage of the extensive framework for the analysis of firm behaviour, technology, and performance provided in the cost-function based applied production-theory literature (Morrison *et al.* 1996).

A cost function approach allows to estimate empirically the direct effect of public capital on firm costs, as well as numerous side effects such as the firm's demand for private factors, the effect of public capital on the production structure and performance of firms, as well as its marginal return rate. The basic assumption is that firms minimise costs subject to technological constraints given by a production function, and face exogenous prices of output and inputs. Firm theory indicates that the behaviour of such firms can be characterised by a cost-function whose arguments are input prices, *w*, production, *Y*, and a technological parameter, *A*. As long as public capital is productive –*i.e.* it is an argument of the production function- and publicly provided –*i.e.* it is not a decision variable of firms' cost minimisation problem-, the cost function also depends on this variable.

Equation 2 $$C_t = C(w_t, Y_t, A_t, G_t)$$

The empirical implementation of equation (2) is not straightforward. First, a functional form must be assumed for *C*. Although a generalised Leontief function is a flexible specification that accommodates a full range of substitution effects, there are examples in the literature where other functional specifications such as Cobb-Douglas or translog cost functions have been used. In order to estimate the relevant elasticities and parameters, along with the empirical version of equation (2), it is necessary to estimate simultaneously private factor demand and a short-run pricing equation to incorporate profit maximisation behaviour (Morrison *et al.* 1996). This econometric strategy has become a common procedure in the economic literature.

An interesting feature of this theoretical framework is that it can decompose the effect of public capital on productivity into two effects. The first one is a direct effect, consequence of the positive marginal product of public capital, which decreases private sector production costs. The second one is an indirect effect due to the existence of complementary effects between public and private capital. If private and public capitals are complements in production, a positive variation in public capital raises the marginal productivity of private capital. At a given rental price of capital, private capital formation increases, increasing private sector output. A similar effect takes place with employment and other input factors depending on whether they are substitute or complements with public capital. This theoretical framework allows testing for those complementary and substitute relationships, hence allowing the nature of the total impact of public capital on productivity to be decomposed (Nadiri and Mamuneas 1998).

4.2 Empirical Research

Morrison *et al.* (1996) use data for the 48 contiguous US states to investigate the links between public capital and production. They estimate a cost-function for the manufacturing sector as well as firms' demands for input factors, and the short-run pricing rule. The paper assumes a generalised Leontief specification for the cost function. They aggregate production factors in four main categories: production-related labour, non production-related labour, energy inputs, and private capital; a classification followed by numerous studies. The authors estimate simultaneously all the equations of the econometric specification using SUR methodology. Their public capital definition only considers core infrastructure, defined for this purpose as motorways, water systems, and sewers.

This paper finds that returns to infrastructure investment are significant. Public infrastructure has a direct impact on productivity growth, due to a direct cost-saving effect. This impact ranges between 0.19 and 0.62 depending on the region. Nevertheless, the indirect production expansion effect appears to have a negative impact on productivity. This suggests that sluggish productivity growth may be attributed partly to a shortfall of infrastructure investment relative to output growth.

Estimated shadow values of public capital range between 0.05 and 0.34 depending on the region and the year, usually exceeding its social cost; however, this result is not robust under different methodologies. The author finds important variations at regional level. Moreover, the positive input cost saving benefit to manufacturing firm from infrastructure investment declines in all US regions from 1970 onward.

Nadiri and Mamuneas (1998) conduct a similar study extending the scope of the analysis to all industry sectors in the US. The paper uses time-series data for 35 industries in the US to estimate a standard cost-function. They find that the impact of highway infrastructure on cost reductions is relatively large in the agriculture, food, transport, trade, construction, and other services industry sectors. In most manufacturing industries, cost elasticises range between 0.04 and 0.05 in absolute value.

They also find a positive output effect of infrastructure; however, they conclude that higher total production costs associated with output expansion are financed almost entirely by cost saving productivity gains. Their results imply that the marginal benefits of motorways capital are positive in all but three industries. For most industries, particularly manufacturing, the marginal benefit of a $1 increase in highway capital ranges between 0.2 and 0.6. This assessment does not consider congestion effects.

Nadiri and Mamuneas (1998) essentially show that motorway infrastructure has a positive contribution to productivity growth in all industries. At aggregate level highway capital accounts for about 50 per cent of total factor productivity growth over the period of study, 1947 to 1991. Moreover, the estimated elasticities imply that the return rate of public infrastructure is equal to the return rate of private capital; however, this does not consider gains to consumers. One problem is that these results are not stable through time, implying that the economic impact of highway capital on producer's cost has declined since the 1980s. Finally, the paper concludes that road infrastructure has positive effects on all factors demands but these effects are of different magnitudes.

4.3 Geographic spillovers

Cohen *et al.* (2003b) present an extension of the cost-function approach that explicitly incorporates geographical spillovers of public infrastructure. They weigh the spillover effect that a state *i* has on a neighbour state *j* using the share of the value of goods shipped between them in the total value of goods shipped from state *i* to all its neighbours. They also assume a spatial auto-correlated structure in the error terms to incorporate the possibility of stochastic geographical spillovers.

They find a positive and significant effect of infrastructure on productivity, which appears to increase over time and is augmented by inter-state spillover effects on costs. The estimated cost elasticity is 0.15 in absolute value. Spatial spillovers complement the cost-saving impacts of public infrastructure investment. The results imply that most of this cost-saving effect is likely to be associated with transport costs. Finally, the results show that public capital is a substitute production factor with respect to private capital, intermediate inputs, and non-productive labour; however, productive labour is a complement input. There is no evidence of any effect on factor demand derived from infrastructure spillovers. This result suggests that public capital investment depresses rather than stimulates private capital investment under a spatial autocorrelation framework.

Cohen *et al.* (2003a) analyse the effects of airport infrastructure on productivity. They consider interstate geographical spillovers as well as spatial autocorrelation, finding that the cost elasticity with respect to airport infrastructure stock is 0.11. The paper finds evidence of positive interstate spillovers.

4.4 Public Infrastructure and Research and Development

Nadiri and Mamuneas (1994) use a cost-function framework to study the effects of public infrastructure and Research and Development (R&D) on the cost structure of US manufacturing industries. The paper follows the cost-function approach, considering a broader definition of public capital, which considers public infrastructure and publicly financed R&D.

The results of this paper suggest that there are significant productive effects from public infrastructure and publicly financed R&D. Infrastructure has a direct cost reduction effect that ranges from zero to 0.21 depending on the industry. The magnitudes of the cost elasticities for each industry are smaller than those reported in previous studies. There are strong differences in the cost structures across industries, and because of that, in the effects on the cost structures. The paper shows that public infrastructure and publicly financed R&D induce productivity growth. The results suggest than an increase in infrastructure capital service leads to a decline in demand for labour and capital in each industry, and to an increase in the demand for intermediate inputs in most of the analysed industries.

4.5 Assessment

The empirical approach of the cost-function studies presented in this section suggests that public capital has a positive effect on cost reductions and hence economic growth. However, the estimated effect appears to be considerably lower than that estimated under the production function approach. Extensions of this approach explicitly capture spillover effects as well as time and spatial autocorrelations, with no major changes in the basic results: public infrastructure still has important effects on firms' behaviour, and this is reflected on variations in factor demands.

One important implication of these papers is that public capital has distributive effects on the composition and productivity of firms across regions, and industry activities.

5 LOCATION EQUILIBRIUM MODELS

The conceptual difference between the aggregate production function and the cost-function approaches presented in sections 2 and 3 is that they are based on contrasting theories of which variables are exogenous to firms in the production process. Under the aggregate production function approach, the implicit assumption is that productive factors are exogenously determined, and firms take their decisions based on the availability of these factors. Under this approach, the idea is to assess whether positive variations of public capital stock increase production.

On the other hand, the cost-function approach implicitly assumes that input prices, not quantities, are exogenous (Haughwout 2002). Thus, given a price vector and a public capital stock, firms take optimal decisions on the quantity of private input factors they demand. Public capital can be analysed from different perspectives: its impact on productivity, and its impact on cost structures. However, this framework, extensively used in the analysis of individual competitive firms, may not be satisfactory for describing production behaviour at large regional levels of aggregation. Regions such as US states have complex factor markets in which perfect competition assumptions are likely to fail (Haughwout 2002).

Recent literature tackles this problem proposing a new microeconomic approach to the topic. The proposal consists of estimating an empirical version of the Roback spatial location equilibrium model. This model assumes two productive factors -labour as a mobile factor, and land as a fixed one- together with public capital. Firms and households are assumed to be profit and utility takers respectively. Under these assumptions, the value of non-priced non-traded regional characteristics -such as climate or infrastructure stock- will be reflected in differences in local factor prices. The model determines regional wages and land rents endogenously. It also predicts that prices respond to variations in the level of specific site productive characteristics (such as infrastructure), and non-productive local amenities. These regional variations can be exploited to identify the effect of public infrastructure on output, taking into account both firms and households behaviour.

The empirical strategy to implement this theoretical framework consists of using individual-level data to fit a hedonic regressions model that relates workers' wages, and land prices to specific regional or local characteristics, and public capital stock. In the econometric specification workers' individual characteristics, as well as land particular features are used as controls.

Rudd (2000) follows this strategy using cross-section data of the 1980 US Census and additional fiscal controls. He finds that the elasticity of output with respect to capital is 0.08, the elasticity of output with respect to *infrastructure* capital, defined as water distribution systems, sewers, and motorways, is 0.12, and the elasticity of output with respect to motorways alone is 0.07. The model also proves that higher levels of infrastructure capital have a positive effect on wages and rents in regions, while non-infrastructure capital has little or no effect.

Following the same approach, Haughwout (2002) uses data from the *American Housing Survey* and a broad definition of public capital in metropolitan areas, to estimate an empirical version of the Roback model for US cities. This paper finds that the marginal productivity of infrastructure is estimated to be non-negative but small. Depending on the specification, it ranges between zero and 0.027.

Despite these findings, the results of the exercise show important effects of public capital on the relative price of input factors. For example, the elasticity of land value with respect to infrastructure stock ranges between 0.11 and 0.22; however, an increase of infrastructure stock has negligible effects on households' wage income. This description indicates that factor markets capitalise the net benefits of non-traded publicly provided goods. Moreover, the study shows that households' willingness to accept lower wages for more public infrastructure outweighs firms' willingness to pay higher wages. Since household benefits are consistently estimated as positive and relatively large, the model has important distribution implications that suggest that households are the principal beneficiaries of infrastructure in cities.

An important feature highlighted in this paper is that these results may be interpreted in a strict *ceteris paribus* sense. Since the public sector budget constraint is not explicitly modelled under this approach, the positive effects on production and wages are in fact the result of increased infrastructure conditional on tax rates and public expenditure. Hence, to observe these effects public infrastructure increments have to be financed by exogenous sources. If this assumption is violated, the effects of public capital on production might be different. This observation opens another research line in the analysis of the link between public capital and production: the vector autoregressive approach, discussed below.

6 VECTOR AUTOREGRESSIVE APPROACH

An alternative research line in the study of this topic is the estimation of models that do not impose any *a priori* assumption about causality on the data. There are several examples in the literature, which use vector autoregressive (VAR) models as an alternative approach to the traditional production or cost function estimations. Besides the flexibility that they offer, an advantage of VAR models is that they allow testing for the presence of effects between all the variables of interest.

Pereira *et al.* (2001b) implement a vector autoregressive error correction VAR/ECM model of twelve US industries. The model considers for its estimation aggregate industry production, public and private investment, and aggregate industry employment. The model estimates the elasticity of aggregate private output with respect to public investment at 0.047. However, in eight out of twelve sectors, the effect of public investment is negative. The effects of public investment on employment appear to be very small: in the long-run, 51 long-term jobs are created per million dollars in public investment. However, the exercise implies that public investment has a positive effect on private capital investment, with an estimated public private capital elasticity of 0.397. Nevertheless, at industry level there is evidence of crowding-in effects only in five out of twelve sectors. In general, public investment has very different effects across sectors. It tends to shift the industry composition of employment toward construction and transport and the composition of private investment to the manufacturing sectors, public utilities, and communications.

In Pereira (2001a), the author investigates the crowding-in effects of public capital in detail. Following the same procedure as in Pererira *et al.* (2001b), the author finds that public investment crowds in private investment. The paper identifies the source of this crowding-in effect as due mostly to public investment in sewage and water supply systems, and of public investment in conservation and development structures. At industry level, the crowding-in effect of public investment is particularly strong only in the cases of industry and transport equipment.

The results presented above confirm the findings of earlier economic literature. However, the estimated policy function at aggregate level suggests that changes in the aggregate public investment are positively correlated with lagged changes in aggregate private output, negatively correlated with lagged changes in aggregate private employment, and uncorrelated with lagged changes in aggregate private investment. These findings suggest that public investment might be dependent on output. This result is an important caveat that should be further explored.

7 FINAL REMARKS

The literature of the late 1980s and early 1990s tackles the analysis of the link between public capital and production by estimating empirical aggregate production-functions. In general, these papers show the importance of public capital for economic growth, suggesting that it has extraordinary return rates. Later studies, focusing on the analysis of regional data, present puzzling conclusions, since at this aggregation level the estimated effect of public capital appears to be negligible, although the same authors argue this does not mean that public capital does not yield important benefits.

The analysis of industry-level data suggests that the relationship between public capital and production is too complex for it to be tackled from the oversimplified perspective of the production-function approach. This, along with the lack of robustness of regional and local estimates of production-functions leads to new empirical strategies. The estimation of cost-production function proves to be a useful approach for tackling this topic. In general, the cost-function analysis makes it clear that public capital -defined as public infrastructure- is an important factor for production and economic growth; however, it has considerably lower returns than that portrait in early aggregate nation production-functions.

Further research has tackled the topic from a spatial equilibrium approach using non-aggregated individual data. These examples corroborate the importance of public capital for the economy, suggesting that despite their modest returns, it plays an important role in the allocation of resources among regions and economic agents.

This review shows that empirical research has been relatively successful in showing the importance of public capital on economic activity. However, more research in this field is needed, as there are still important caveats. First, the source of divergence between national, regional, and local effects of public capital suggested by production-function estimates has not been fully identified. A possible research line, portrayed in some of the papers reviewed here, is the addition of structures in the specification that considers geographical spillovers, and time and spatial autocorrelation. Second, the link between public capital and production appears to be a non-linear process with multiple cross-interactions, and this could (and should) be subject to further research. Third, firm behaviour and location equilibrium models somehow have to incorporate and test bidirectional effects between public capital and production found empirically in VAR models. Finally, the measurement of public capital has to be refined, and perhaps replaced, by a measure that fully captures network, congestion, and quality effects of this variable.

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ANNEX: PUBLIC CAPITAL INFRASTRUCTURE AND ECONOMIC ACTIVITY – SUMMARY OF PAPERS REVIEWED

Author	Title	Date	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Aschauer, D.A.	Is public expenditure productive?	1989	Journal of Monetary Economics	US: National	OLS. Complementary regressions are run using First Order Autocorrelation Coefficient (FOARC), Instrumental Variables (IV), and Non Linear Least Squares (NLLS) to test the robustness of the results.	Cobb-Douglass production-function estimated for absolute levels and Total Factor Productivity.	Annual 1949-1985	Time-Series	Monetary value of public capital stock defined as federal, state, and local capital stock of equipment and structures.	Elasticity of public capital is 0.35 Core infrastructure –*i.e.* motorways, airports, electrical and gas facilities, water sewers- accounts for 55% of the effect of public capital stock on productivity.
Boarnet, M.	The direct and indirect economic effect of transport infrastructure.	1996	University of California at Irvine. Working Paper	California: Counties	OLS. Complementary regressions are run using pooled long differences.	Cobb-Douglass production-function with fixed county level estimated in long differences. It controls for fixed geographical spillovers.	Annual 1969-1988	Panel Data	Monetary value of street and highway capital stock.	County infrastructure has a positive and significant effect on output: Estimated elasticity ranges between 0.16 and 0.22. County infrastructure appears to have negative and significant geographical spillovers.
Boarnet, M.	Spillovers and the locational effects of public infrastructure.	1998	Journal of Regional Science	California: Counties	Pooled OLS long differences. Complementary IV regressions are run to test endogeneity of public capital.	Cobb-Douglass production-function with fixed county level estimated in long differences. It controls for fixed geographical spillovers.	Annual 1969-1988	Panel Data	Monetary value of street and highway capital stock.	County infrastructure is productive with an estimated elasticity ranging between 0.23 and 0.30 depending on the specification. There are negative spillovers from public capital and these are stronger across similar urbanised counties.
Cohen, J. and Morrison, C.	Airport infrastructure spillovers in a network system.	2003	Journal of Urban Economics	Manuf. US: 48 Contiguous States	OLS. Complementary regressions are run under Generalised Method of Moments (GMM) with Spatial Autoregressive Error (SAR) regressions to test the robustness of the results.	Generalised Leontief cost-function. It controls for fix geographical spillovers and spatial autocorrelation.	Annual 1982-1996	Panel Data	Monetary value of airport infrastructure stock.	Airport infrastructure is productive with an estimated cost elasticity of 0.113 in absolute value. Airport infrastructure has positive spillover effects.
Cohen, J. and Morrison, C.	Public infrastructure investment, inter-state spillovers, and manufacturing costs.	2003	Mimeo.	Manuf. US: 48 Contiguous States	Maximum Likelihood (ML) with spatial autocorrelation (SAR); and Seemingly Unrelated Regressions (SUR).	Generalised Leontief cost-function. It controls for fixed geographical spillovers and both spatial and time autocorrelation.	1982-1996	Panel Data	Monetary value of motorways capital stock.	Infrastructure is productive but presents small returns: cost elasticity estimated at 0.15 in absolute value. Spatial and temporal autocorrelation adjustments change the magnitude but not the direction of the effect
Duggal, V., Saltzman, C., and Klein, L.	Infrastructure and productivity: a nonlinear approach.	1999	Journal of Econometrics	US: National	Two Stage Non Liner Square: OLS in the first stage and for the second state Levenberg-Marquardt nonlinear method.	A neoclassical S-shape production function estimated for absolute levels. Public Capital is modelled as a constraint of the technological index.	Annual 1960-1989	Time Series	Monetary value of public infrastructure stock, defined as motorways and streets, other buildings including police, fire stations, court houses, auditoriums, and passenger terminals, as well as other structures including electric and gas facilities, transit systems and airfields	Elasticity estimated at 0.27. The specification finds positive evidence of non-linearities in public capital effects.

Author	Title	Date	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Evans, P. and Karras, G.	Are government activities productive? Evidence from a panel of U.S. states.	1994	The Review of Economics and Statistics	US: 48 Contiguous States	Modified OLS Between-Groups. A complementary Instrumental Variables (IV) regression is run to test endogeneity of public capital.	Cobb-Douglass production-function with fixed state level effects estimated for both absolute levels and differences. It controls for time autocorrelation.	Annual 1970-1986	Panel Data	Monetary value of public infrastructure defined as motorways, water and sewer systems, and other infrastructure capital.	Public capital has negative productivity. This may be caused by an oversupply of public infrastructure in the US. Government services have a positive impact, in particular current spending in education is productive.
Fernald, J.	Roads to prosperity? Assessing the link between public capital and productivity?	1999	The American Economic Review	US Sectors: National	Seemingly Unrelated Regressions (SUR) methodology	Cobb-Douglass production-function depending on transport services. Transport services depend upon the aggregate stock of government roads as well as the stock of vehicles in the sector of aggregate stock of government.	Annual 1953-1989	Time-Series	Monetary value of aggregate stock of government roads.	There is a positive relationship between growth rate of aggregate stock of government roads and productivity. The estimated elasticity is 0.35 The average contribution of roads to GDP in the US was 1.4 percent per year before 1973, and 0.4 percent after 1973. After this year the marginal effect of roads on productivity decreased. Roads productivity is smaller in non-vehicle intensive industries.
Garcia-Mila, T., McGuire, T., and Porter, R.	The effect of public capital in state-level production functions reconsidered.	1996	The Review of Economics and Statistics	US: 48 Contiguous States	OLS for the fixed effect specification. Generalised Least Squares (GLS) for the random effect specification	Cobb-Douglass production-function estimated both under fixed and random state effects. The specification is estimated for both absolute levels and differences.	Annual 1970-1983	Panel Data	Monetary value of motorways and monetary value of water and sewer system.	Public capital has negligible effects on the aggregate production function.
Haughwout, A.	Public infrastructure investment, productivity, and welfare in fixed geographic areas.	2002	Journal of Public Economics	US: Households	A two stage estimation procedure using OLS and Generalised Least Squares (GLS).	Two modified Mincerian-earning equations representing an empirical implementation of a spatial equilibrium model: wages and land rents in terms of workers', households', and specific spatial characteristics. Both equations include local public capital stock.	Annual data but with no regular periodicity 1974-1991	Pooled cross-section.	Monetary value of public capital stock in metropolitan areas.	The marginal productivity of infrastructure is estimated to be non-negative but small. Depending on the specification it ranges between 0 and 0.027 The elasticity of land value with respect to infrastructure stock, conditional on fiscal variables, is estimated between 0.11 and 0.22. Household benefits are consistently estimated as positive and relatively large.
Holtz-Eakin, D.	Public-sector capital and the productivity puzzle.	1994	The Review of Economics and Statistics	US: 48 Contiguous States	OLS Fix Effects. Generalised Least Squares (GLS) Random Effects. Instrumental Variables (IV) and Holtz-Eakin-Newey-Rosen (HNR) to test endogeneity and simultaneity respectively.	Cobb-Douglass production-function estimated both under fixed and random state effects. The specification is estimated for both absolute levels and differences.	Annual 1969-1986	Panel Data	Monetary value of public capital stock including motorways, water and sewer systems, and other infrastructure.	Public capital has non-significant effects on production.

Author	Title	Date	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Holtz-Eakin, D. and Shwartz A.E.	Infrastructure in a structural model of economic growth.	1995	Regional Science and Urban Economics	US: 48 Contiguous States	Constrained OLS and Seemingly Unrelated Regression (SUR) method.	Public Capital and Production in labour intensive form in log levels. The system is derived from an IRS Cobb-Douglas function, with labour, private capital, and public capital as input factors.	Annual 1971-1986	Panel Data	Monetary value of infrastructure defined as streets, motorways, sanitation and sewer system, electric and gas facilities, and water distribution system. An alternative definition where infrastructure includes all capital owned by state and local government in each state is considered.	Elasticity is negative and significant. Public capital investment rate can explain state variations of public capital stock but fails to explain cross-state differences in productivity in the long run (cross-section regressions)
Kelejian, H. and Robinson, D.	Infrastructure productivity estimation and its underlying econometric specifications: a sensitivity analysis.	1997	Regional Science	US: 48 Contiguous States	OLS; Non Linear Least Squares (NLLS); Non Linear 2-Stage Leas Squares (NL2SLS); and Generalised Methods of Moments (GMM).	Cobb-Douglass production-function with fixed state effects. The specification is estimated for absolute levels considering time and spatial autocorrelation.	Annual 1969-1986	Panel Data	Monetary value of public capital stock defined as motorways, water and sewer system and other structures.	Production function estimates are not robust to the econometric specification or estimation method. The only robust result is that the elasticity of labour input and productivity spillovers are significant, positive, and reasonably stable.
Morrison C. and Schwartz, A.E.	State infrastructure and productive performance.	1996	The American Economic Review	Manuf. US: 48 Contiguous States	Seemingly Unrelated Regression (SUR) method.	Generalised Leontief cost-function estimated for absolute levels.	Annual 1970-1987	Panel Data	Monetary value of public capital stock defined as motorways, water systems, and sewers.	Shadow values for public and private capital are positive and significant, estimated between 0.05 and 0.34 depending on the region and year. Public infrastructure has a direct impact on productivity growth, due to a direct cost-saving effect. This is estimated between 0.19 and 0.62 depending on the region. The positive input cost saving benefit to manufacturing firms from infrastructure investment declines in all US regions from 1970 onward.
Nadiri, M.I., and Mamuneas, T.	The effects of public infrastructure and R&D capital on the cost structure and performance of the U.S. manufacturing industries.	1994	The Review of Economic and Statistics	Manuf. US: National	Constrained OLS on pooled time-series cross-section data.	Translog cost-function estimated for absolute levels. Public capital is defined as public infrastructure and publicly financed R&D investment.	Annual 1956-1986	Pooled Panel	Monetary value of net government physical capital stock of civilian structures and equipment. It also includes a estimated monetary value of "R&D stock".	Infrastructure has a direct cost reduction effect from 0 to 0.21 depending on the industry. Public infrastructure and R&D induce productivity growth**.**
Nadiri, M.I., and Mamuneas, T.	Contribution of highway capital to output and productivity growth in the U.S. economy and industries.	1998	US Department of Transportation	US Sectors: National	OLS	Translog cost-function estimated for absolute levels.	1947-1991	Time-Series	Monetary value of motorway capital stock.	In most manufacturing industries, cost elasticities range between 0.04 and 0.05 in absolute value. The contribution of highway capital to productivity growth is positive in all industries. At aggregate level highway capital accounts for about 50% of TFP growth over the period of study. The economic impact of highway capital on producer cost declined during the 1980s.

Author	Title	Date	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Pereira, A.	On the effects of public investment on private investment: What crowds in what?	2001	Public Finance Review	US Sectors: National	Vector Autoregressive Error Correction Method (VAR/ECM)	A VAR model estimated in log differences for each industrial sector in the US including GDP, Public Investment, Private Investment, and Employment.	1956-1997	Panel Data	Public investment in motorways, and streets, electric and gas facilities, sewage and water supply systems, education buildings, hospitals, police and fire stations, and conservation and development structures.	Public investment crowds-in private investment. Its effects on employment are almost negligible. It has a positive effect on private output with an estimated elasticity of 0.042.
Pereira, A. and Andraz J.	On the impact of public investment on the performance of U.S. industries.	2001	Public Finance Review	US: National	Vector Autoregressive Error Correction Method (VAR/ECM)	A VAR model estimated in log levels for each industrial sector in the US including GDP, Public Investment disaggregated in 7 categories, Private Investment disaggregated in 5 classes, and Employment.	1956-1997	Panel Data	Aggregate public investment in civilian structures and equipment.	Elasticity of private employment with respect to public investment is 0.013. Elasticity of private investment with respect to public investment is 0397. At industrial level, there is evidence of crowding-out in 5 out of 12 sectors. Elasticity of private output with respect to public investment is 0.047. However, in 8 out of 12 sectors, the effect of public investment is negative.
Rudd, J.	Assessing the productivity of public capital with a location equilibrium model.	2000	FEDS WP. 2000-23	US: Urban Areas	Huber adjusted OLS.	Two modified Mincerian-earning equations representing an empirical implementation of a spatial equilibrium model: wages and land rents in terms of worker's, household's, and specific spatial characteristics. Both equations include local public capital stock and tax controls.	1980	Cross-Section	Monetary value of public infrastructure stock defined as motorways, streets, water system, and sewers.	The estimated output-public capital elasticity is 0.08. The elasticity for infrastructure capital is 0.12, and the elasticity for highways is 0.07. Elasticity of wages with respect to public capital stock is 0.07. When no tax controls are present, the effect of public stock on land rent is positive and significant, estimated at 0.21.
Shioji, E.	Public capital and economic growth: A convergence approach.	2001	Journal of Economic Growth	US: 48 Contiguous States Japan : 47 Prefectures	OLS, Least Squares Dummy Variable (LSDV), and Generalised methods of Moments (GMM).	Generalised neoclassical production function expressed out-of-steady state	USA 1963-1978 Japan 1975-1995	Time-Series	US. Monetary value of public capital stock defined as infrastructure and structures and equipment related to education sector. Japan. Monetary value of public capital stock defined as infrastructure, and public capital related to education, conservation of land, and agriculture.	The long run equilibrium elasticity of infrastructure is estimated in a range of 0.09 to 0.143 for the US, and 0.10 to 0.169 for Japan. This estimate contrasts with the short run effect since both countries present similar numbers.