COMPETE

Analysis of the contribution of transport policies to the competitiveness of the EU economy and comparison with the United States

COMPETE Annex 6

Impact of transport infrastructure on economic growth

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€	EURO
BEA	US Bureau of Economic Analysis
BSIM	Barro and Sala I Martin model
DM	Deutsche Mark
EU	European Union
EU-15	The 15 EU countries before the 2004 enlargement.
GDP	Gross domestic product
ISTAT	Istituto di Statistica (Italian statistical office)
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
R&D	Research and Development
SUR	Seemingly Unrelated Regressions
TFP	Total factor productivity
UK	United Kingdom
US	United States of America
VAR	Vector Auto Regression
VECM	Vector Error Correction Model

Annex 06: Impact of transport infrastructure on economic growth

1 Introduction

Public infrastructure in general, and in particular transport networks (such as roads, railways, airports, and waterways) have long been considered important inputs to economic and productivity growth. The basic intuition behind this is that improvements in public infrastructure (e.g. better roads) would be expected to raise the productivity of private inputs (say, by reducing the time and cost of transporting goods from factory to retail outlet), reducing the costs of production and raising the rate of total factor productivity growth. However, although some research on the effects of public capital on productivity growth can be traced back to the pioneering works of Meade in the 1950s and contributions published in the following decades (for instance, Mera, 1972 and De Rooy, 1978), it was the seminal contribution of Aschauer (1989a) that spurred recent academic interest in the field.

Aschauer (2000) ascribes this renewed interest to two factors. The first is that in the US public investment spending, as a share of GDP, had declined significantly in the run-up to this period. The trend seems to have been common to many other developed countries (for instance, evidence on OECD countries reported in Kamps (2004) shows that the average public investment to GDP ratio declined over the 1971-1990 period and there appear to be important differences between countries (as one might have expected). Secondly, the fact that the US non military capital accumulation, as a fraction of GDP, peaked in the late 1960s has been seen by some authors (Aschauer, 1989a and Munnel 1990a) as one of the possible explanations for the productivity growth slowdown that characterised the following two decades.

The early studies of this period suggested that public capital stock had a quantitatively important impact on productivity. For instance, Aschauer (1989a) estimated a production function using US annual data for the period 1949-1985 and found that a one per cent increase in the stock of public capital infrastructure would have increased output by about 0.35 per cent. Similar results were also found by Munnell (1990a) and Flores and Pereira (1993) and by Aschauer (1989b) for the G7 countries. Interestingly, these studies suggested that core public infrastructure (which is more closely related to the concept of transport infrastructure than the wider stock of public infrastructure) had in general the highest impact on private output, with the remaining categories of public capital playing a far smaller role.

These early results (which were mainly based on US samples) were widely regarded as implausibly high and did not however find robust support in the studies that immediately followed. For instance, Munnell (1990b) using a panel of US states, found a positive but significantly lower effect of public capital on output. Tatom (1991), Holtz-Eakin (1994) and Kelejian and Robinson (1997) were unable to find any significant effect of public capital on output once appropriate econometric techniques had been employed and similar results were also found (using a sample of OECD countries) by Evans and Karras (see Gramlich’s 1994 literature review for a comment on the early contributions).

In general, studies that were conducted at a more disaggregated level (such as by sector or state or region) tended to produce smaller estimates than these identified by studies employing national level data (Munnell, 1990 and Morrison and Schwartz, 1996) and also tended to display an interesting variability both across time and cross-sectionally. Munnell (1991) argued that it is intuitively to be expected that estimates of the effect of public infrastructure on output should rise with the level of aggregation: studies which employ regional level data are likely to find lower estimates than those focusing on national samples, as the former would neglect potential spillover effects of infrastructure investments: a highway in region A might well help increase production in region A, but also in the neighbouring region B. While most subsequent research has neglected this consideration, a few studies (Cohen and Morrison, 2003, for instance) tried to incorporate spatial effects and the effects of spillovers into the analysis.

The main objections that were raised against the studies supporting the Aschauer findings related to various weaknesses of the statistical analysis. For instance, it was argued that insufficient account had been taken of the possibility that rises in the stock of public capital are driven by rises in GDP, rather than the other way round. Furthermore, production functions might yield biased estimates if the simultaneity between output, capital and labour inputs is not properly addressed.

Thirdly, it is known that some macroeconomic variables (such as capital stocks and GDP) reflect non-stationary processes: neglecting this possibility is likely to yield spuriously high impacts of public capital stock on productivity growth. On the other hand, removing the problem by first differencing the series might cause the analysis to miss long run links between the series if they happened to be cointegrated.

Finally, early studies using the production function framework relied on the Cobb-Douglas functional form, which has come to be regarded as too simplistic a representation of technology.

More recent research has attempted to take account of some of these criticisms: production functions have been generally estimated after performing preliminary analysis on stationarity and cointegration; the use of cost functions has become more common, especially in the case of studies using regional or sectorial data and vector auto-regressive models (VARs) have been increasingly used in the most recent studies that rely entirely on time series data.

While the first papers following Aschauer’s (1989) study did not manage to provide strong evidence in favour of or against the hypothesis that public infrastructure did have a positive impact on GDP, the evidence in the most recent papers has generally been felt to point to the existence of small but positive effects of public infrastructure expenditure on GDP. However, the general view is that the most recent research also suggests that there is a danger of over-generalising these findings, as there are often important differences in the effects across states, regions and sectors.

Another set of possible criticisms of the empirical literature relates to the definition of the public infrastructure stock: while some studies adopt a broad definition of public infrastructure, other focus on the so called core infrastructure (railways, roads, water and sewer mains, etc), with a minority focusing on transport infrastructure or particular kinds of it, such as roads or highways. It should be noted that the empirical results that can be found in the literature should be viewed bearing the definition of infrastructure capital firmly in mind, as it might be argued that core infrastructure should be "more productive" than education and office buildings and, comparing the results, the issue of the definition of public infrastructure should be addressed. Furthermore, the measurement of the public infrastructure stock is not an easy task (for instance, it is not clear how to assess the impact of congestion on the effectiveness of a given stock of transport infrastructure). In addition, estimating the value of public capital involves significant methodological challenges, since market values for public infrastructure and equipment are often not available. In the US, the BEA uses a perpetual inventory methodology to asses the value of public capital. Alternative measures of public capital use time-series of government expenditure on public investment, assuming an explicit depreciation rate to public capital.

An important problem when using a monetary value of public capital for studying its linkage with economic activity is that this methodology may not be appropriate to study spatially interconnected networks. The internal composition of the stock matters, because 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. Furthermore, as observed by Prichett (1996), the use of monetary values to compute the stock of public infrastructure might give a distorted picture of the actual services provided by the stock given the different degrees of efficiency that might have characterised past government investments.

Given these inherent problems in the measurement of the public capital stock, some economists have even questioned the use of monetary values to measure it, preferring "physical" measures of the public infrastructure stock, such as road length, kilometres of railways, etc. A drawback of such measures, however, is that they tend to neglect the quality of infrastructure.

Interestingly, the empirical literature on the effects of public infrastructure on output and productivity growth developed largely independently from the research programme which sought to explore the theoretical links between infrastructure capital and economic and productivity growth. As Aschauer (2000) noted, the finding that public capital might be productive, does not necessarily imply that increasing public capital investment spending would lead to higher growth rates of GDP. In fact, conventional growth models a la Solow predict that higher investment (both private and public) would have effects only on the level of GDP, rather than on its rate of growth. However, more recent theories suggest that public investment might have long run effects on the rate of growth of GDP. For instance, a higher stock of public infrastructure might reduce costs of production by allowing greater specialisation, thereby generating more output. In addition there may be further changes in factor markets and firm location decisions that allow the development of spatial clusters of economic sectors, thereby affecting innovation and allowing further reduction in costs (Lakshmanan and Anderson, 2002). More recent theoretical and empirical research has sought to analyse the effects of public infrastructure in general equilibrium models that allow the joint addressing of issues such as the optimal provision of public infrastructure capital, taxation and technological progress.

Our view is that the analysis briefly sketched above suggests that, in order to gain a better understanding of the links between public infrastructure and productivity growth, it is necessary to develop a through understanding of the theories that have been proposed to explain these links. With this theoretical background, it is then necessary to critically evaluate the empirical contributions: in particular, it is necessary to discuss the methodological approach, the main results and the potential limitations of the analysis: this is important because if a given result were supported by fairly robust studies employing different methodologies, our confidence in that result would be greatly enhanced.

Given this approach, the remainder of this section is organised as follows. In Section 2 we will review the recent theoretical literature on the links which exist between economic growth and transport infrastructure. In Section 3 we will provide a background discussion on the main approaches that have been used to empirically investigate the impact of public infrastructure on economic and productivity growth: production functions, cost functions and the Vector Auto-Regressive model. In Section 4 we will discuss the main empirical results that have been found in the literature. Some studies have sought to provide critical reviews of the empirical evidence in this field, the most recent and up to date being perhaps these provided in Sturm and De Haan (1998) and Romp and De Haan (2005): in this report we build on these to add the most recent studies and some older ones not covered in those reviews. In particular, given that the overall project is to include a comparative assessment of the situation in the EU and the US, we will deal separately with the empirical evidence related to the US and the EU. Finally, section 5 contains some conclusions that can be drawn from the literature review. Section 8 includes tables summarising the main results and methodological features of each study that has been reviewed, as well as a more in depth review of the theoretical literature on the effects of transport infrastructure on economic growth.

2 Review of the theoretical literature

2.1 Introduction

As discussed in the introduction of the economic analysis in the main part of the Interim Report (see section 7), although many studies consider the impact on economic growth of public infrastructure investment (specifically or including transport), there is only limited consensus. In such an environment, one of the important roles of economic theory is in seeking to develop understanding of the nature of the relationships in question. This primary focus of this section is on the class of models that either explicitly model transport costs or are capable of being modified to do so. The theoretical literature can be divided into the following categories. These categories are not entirely distinct, leaving room for occasional overlap, but are nevertheless useful for understanding the literature:

- Exogenous growth models,
- Endogenous growth models,

- Public infrastructure enters as an input,
- Public infrastructure enters via technology,
- Micro-economic linkages via increasing returns and specialisation, and
- Spatial agglomeration effect

The aim of this section is to describe and evaluate a number of different approaches to the question at hand. We describe the major common approaches taken and the adaptations that are particularly interesting for the analysis of the transport sector.

2.2 Exogenous growth models

In neoclassical exogenous growth models, exemplified for example in Solow (1956), public capital can be included as an input along with physical capital and labour. Since all inputs are subject to diminishing returns, increases in public capital will not lead to long run growth effects, but would have a level effect on the economy. This class of models depends on exogenous technical progress, reflected in total factor productivity, to lead to long run GDP per capita growth and since there is no room for public capital to affect technical progress, it cannot have growth effects.

Real Business Cycle models can also be extended to include public capital. Baxter and King (1993) for example introduce public capital into a Real Business Cycle model. They find that productive government spending can have large level effects on output, as there is a direct output affect and an indirect effect via marginal products of labour and capital. However, as before, capital does not affect long run growth.

2.3 Endogenous growth models

The endogenous growth models introduce mechanisms whereby capital (defined more broadly now to include other forms such as human capital) is not subject to diminishing returns. Thus public capital has the potential of leading to long run growth effects. There are two streams of work within this broad class of models which have attempted to introduce public capital into the production function: one where public capital enters as a standard input to the production function along with labour and physical capital, and the other where public capital affects the productivity of the standard inputs by affecting the technology variable. We discuss each approach below.

2.3.1 Public Infrastructure enters as an input in the production function

The Barro (1990) endogenous growth model is a useful starting point, and is used as the basis for much further work (e.g. Barro and Sala-i-Martin (1992), Turnovsky (1997)).

The model begins with an infinite-lived household in a closed economy, maximising a standard time discounted utility function:

$$U = \int_0^\infty u(c) e^{-\rho t} dt$$

Where c is consumption per capita and ρ > 0 is the constant rate of time preference. The utility function u(c) is then defined as one which exhibits constant elasticity of marginal utility, -σ as follows:

$$u(c) = \frac{c^{1-\sigma} - 1}{1-\sigma}$$

Each household has access to a production function,

$$y = Ak$$

Where y is output per worker and k is capital per worker. k is used flexibly to encompass physical capital plus other forms such as human capital. Although there are diminishing returns to each factor independently, together they exhibit constant returns to scale.

Adding public services provided, g, as an input, the production function becomes:

$$y = k.\Phi\left(\frac{g}{k}\right)$$

where the function Φ exhibits positive and diminishing marginal products. The marginal product of public capital, holding private capital fixed, is given by:

$$\frac{dy}{dk} = \Phi\left(\frac{g}{k}\right)\cdot\left(1 - \Phi'.\frac{g}{y}\right) = \Phi\left(\frac{g}{k}\right)\cdot(1-\eta)$$

where η is the elasticity of y with respect to g.

We then add financing considerations to the model. Public capital is financed by distortionary taxes under a balanced budget constraint.

$$g = T = \tau y = \tau \cdot k \cdot \Phi\left(\frac{g}{k}\right)$$

where T is government revenue and τ is the tax rate. With households normalised to unity, g and T represent aggregate expenditures and revenues.

The solution to the private optimisation problem yields the following growth path for per capita consumption:

$$\gamma = \frac{\dot{c}}{c} = \frac{1}{\sigma}.\left[(1-\tau)\cdot\Phi\left(\frac{g}{k}\right)\cdot(1-\eta) - \rho\right]$$

As long as g and T grow at the same rate as y (and therefore τ and g/y are constant), the growth rate γ will be constant.

From the equation above we can see two effects of the size of government: an increase in tax reduces consumption growth, while an increase in expenditure increases growth. When government is small, the second effect is likely to dominate. The model yields the result that growth is maximised when the government sets its share of GNP, g/y, equal to the share it would get if the services were provided competitively as an input to production. There is thus an optimal level of infrastructure capital. Investment in capital below this level is growth enhancing, while increases beyond this level have negative growth effects.

The Barro (1990) model has since been extended in several different ways. For example, the original model treats public capital as a "pure" public good i.e. both non-rivalrous and non-excludable. Some adaptations have attempted to incorporate the rivalrous nature of consumption that may arise in public infrastructure due to congestion. Other treatments incorporate the fact that public goods may be made excludable by charging a user fee (transport examples include charges for the use of highways or airports).

Of the most recent of this literature, Ott and Turnovsky (2005) extend the Barro (1990) model to include both rivalry and excludability. A conventional non-excludable public input, financed out of tax revenue, is included alongside an excludable public input that requires users to pay a fee. Keeping to the original Barro terminology of representing privately owned capital by k, government owned capital, g, is now split into an excludable Es and a non-excludable part, Gs.

In addition, both inputs are subject to rivalry due to congestion effects, modelled by the following standard congestion equations:

$$E_s = E\left(\frac{k}{K}\right)^{\varepsilon_E} \quad \text{and} \quad G_s = G\left(\frac{k}{K}\right)^{\varepsilon_G}$$

where 0 ≤εE, εG ≤ 1 and K = nk denotes the aggregate stock of private capital. When εE and εG equal 1 there is no congestion.

They then add an aggregate resource constraint (where output can either be consumed or accumulated as capital) and solve the inter-temporal utility maximisation problem under centralised (government based) and market determined scenarios. They consider the interactions between the two inputs in production in conjunction with pricing and financing issues. The optimal financing system given by the model depends on the partial production elasticities of the two inputs and their respective degrees of congestion. In particular, congestion raises the optimal income tax and lowers the optimal user fees.

Another interesting approach to including transport as a factor input is developed in Fernald (1999) who incorporates transport services provided by the government into each sector's production function. In addition, sectoral output depends on the transport services produced within the sector. The production function for each sector is given by:

$$Y_i = U_i F^i (K_i, L_i, T(V_i, G))$$

Where Yi is the value added output, Ui is the level of technology, Ki is non-vehicle capital, Li is labour, T represents transport services as a function of Vi (the stock of vehicles in sector i) and G (the aggregate stock of government roads). This formulation allows the researcher to vary the effect of G on Y between sectors that are vehicle-intensive and those that are not. In addition, Fernald models both the network nature of public transport infrastructure (i.e. that the productivity of any particular node in the transport network is inherently linked with the capacities of the other nodes and the set-up of the transport system) and congestion effects (where the effect of an additional user on the congestion experienced by the remaining users is not constant).

2.3.2 Public Infrastructure enters as an input to the technological constraint

The models described above incorporate public capital as a factor input. This approach has been criticised on the grounds that it assumes that firms know the marginal cost of infrastructure and can therefore use it in the optimisation problem. Since public infrastructure is financed mostly from government revenue, the per-unit cost of infrastructure is not market determined and is unrealistic to calculate for each firm (Duggal et al. (1999)).

Other approaches have, therefore, developed which incorporate public capital in the technology constraint rather than as a factor input. Shioji (2001) specifies such a model, using an approach in which output is affected via technology in an open economy. They start with a standard production function in which a region's output, Yt, depends on a technology variable, A, in addition to capital, Kt and labour Lt,:

$$y_t = A \cdot K_t^{\alpha} \cdot L_t^{1-\alpha}$$

The level of technology is defined to be a positive function of public capital per capita:

$$A = B\left(\frac{G}{L}\right)^{c}$$

where G is the public capital, B represents the intrinsic productivity of the region and it is assumed strictly positive, c is a non negative parameter and L, the labour input, is assumed constant over time.

Thus increases in public capital per capita improve productivity and therefore the output via an external effect. They also incorporate an adjustment cost for investment: capital is mobile between regions but with a cost. The cost of investment is given by:

$$I_t \cdot \left(1 + \frac{\zeta}{2} \cdot \frac{I_t}{K_t}\right)$$

Where It is the investment at time t and ζ is a positive constant i.e. the firm pays both the price of the investment good (one unit of output) but also the adjustment cost.

Each firm maximises the present value of its net cash flow in an infinite time horizon. Their model yields the result that the elasticity of output with respect to public capital is greater in the long run because public capital influences output not just because of its own productivity impact but also by attracting more private investment to the region.

In a similar vein, Duggal et al. (1999) also incorporate infrastructure in the technological constraint. In their model, infrastructure lowers costs and therefore increases productivity. In addition, infrastructure allows markets to expand and economies of scale to be achieved, further lowering costs. Technology, At, is modelled as a non-linear function of infrastructure and time:

$$A_t = e^{gt}$$

Where g, the growth rate of the technological index is given by

$$gt = e^{f^{\gamma}} e^{t^{\phi}} e^{c}$$

where f is infrastructure capital, t is the time trend and c is a constant.

They incorporate this growth rate into a non-standard production function that follows an S-shape:

$$\ln Q = \ln A + \alpha \ln K + \beta_1 \ln L + \beta_2 \left(\frac{1}{L} - \frac{\beta_3 K}{L^2} \right)$$

where Q is real output, K is the stock of non-residential capital adjusted by the rate of capital utilisation, and L is the number of worker hours.

In the solution to the optimisation problem, they find that the impact of infrastructure is positive, but not constant. Increases in infrastructure enhance the total productivity of capital and labour and thereby reduce costs and allow expansion in output.

2.4 Micro-economic linkages via increasing returns and specialisation

The macro-economic models described above link public capital to the production function, but do not specify the process by which the capital leads to growth. In this sense, they give us an idea of the existence and extent of the effect of public capital, but give no satisfying answer to how, and thus have limited use in directing future public capital. Other approaches have since then tried to incorporate micro-economic based processes into the model, for example through reduced travel times and costs which lead to economies of scale and specialisation, and thus to growth.

Romer's (1987) model of endogenous growth with specialisation in production is a useful starting point as it forms the basis for several extensions that include infrastructure. He starts with a production function that uses labour, L, and intermediate inputs, where x(i) is the amount of intermediate input i used:

$$Y(L, x) = L \int_{\Re+} g\left(\frac{x(i)}{L} \right) di$$

g is defined as an increasing, strictly concave function, for example, g(x) = xα. He then adds the assumptions that output increases with the degree of specialisation, and that there are returns to scale in the production of intermediate goods. Specifically, Romer (1987) adds fixed costs to the model to produce a u-shaped average cost curve, which limits the degree of specialisation. In the dynamic version of the model, a primary resource constraint is added which is interpreted as durable, general purpose capital good. A conventional inter-temporal utility function is defined (similar to the one described in Barro (1990) above). Consumers are each endowed with a stock of general purpose capital which they rent out to intermediate goods producers. Every individual receives some output which must be allocated between capital and investment in additional capital. Thus additions to the capital stock are defined by

$$\dot{Z} = Y(1, x) - c$$

where Z is the durable capital (the primary input defined earlier) and c represents consumption.

The effect of a private production model with imperfect competition is that there is a divergence between marginal costs and price. Private returns to savings received by individuals are lower than the social returns. Therefore, individuals do not fully internalise the benefits of a higher savings rate and as a result save and invest too little. In contrast a social planner takes into account that a higher rate of savings leads not just to higher investment but also to higher labour income.

Schiffbaur (2005) augments the standard model by specifying a more comprehensive microeconomic linkage between infrastructure capital and productivity growth. First, productivity and technological change are endogenised using the Romer (1990) closed economy model as a starting point. Schiffbaur (2005) assumes that intermediate goods that are used in the production of final output include proportional transportation and coordination costs. An improvement in infrastructure capital reduces these costs and therefore allows specialisation in the production of intermediate goods. As the expected future profits of the intermediate sector increase, the incentives to invest in R&D also increase. This endogenous technical change is the only source of GDP growth in equilibrium and therefore GDP grows at the same rate as the stock of technologies. Since labour is diverted to R&D from manufacturing, the productivity of the sectors also determines the growth effect. The model is further enhanced by endogenising capital stock. Firms pay for their use of infrastructure capital. He considers three separate ownership structure of infrastructure capital: a private monopoly, a composition of price regulation and tax financing, and a public monopoly on a balanced budget, finding that public provision provides the highest growth rates. The model is particularly interesting because it reveals complementarities between infrastructure investments and variables that affect the productivity of the R&D sector. This implies that differences in the productivity of the R&D sector (driven for example by property rights or human capital) can explain differences in growth, even if levels of public infrastructure capital are similar.

Bourgheas et al (2000) also model infrastructure as reducing the costs of producing intermediate goods. They start with the Romer (1987) model in which output Y(x) is a function of a vector of inputs x(i):

$$Y_x = \int_{\Re^+} x(i)^{\alpha}\, di$$

Where 0 < α <1. A cost function which includes fixed costs is added, the fixed costs limiting the degree of specialisation, so that the average cost curve is u-shaped as in the original Romer model. Borgheas et al. (2000) endogenise the fixed costs element as a way of including infrastructure in the model. The cost function is specified as:

$$h(x(i), G/Y) = \frac{C(G/Y) + x(i)^2}{2}, \forall i$$

Where G is the stock of public capital, C’ < 0 and C’’ >0 i.e. that fixed costs vary inversely with the stock of public capital relative to the size of the economy.

Finally a primary resource constraint for the economy is added to the model along with the assumption that the government runs a balanced budget and finances infrastructure by a proportional tax of final output. The process of infrastructure accumulation is also modelled explicitly as assuming that resources must be diverted from producing output in order to accumulate capital. Thus the accumulation of infrastructure also comes at a cost in terms of output lost.

There is both a positive impact on output that comes from a reduction in fixed costs and an increase in specialisation, and a negative effect that comes from output diverted to accumulate capital. Both the positive and negative effects of infrastructure accumulation on output growth interact to give a non-monotonic relationship between the two. A unique tax rate is found that maximises growth by balancing savings between private and infrastructure capital.

2.5 Spatial Agglomeration Effects (New Economic Geography models)

Models that feature specialisation and scale effects have been enriched further by the New Economic Geography models which include general equilibrium and imperfect competition in the model. General equilibrium allows the improvements in transport to affect the markets for other factor inputs, such as labour markets, and these effects to be traced back to output. It is thus possible, at least in theory, to capture the various multipliers, interactions and feedback effects that an economy naturally goes through. Furthermore, relaxing the perfect competition assumption and allowing product variety also allows for willingness to pay and monopoly power to determine how much of the reduction in costs will be passed on to consumers. Public infrastructure has the effect of dropping transport costs and allowing economies of scale to be achieved. As a firm in a given location has access to a larger market area and gains dominance, other suppliers are encouraged to locate close by, making the area more attractive for successive firms as the required markets are located conveniently (in economic jargon, external economies of scale lead to the process of cumulative causation). This process encourages spatial concentration – the principal result of the New Economic Geography models.

The Dixit and Stiglitz (1977) model is a starting point for several of the New Economic Geography models. Krugman (1990) builds upon this model to produce the first bench-mark paper for this series of literature. A two-region, two-factors of production model is proposed where the utility function for all individuals is defined as:

$$U = c_M^{\mu} c_A^{1-\mu}$$

where cA and cM represent the consumption of agricultural and manufactured aggregates respectively. Imperfect substitution and variety is then introduced by defining the manufactured aggregate as:

$$c_M = \left(\sum_{i=1}^{N} c_i^{(\sigma-1)/\sigma} \right)^{\sigma/(\sigma-1)}$$

where N are the number of potential products and σ > 1 is the elasticity of substitution between the products.

The first sector is agriculture, which requires one unit of labour per unit of output. Peasants who provide agricultural labour are assumed to be completely immobile. However, workers can move between the two regions. The total number of workers is:

$$\mu = L_1 + L_2$$

Where L1 and L2 are the labour supplies of region 1 and region 2 respectively. Economies of scale are introduced by specifying the production of manufactured goods to include both a fixed cost and a constant marginal cost. The amount of labour used in producing xi units of good i is:

$$\mu_i = \alpha + \beta x_i$$

The transport sector is introduced via two assumptions. Firstly, agricultural goods are costless to transport. Secondly, there are "iceberg" transportation costs for manufactured goods – i.e. that only a fraction of each unit that is shipped out arrives and the value of the rest "melts" away in transition. The fraction that arrives is inversely proportional to transportation costs.

Profits maximising firms set price equal to p1, taking the wages of workers in region 1, w1 as given:

$$p_1 = \frac{\sigma}{\sigma - 1} \beta w_1$$

and similarly for region 2. Free entry is allowed so that profits are driven to zero. The solution to the zero profit condition yields the result that output per firm is the same in every region – irrespective of wage rates. This in turn implies that the number of manufactured goods produced in each region is proportional to the number of workers – i.e. n1/n2 = L1/L2

Equilibrium conditions are investigated by solving for consumption for each good by region (where transported goods are suitably discounted) and also by taking into account the movement of workers to the region offering higher real wages (i.e. nominal wages adjusted for the relative price of goods in the region). There are three effects operating in the model that are relevant for location. The first is the home market effect, which is that wages are higher in the larger market. The second is the price index effect, which is that if wage rates are equal, a movement of workers towards region 1 will lower the price index in region 1 and thus raise real wage. The second is the price index effect: workers in the region with a smaller manufacturing operation will face less competition for the local peasant market than those in the more populous region. The first two effects work towards divergence while the third works towards convergence. Which force dominates depends on the value of the parameters. In particular, he finds that when transportation costs are high, we would expect to see convergence.

Holtz-Eakin and Lovely (1996)'s two-sector model, similarly, specifies a mechanism by which infrastructure allows a lowering of costs in the manufacturing sector and greater industry-level external returns to variety. A general equilibrium framework is used which allows the reallocation of factor inputs and prices in response to changes in infrastructure. The two factor inputs, capital and labour, are assumed to be inter-sectorally mobile and are allocated competitively.

Intermediates are introduced in the production function, the production of which is characterised by internal economies of scale. These economies of scale, together with the external returns to variety described earlier, provide a mechanism for public infrastructure provision to impact output. The model is further enriched by introducing market power in the market for intermediate goods. Intermediate goods are assumed not to be traded and final goods are produced from intermediates produced locally. As market power declines, the mark-up of price over marginal cost declines and each firm produces more as its variety is easily substituted for other varieties.

An increase in the provision of infrastructure in this model leads to a reduction in fixed costs, an increase in the number of component producers and improvements in the external economies of the manufactured good industry. However, the final effect on output in the manufacturing sector is indeterminate and is influenced by the degree of monopoly power. Therefore, in this model, there are not necessarily any growth effects resulting from an increase in the provision of public infrastructure.

New Economic Geography models have a number of advantages over the other approaches: firstly, the assumptions and mechanisms of the model are in line with what we observe in modern economies – product differentiation and increased variety, spatial agglomeration and persistent regional differences in wages, and specialisation that is not explained by the comparative advantage theory or differences in natural endowment.[1] Secondly, the assumption of general equilibrium is highly useful for capturing the full benefits/costs to the economy rather than the more static partial equilibrium approach which could significantly underestimate benefits as the economy responds dynamically to the opportunities presented by improved infrastructure.

2.6 Conclusions from the literature review

This section has described and discussed the theoretical models that have been used, or have the potential to be used, to explain the linkage between public infrastructure and growth. The “black box” models of exogenous growth and traditional endogenous growth models that incorporate infrastructure but simply assume a positive effect are no longer satisfactory to take to the data. Empirical work on the basis of these models has thrown up the weakness that these models do not specify sufficient form to allow an interpretation of the controversial empirical results.

A satisfactory model, from the public policy point of view, must be able to go behind the link between growth and public capital, understanding and explaining the mechanisms that allow infrastructure to lead to significant economic effects. The models that have so far been put forward for this purpose have been those that include micro-economic linkages in the cost or production function. These models typically include specialisation and increasing returns, and in the case of the New Economic Geography models, general equilibrium effects and imperfect competition. These models, which offer a richer structure for studying the mechanisms behind the link between transport and growth, appear to have the highest potential to be used effectively in further research of the effects of transport infrastructure.

[1] Lakshmanan and Anderson (2002) quote the example of trade between Canada and the US, where much trade is intraindustry rather than interindustry.

3 Review on the main methodological approaches in empirical analysis

The empirical approaches that have sought to analyse the relation between public infrastructure and productivity growth have been subject to some criticisms. While some of these critiques are more likely to be important when a production function is used, others are of more general validity and could also apply to a cost function approach. While we will analyse these "more general" critiques when discussing the production function approach (mainly because it is in that context that were first formulated (see, for instance, Holtz-Eakin, 1994 and Sturm and De Haan, 1995) their more general validly should be borne in mind.

3.1 The production function approach

The production function approach to the study of the effects of public infrastructure on economic growth and productivity starts from a neoclassical production function like the one represented in equation 1:

$$Y_t = F(A_t, KP_t, L_t, KG_t)$$

Y represents output, KP represents the stock of private capital, L the number of employed workers (or the number of hours), KG, generally measured in monetary terms, represents either the overall stock of public capital, or narrower aggregates like core infrastructure and transport infrastructure and A represents the total factor productivity level of the country. KG is inserted in the production function as an additional input.

Most studies (and virtually all the older ones) assume a Cobb-Douglas functional form for equation 1:

$$Y_t = A_t KP_t^{\beta} L_t^{\alpha} KG_t^{\gamma}$$

Equation 2 is commonly estimated in logarithm form:

$$y_t = a + \beta kp_t + \alpha l_t + \gamma kg_t + \varepsilon_t$$

Where ε_t is the usual error term appended to the regression equation. Some authors estimate a version of equation 3 with other additional regressors, like a capacity utilisation index to account for business cycle fluctuations and a time trend, or assume constant returns to scale to private inputs or to all inputs.[2]

If a version of equation 3 is estimated with panel data, it could be re-written as:

$$y_{it} = a_i + \beta kp_{it} + \alpha l_t + \gamma kg_{it} + t_i + \varepsilon_{it}$$

The subscript i denotes the cross sectional unit (e.g. a US state, an OECD country, a Spanish region or a specific sector) and t the time dimension (usually year). The a_i denotes an "individual" effect which accounts for any unobservable time invariant factor that might affect the productivity of each unit of observation (for example the level of level of managerial abil-

[2] Some authors (see, for instance, Sturm and de Haan, 1995) test for the validity of the constant returns to scale assumptions, others do not. In the appendix it is explicitly mentioned whether or not untested assumptions like constant returns to scale are made.

ity, institutional features of the country/region, etc), and t_i is a vector of time dummies which accounts for any shock which is common to all units of observation (e.g. a fiscal stimulus from the central government in a given year, or the effects of neutral technical change).

The γ coefficient represents the elasticity of output with respect to public infrastructure capital, as it tells how much output would increase if the public infrastructure stock were increased by 1 per cent. It can be shown that $\gamma = (MP_{KG}) * KG / Y$, where MP_{KG} is the marginal product of KG, i.e. the increase in GDP brought about by a unit increase in KG. The marginal product of capital is taken in some studies as a measure for the rate of return of public infrastructure: however, as it depends on the public capital to output ratio, most studies prefer to report the elasticity measure, which is invariant to the units of measurement.

A first set of criticisms of using equations 3 and 4 relate to the assumption of a Cobb-Douglas functional form to represent the underlying production technology. The Cobb-Douglas is in fact a very simple and convenient representation of the production technology, but it is based on some simplifying assumptions that often do not hold true in the data. For instance, the Cobb-Douglas imposes a unitary elasticity of substitution between inputs which implies, among the other things, that increases in public capital are assumed to raise the marginal and average product of both labour and private inputs. Furthermore, returns to scale are independent of the scale of output, thereby "forcing" the same value for returns to scale to hold for every observation unit (Portugal and Germany in a panel of EU countries, for instance). These drawbacks of the Cobb-Douglas production function led some economists (Everaert and Heylen, 2004 among the others) to estimate the more flexible translog production function, which adds squares and cross products of each input as additional regressors. However the translog tends to consume degrees of freedom and suffers of strong multicollinearity problems: as a consequence, the Cobb-Douglas is still widely used, even if there seems to be a trend of abandoning the production function approach altogether for the cost function and VAR framework (see below).

A second criticism moved to equations like 3 and 4 is that the public infrastructure stock is treated symmetrically to the private inputs, which would be strictly valid only if it could be safely assumed that there exists a market determined unit price of public infrastructure that is known to individual firms (Duggal et al, 1999): as these conditions are unlikely to hold, production functions like those in equations 3 and 4 are likely to violate standard marginal productivity theory according to which input factors are paid according to their marginal product.

A series of issues arise in the estimation of time series regressions like those exemplified by equation 3. The first is the spurious correlation result that might arise in a time series framework when some variables used in the estimation are not stationary. In very simple terms, a time series is stationary when the first two moments of its statistical distribution (i.e. its mean and variance) are constant.[3] Ordinary econometric techniques are not well suited to deal with

3 And the value of the covariance between two time periods depends only on the distance between the two periods and not on the actual time at which the covariance is computed. See Greene (2003) for a discussion of stationarity.

non-stationary time series and the usual inference procedures are in general not valid. The problem is that the time trends in non-stationary variables might lead to identify a close relationship between variables when in fact none exists. While some early studies like Aschauer (1989a) did not test for stationarity, subsequent ones did: in particular, if the series are not stationary, first differences of the series in general are (even if that should be tested rather than assumed). Therefore many studies estimate versions of equation 3 in first differences. While in principle the estimation in first difference should yield similar results to that in levels, in practice it ignores the long run relationship that might exist between the variables, "throwing-out" valuable information. It is however possible that equation 3 represents a long run relationship even when the variables are not stationary, if the variables move together in time, i.e. if they are cointegrated: more recent studies have therefore employed all the "battery" of statistical procedures to test for stationarity and cointegration. The empirical evidence suggests that neglecting the non-stationary aspects of time series could be seriously misleading. For instance, Sturm and de Haan (1995) found that the estimation on US data of an equation similar to 3 yielded a positive and statistically significant elasticity of public capital, whereas the estimation of the more appropriate first difference version of the equation 3 yielded a lower and not statistically significant elasticity.

Production functions like these represented in equation 3 and 4 have been usually estimated assuming that capital and labour are exogenous: however, it is well known that production functions are likely to suffer from simultaneous equation bias which might arise for a variety of reasons. For instance, in a panel data context, simultaneity might arise because the a_i in equation 4 are correlated with the inputs (for instance because some country specific shocks which increase output might be correlated to, say, labour input): in this case the fairly standard fixed effects estimator will remove the simultaneity problem.[4] However, simultaneity might arise also because input quantities are correlated with the ε_{it} in equation 4, a fact that has been often neglected in the empirical literature on the effects of public infrastructure on economic growth: in this case, conventional estimation of equations 3 and 4 are likely to be biased.5 It could be observed, in addition, that in the case of equation 4, the conventional fixed effects estimator will be biased and inconsistent (Nickell, 1981). The simplest solution to the simultaneity issue is to use simple instrumental variables techniques6: a possibility would be to first difference equation 4, using as instruments for the endogenous variables appropriate lags of the same endogenous variables (see for an application Holtz-Eakin, 1994).

More attention has been paid to the reverse causality between output and capital: as long as public capital investment depends on the level of output (for instance because public capital investment are financed from government savings), there might be a feedback which goes from output to capital, rather than the other way round, which might cause equation 3 to

[4] The fixed effects estimator however relies for the estimation on the time variation within each observation unit, discarding the potential useful information which is contained in the variation between units (countries, regions). Furthermore, it is a common finding in the empirical literature on production functions that the within variation is sometimes very badly measured, which can make the fixed effects estimates not as reliable as one might think.

[5] Unless some restrictive assumptions are made (see Griliches and Mairesse, 1998).

[6] Like these based on the generalised method of moments.

overestimate the elasticity of output with respect to public capital.[7] Canning and Bennathan (2000) have provided a useful example, as they assume that capital investments depend on output according to the relation:

$$\Delta K_t = s(Y_t) - dK_t$$

where s(Yt) is a saving function and d the depreciation rate. In the long run, the previous relation implies that:

$$K_{it} = \frac{s(Y_t)}{d}$$

which shows how output might "cause" the public capital stock.

The reverse causality between output and the stock of public infrastructure has been dealt with in different ways.

One possibility is to use instrumental variable techniques such as those described above, which in general requires data in the form of a panel but do not require further information.

Fernald (1999) argued that if one has access to sector level data, an indirect test of the importance of reverse causality would be to explore the magnitude of public capital elasticity across different sectors. In fact, according to Fernald (1999), if the results showed that changes in transport infrastructure were particularly productivity enhancing in sectors that are intensive users of transport relative to other sectors of the economy, then it might be argued that reverse causality is not a major issue, as we should not expect any higher effect of public infrastructure in transport intensive sectors relative to the economy if transport infrastructure were in fact endogenous.

Cohen and Morrison (2003), in a cost function framework, tested for and could not reject the exogeneity assumption of public infrastructure (highways in their case): the intuitive explanation that they gave for their finding was that policy decisions are not likely to be driven by economic conditions in the manufacturing sector of a state, given the relatively small share of manufacturing costs over output (note that their sample was made up of the manufacturing sectors of 48 US states). This implies that samples where the cross sectional units of observations are single (often manufacturing) sectors, the reverse causality issue might be less likely to be important: of course, restricting the focus to the manufacturing sector is likely to underestimate the overall benefits to the economy as a whole brought about by investments in public infrastructure capital.

Canning and Bennathan (2000) argued that, under particular assumptions that they think are in general backed by empirical evidence, the use of panel data could help overcome the reverse causality problem as it would be possible to estimate equation 4 with a simple dynamic

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7 The direction of the bias is however not completely clear a priori, because as long as public capital investment is undertaken as a countercyclical policy, we will tend to see high public capital stocks associated with relatively low level of outputs, implying that the estimation of equation 3 might underestimate γ if the cyclicality in the data is not adequately accounted for.

ordinary least squares technique with no need to use instrumental variable methods, provided that the variables in equation 4 are integrated of order one, the production function relation 4 is homogenous across countries and the investment relation 6 differs across countries.[8]

Other contributions have dealt with the reverse causality issue in a more structural approach. While the details might differ, the basic idea has been to estimate equation 4 jointly with an "infrastructure equation". Examples of this strategy are Charlot and Schmidt (1999), Cadot et al (1999), Cadot et al (2004) and Kemmerling and Stephan (2002). The basic idea behind these studies was to endogenise public infrastructure by building an equation which seeks to explain the process driving public capital formation (a part from GDP) and to estimate it jointly with the production function using appropriate estimation techniques.[9]

3.2 The cost function approach

The production function is a technological relationship which tells the maximum possible output that can be produced, given the input quantities. As such, it does not impose any economic assumption on producer's behaviour.

By way of contrast, the cost function is built on the assumption that, given market determined input prices and conditional on output Y and on other technical variables Z, producers combine inputs to minimise the costs of producing Y. A cost function can therefore be represented as:

$$C = C(W,Y,Z) = C(W,Y,T,KG)$$

W is a vector of factor prices (usually labour, capital and intermediate inputs), Y is the output level and Z are technical variables beyond the control of the firm. Usually, Z variables are represented by a time trend (as a proxy for the time varying level of technology) and KG, the stock of public infrastructure, which the firm is assumed to take as a public good, for which no price is paid (and which therefore can be seen as an externality for the individual firm).

It is sometimes assumed that private capital is fixed in the short run, and therefore a variable cost function -which has the private capital stock as one of its arguments- is estimated:

$$VC = VC(W,Y,Z) = VC(W,Y,T,KG,KP)$$

In the cost function framework, input quantities and costs are endogenous, while factor prices and output levels are assumed exogenous. While the assumption of exogenous factor prices is usually defendable —especially in panels where the units of observation are (relatively small) individual economic sectors or (probably to a lesser extent) regions — the endogeneity assumption of output might be perhaps more problematic, even if most of the literature seems to have implicitly assumed away this problem.

The Cobb Douglas functional form has rarely been used for cost functions (see, for instance, La Ferrara and Marcellino, 2000), while flexible functional forms like the Translog or the Gen-

[8] See Baltagi (2001) for a discussion of stationarity and cointegration in a panel data setting.

[9] Another study that have attempted to estimate simultaneous equation models to solve the reverse causality bias is Esfahani and Ramirez (2003).

eralised Leontief have proved to be much more popular among applied researchers. These two functional forms are flexible because, unlike the Cobb Douglas, they do not impose any a priori restriction on the technology (see above). Flexible functional forms however require the estimation of many more parameters than the simpler Cobb-Douglas and they often suffer from severe multicollinearity problems that tend to reduce the precision of the estimates. However, the multicollinearity problem is in part reduced because, using economic theory, the cost functions in 6 or 7 are usually estimated together with the conditional input demand equations[10]: the joint estimation of the cost function and the input demand equations as a system allows additional degrees of freedom and ensures more efficient (i.e. precise) parameter estimates.

An additional advantage of the cost function over the production function approach that has been extensively exploited in the empirical literature, is the possibility of estimating the effect that public infrastructure has on private sector demand for private inputs or, to put it another way, the estimation of a cost function allows the researchers to test whether the stock of public infrastructure is a substitute or a complement for each private input — for instance, it is possible to test the a priori reasonable intuition that public infrastructure is a complement to private capital (i.e. an increase in the former tends to increase the efficiency of the latter, leading to higher production).

The information directly provided by the cost function is not directly comparable to that which researchers can derive from the estimation of a production function. While the latter provides a value for the elasticity of output with respect to public infrastructure, the former provides information on the elasticity of costs with respect to public infrastructure:[11] if that is negative, then private costs fall when the stock of public infrastructure is raised.[12] From the elasticity of costs with respect to public infrastructure, it is possible to compute the effect that an extra euro of public infrastructure has on the private sector in terms of cost savings in a given year — the gross return of public infrastructure, also known as the shadow price of public infrastructure[13]. The shadow price of public infrastructure can be regarded as the average benefits accruing each year to the private sector firms when an additional euro is spent on public infrastructure: a positive value is a necessary condition for the public capital stock to be "productive". However, from Society's point of view, the investment in public infrastructure also has a social user cost, to which the shadow price should be compared to evaluate the net benefits of an additional unit of public infrastructure.

[10] Which, applying Sheppard's lemma, are derived as the derivative of equations 6 or 7 with respect to input prices.

[11] See Morrison and Schwartz (1996) for a discussion on when the two measures are equivalent.

[12] Some studies (see, for instance, Demetriades and Mamunes, 2000 and Bosca et al, 2002) have also used duality theory to provide estimates of the elasticity of output with respect to public infrastructure, in order to enhance the comparability with that part of the literature that adopts a production function framework.

[13] The shadow price of public infrastructure is measured as minus the derivative of the cost function with respect to the stock of public infrastructure, so that a positive value means that an extra unit of public infrastructure reduces private costs.

Nevertheless, as noted by Morrison and Schwartz (1996), building a social user cost of public infrastructure is not an easy task: first of all, it is necessary to specify a depreciation rate and an opportunity cost of public funds. Furthermore, public capital is financed out of distortionary taxation, which is well known to impose a cost on the economy (the marginal cost of public funds due to the excess burden of taxation). Morrison and Schwartz (1996) have computed the social user cost of public infrastructure for the US states, assuming depreciation rates similar to these used for private capital, using the Moody Baa bond yield on public investment as a proxy for the opportunity cost of public funds and adopting a range of assumptions taken from the literature for the marginal cost of public funds. However, the difficulties in building the social user cost has led many authors to assume it to be zero, or to simply warn the reader that the net benefit of public infrastructure is likely to be lower than what the shadow price might suggest. A further issue is that the few studies that have compared the shadow price and the social user cost of public infrastructure have implicitly assumed that the benefits to consumers are zero or negligible, even if this is unlikely to happen in practice, as consumers may gain from more investment in public infrastructure (for instance in terms of increased leisure if the infrastructure reduces journeys' times).

Cost functions could also be used (see, for instance, Morrison and Schwartz, 1996) to quantify the contribution of infrastructure capital to the rate of growth of total factor productivity, even if this use of the cost function has been less popular among applied researchers. Morrison and Schwartz (1996), for instance, have shown that the total contribution of infrastructure capital to total factor productivity growth can be decomposed into a direct and an indirect effect and that a positive shadow price of public infrastructure is not a sufficient condition for public infrastructure to foster total factor productivity growth.[14]

We mentioned above that the assumption that output is exogenous is not a minor one. This has led some authors (see, for instance, Demetriades and Mamuneas, 2000) to estimate a profit rather than a cost function. The profit function is the result of producers who choose input and output quantities, given output and input prices, in order to maximise firms' profits.

This yields a function analogue to equation 7 above:

$$\Pi = \Pi(P, W, Z) = \Pi(P, W, T, KG)$$

The profit function has, as arguments, the input and factor prices, assumed exogenous, and a trend variable to proxy for technical progress and the stock of public infrastructure.[15] Although the theoretical advantages of the profit function approach are fairly clear, whether, from a methodological point of view the profit function is to be preferred to the cost function in empirical studies is not entirely clear— so far, the latter is still a much more common

[14] For public infrastructure to have a positive impact on productivity growth, it is necessary that, given a positive shadow price, the rate of growth of public infrastructure more than keeps pace with output expansion and "therefore has an impact in addition to the required input [public infrastructure] increase to support output growth" (Morrison and Schwartz, 1996).

[15] An example of a profit function is Demetiades and Mamuneas (2000) who have estimated a variable profit function (which differs from 9 as it has the stock of private capital as an additional regressor because private capital is assumed fixed in the short run) within a system of simultaneous equations derived from an intertemporal profit maximisation framework.

approach among applied researchers who have however not yet addressed, to the best of our knowledge, issues such as reverse causality or output endogeneity in a cost function framework.

3.3 A theoretical comparison of the two approaches.

From a theoretical perspective these two approaches are very similar and in some special cases they are exactly the same. Let's start by assuming that transport infrastructure affect costs. We can write a production function $y = f(k,n)$ and a cost function $c = w(tn) + i(tk)$ where we assume that t is larger than one so that total costs are higher in the presence of transport costs[16]. We can write the profit maximisation problem as $\max \pi = py - c = pf(k,n) - wtn - itk$ so that the first order conditions would be $i = \frac{df}{dk}\frac{1}{t}p$ and $w = \frac{df}{dn}\frac{1}{t}p$.

In the alternative approach we can imagine that labour costs t have a negative effect on the productivity of labour and capital so that we could write $y = f(\frac{1}{t}k, \frac{1}{t}n)$ while firms pay the costs of capital and labour not corrected for transport costs: $c = wn + ik$. The maximisation problem would become $\max \pi = py - c = pf(\frac{1}{t}k, \frac{1}{t}n) - wn - ik$ and the first order conditions would be equivalent:

$$i = p\frac{df(\frac{1}{t}k, \frac{1}{t}n)}{dk} = p\frac{1}{t}\frac{df(k, \frac{1}{t}n)}{dk} \quad \text{and} \quad w = p\frac{df(\frac{1}{t}k, \frac{1}{t}n)}{dn} = p\frac{1}{t}\frac{df(\frac{1}{t}k, n)}{dn}$$

3.4 The VAR approach[17]

As discussed in previous sections, empirical studies that have assessed the impact of public infrastructure capital on output and productivity have adopted a "structural" approach, based on either the production or the cost function. Vector autoregressive models (VAR), instead, impose less theoretical a priori restrictions between the variables:[18] for instance, while the production function estimation is carried out assuming a causal relation which goes from private and public inputs to output, VAR models do not impose any causal link, but rather they facilitate the ascertaining of whether there are substantial feedback effects which goes from, say, output to the stock of public infrastructure. Furthermore, while the production function approach specifies the impact of public infrastructure on output, given the other variables in the model, the VAR approach estimates of the long run effect of public infrastructure on output incorporate both the direct effect that public infrastructure has on output and also the indirect effects (e.g. through the impact that it has on private inputs). An

[16] Of course if transport costs enter the function additively they have no effects at the margin.

[17] This section draws heavily on Kamp (2004).

[18] Roughly speaking, given k variables, a VAR consists of a system of k equations, where each variable is regressed on past lags of itself and the other k-1 variables.

additional advantage of VAR is that, unlike in the production function approach, the researcher is not forced to assume that only one long run cointegration relation exists between the variables. Another advantage of VAR is that they can be estimated with simple OLS equation by equation, even when some of the variables are non stationary.

However, without imposing any restriction on the data, VAR estimates cannot be given a structural (causal) interpretation, and are therefore not very useful for policy purposes: researchers therefore impose some restrictions on the variables which are based on theoretical assumptions (for instance, that public capital does not react contemporaneously to shocks to other variables in the system, or that private capital does not react contemporaneously to shocks to GDP but is affected contemporaneously by shocks to public capital)[19] whose impact on the main results should be in principal carefully investigated.

Furthermore, the presence of non-stationary data is likely to distort the estimates of impulse response functions, which are often the main output of the VAR approach, as they tell the response of macroeconomic variables (like employment, private capital and GDP) to an unexpected change in one variable (say, public infrastructure). When non stationary variables are present, it is therefore necessary, as in the production function approach, to first difference these variables or, if one or more cointegration relations exist, the VAR equivalent to error correction models (VECM) could be estimated.

Kamps (2004b) has noted that the majority of VAR studies that have sought to estimate the impact of public infrastructure on GDP have not reported confidence intervals for the impulse response functions. This is unfortunate because a positive and large impact of public infrastructure on GDP could well be not significant, as some evidence reported in Kamps (2004) seems to suggest. Therefore, in the Appendix, we will carefully report, for each VAR study analysed, whether or not the results are accompanied by confidence intervals.

4 The empirical evidence

The main aim of this section is to provide an overview of some of the studies that we have analysed for the literature review on the effects of transport and public infrastructure on economic growth and productivity.

The tables in the Appendix list all the studies that we have been able to identify so far and that should provide a robust picture of what can be found in the empirical literature on the subject. For each study we have identified the authors, year of publication, source, geographical area (e.g. Spain, German regions, OECD countries, etc), approach (VAR, production function, etc), a summary of the specification and estimation methodology, sample period, sample type (time series rather than panel data), sector (total economy or, say, manufacturing sectors), definition of the public infrastructure variable used in the study (public capital, core infrastructure, transport infrastructure) and the study's main results. In the light of the methodological discussion of section 3, the tables in the Appendix should provide sufficient

[19] See Kamps (2004b).

information on the type, quality and relevance of the studies that we have analysed in this literature review.

Having said that, in the remainder of this section we will discuss in some more detail some studies that we believe represent well the main approaches that have been used in the applied research: in particular, we will structure the discussion on the basis of the methodological approach employed in the individual studies.

A further comment might be important: the scope of the project is to assess the contribution of transport infrastructure to economic growth. Unfortunately, most of the literature is concerned on the measurement of the effects of public capital: while we believe that that literature can provide useful insights on the effects of transport infrastructure on economic growth -given that the latter constitutes a large fraction of public infrastructure and it is reasonable to expect that it is also the most productive- nevertheless we will put more emphasis on these papers that have focused their attention to narrower definitions of the stock of public capital, such as core infrastructure or transport infrastructure rather than the overall public capital stock.

In addition a number of studies have provided empirical estimates for a series of countries (either alone or within panel data studies) the bulk of which was made up by EU countries. In that case we have decided to review the relevant study in the relevant EU section [20]

Finally, It is important to note that, given the focus of the project, we have focused the literature review on the US and EU empirical evidence. Although that covers the large majority of studies that have been published in the field, it does not exhaust all the international empirical evidence. There are also for instance some empirical estimates for countries such as Canada, Japan and Australia, plus a series of cross country studies focusing on developing countries. While not covered in detail in this report, that evidence does not seem to alter significantly the main conclusions that could be drawn from the EU and US evidence (see Romp and de Haan, 2005).

4.1 The US evidence: production functions[21]

The seminal US paper is Aschauer (1989), to which many later papers are responses. The main motivation behind this paper is to test empirically 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

[20] The tables in the Appendix allows their identification.

[21] This section draws heavily on Duran-Fernandez (2006)

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 economic literature to the point of being known as the 'production function approach', as discussed in section 3.1. His results raised several questions and prompted many further studies of the effects of public infrastructure on the economy. Although few authors have questioned that infrastructure should be expected to have an impact on production, the magnitudes of the effects estimated by Aschauer have come under considerable challenge. 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 (in fact, 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).

One criticism of Aschauer's study is that the aggregate correlation that he finds does not imply any causal relationship between production and infrastructure. Garcia-Mila et al (1996), and Evans and Karras (1994) suggest that if these variables are non-stationary, this relationship might reflect only a spurious correlation. A more fundamental criticism concerns the causal direction of any correlation: do public capital increments actually cause economic growth, or does the causality operates in the opposite direction?

Other attempts to review Aschauer's work focus on the estimation of aggregate production functions at state level, such as Evans et al. (1994), Garcia-Mila et al (1996), Hotz-Eakin (1994), and Kelejian et al. (1997). Conceptually, these papers follow the same empirical strategy (based on panel data) and in most cases use the same definition of public capital. The main advantage of this panel data approach in this context is that state level samples are large enough to produce more reliable estimates than would be obtained by a time series approach. The most important problem is the lack of primary data on public capital stock at state level. Consequently, 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 estimations. 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 desegregated levels of public capital, confirming that at the state level, the effects of public capital stock on absolute production levels are negligible. This paper also performs formal tests that fail to reject endogeneity of public capital.

The empirical estimates in Evans and Karras (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, this paper concludes that public capital does not have an important quantitative role in explaining the growth patterns across states in the US.

The use of panel data answers some of the criticisms of 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 state level production functions under several econometric specifications. 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.

Following the same line Garcia-Mila et al. (1996) find that there is no evidence of a positive linkage between public capital and private output when studied within the aggregate production function framework. Their results however are assessed within a very narrow framework that does not exhaust all possible methods for examining the linkage between public capital and productivity.

One promising strategy to address 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 identifying 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 and 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 estimation. 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 clear that the estimated effect of road infrastructure into 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 to imply that similar levels of investment in road infrastructure would have the same return in the margin 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 –i.e. that the stock of existing roads matters in determining the marginal effects.

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 output with respect to infrastructure 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.

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. Rather than define a static production function, they estimate how the economy converges to a steady state. The steady state level of output is a function of public capital and the change in output for each region depends on the distance between current output and steady state output. This formulation 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 estimations of this paper show that the effects of public infrastructure in the US and Japan are similar. The empirical analysis supports evidence 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 in a range between 0.09 to 0.143 for the US, and 0.10 to 0.169 for Japan. These values are considerably lower than the short run elasticities estimated in previous literature, suggesting 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 suggests that the contribution of public infrastructure in the post-war period has been modest.

From a theoretical point of view, the expansion of public capital stock in one region might 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 might lead to 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 finding 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 between 0.16 and 0.22, considerably smaller than the estimation obtained with national aggregated 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 the 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 that are more likely to lead to 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, these effects are smaller than in earlier literature. Finally, the paper suggests that the most important gains of public infrastructure are found at the local level, and that these gains have important distribution effects across locations.

A few comments on the main findings of the production-function approach are warranted. The Aschauer (1989a) paper highlighted the importance of public capital on economic activity: although some early papers broadly confirmed his main findings, there seems to be a consensus that the early estimates of the effects of public capital on economic activity overstated the magnitude of the effect. Moreover, the econometric methodology that the early papers used is subject to severe critics. Furthermore, it was generally found that studies based upon state level information, tend to generate smaller estimates, and solve some of the econometric problems found in the earlier literature. However, in general they failed to estimate robust results in the sense that they were 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 that were often underestimated in the early literature. One issue with 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 might consider marginal productivity conditions as well as the production function, independently of whether the subject of analysis is national, regional, or local level aggregated data (Nadiri et al. 1998).

4.2 The US evidence: cost functions

Despite providing useful information on the linkage between public capital and production, the production function approach may not capture behavioural responses of firms to variations in public capital (Nadiri et al. 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).

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 *et al.* (1998) conduct a similar study extending the scope of his 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 elasticities range between 0.04 and 0.05 in absolute value.

They also find a positive output effect of infrastructure; concluding however that higher total production costs associated with output expansion are financed almost entirely by cost saving productivity gains. The 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 $1.0 increase in highway capital range between 0.2 and 0.6. This assessment does not consider congestion effects.

The paper suggests that motorway infrastructure has a positive contribution to productivity growth in all industries. At an 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 (note that this does not include 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 factor demands but these effects are of different magnitudes.

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 suggest 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.

Nadiri and Mamuneas (1994) use a cost-function framework to study the effects of public infrastructure and 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 suggests that public infrastructure and publicly financed R&D induce productivity growth. The main results are that an increase in infrastructure capital services leads to a decline in the demand for labour and capital in each industry, and to an increase in the demand for intermediate inputs in most of the analysed industries.

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 the assessments carried out 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 in 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 on industry activities.

The conceptual difference between the aggregate production function and the cost-function approaches 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 some authors argue that perfect competition assumptions fail (Haughwout 2002).

4.3 The US evidence: other approaches

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) use data from the *American Housing Survey* and a broad definition of public capital of 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 evidence important effects of public capital on the relative price of input factors. For example, it shows that 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 through possibly time savings.[22].

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 the exact description of the events described above, 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 linkage between public capital and production.

4.4 The US evidence: VAR 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, even those which theory may not usually consider.

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. 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 in-

[22] It should be noted that the welfare gains identified in Haugwout (2002) are not considered in GDP growth accounting. Nevertheless, they sometimes represent important welfare gains for individuals and families. Furthermore, there are other important economic implications of transport infrastructure that are not considered in GDP computations, such as the impact on the environment, the enhancement of social networks and so forth.

vestment 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 paper presents a discouraging conclusion that might have important implications on previous works. The estimated policy function at an 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. This finding suggests endogeneity of public investment with output. This result is an important caveat that should be further explored.

4.5 The EU evidence: production functions

We have identified 17 studies that have presented empirical evidence on the relation between public infrastructure and economic growth and that have used a production function approach. Of these, 3 (Evans and Karras (1994) Kamps (2004) and Kamps (2005)) used "international samples", while the others relied on national samples; 4 used time series analysis (with appropriate econometric techniques to deal with non-stationarity issues) with the others using a panel data approach.

The evidence displayed in the Appendix tables suggest that most studies estimating production functions (or employing the related total factor productivity regression approach) identify a positive effect of public infrastructure on output and productivity. With some notable exceptions (for instance, Sturm and de Haan, 1995 and Stephan, 2003 who find elasticities in the range of 0.6-0.8 and 0.38-0.65[23], respectively) the elasticities of output with respect to the stock of public capital tend to range between 0.10 and 0.20, a far smaller value than the 0.35 originally identified by Aschauer (1989) and more in line with the findings of Munnell (1990b) who found an elasticity of about 0.15.

For example, Bajo Rubio and Sosvilla-Rivero (1993) estimated a production function using time series data for the Spanish economy using the Phillips and Hansen procedure and found an elasticity of output with respect to public capital of about 0.2, depending on the exact specification of the production function.[24] Kamps (2005) followed Aschauer (2000)[25] and estimated an endogenous growth model which allows exploring the non linear link that might exist between economic growth and infrastructure capital (the non linearity arising

[23] This would correspond, in his sample, to a rate of return of about 43-73 per cent and 26-45 per cent, depending on the output to public capital ratio.

[24] They also found that the marginal productivity of public capital was slightly higher than that of private capital (0.61 versus 0.36, respectively), which they interpreted as a suggestion that even in the presence of a complete crowding out of private capital, private output would still be increased by increasing public capital.

[25] Who built on Barro (1990).

from the government financing public capital through a tax levied on the private sector) and deriving the growth maximising public capital stock: he found that, for a panel made up of the "EU-15", the elasticity of output with respect to public capital was about 0.20, a very similar result from Kamps (2004a) who reported an elasticity of about 0.22 from a production function for a panel of OECD countries. Picci (1999) estimated a production function for the Italian regions and found, after first differencing the variables to take into account possible non stationarity, an elasticity of about 0.18.[26] Stephan (2001) estimated a production function for a panel of German and French regions and found a positive elasticity of about 0.08-0.11

A few studies even found negative or insignificant elasticities (Evans and Carras (1994), who used a panel of five EU countries plus US and Canada, and Delgado and Alvarez (2000) who used a panel of Spanish regions). Bonaglia et al (2000) and La Ferrara and Marcellino (2000), using panel data for the Italian regions, found a positive but insignificant elasticity and a negative and significant elasticity, respectively[27]. The same authors, however, report that public capital significantly increased the rate of growth of total factor productivity and that the elasticity of output to public capital was about 0.47 which is in a clear conflict with the findings based on the production function[28] and that cast some doubts over the overall "stability" of the results.[29]

We have noted above that one of the explanations for the high results of Aschauer (1989a) was the possibility of reverse causation between public capital and output. The large majority of studies we have reviewed which employed the production function approach did not investigate the issue, perhaps taking the view that, in a panel context, allowing for fixed effects would have been enough to solve the problem (notable exceptions are Bajo-Rubio and Sosvilla-Rivero, 1993, La Ferrara and Marcellino, 2000 and Percoco, 2004).[30] A similar consideration could also be made for the possible simultaneity between output and private inputs.[31]

[26] It is interesting to note that the regressions in levels yield a much higher value (about 0.5).

[27] La Ferrara and Marcellino (2000) present estimates that should be robust to reverse causality bias, even if the simple OLS results do not change the picture significantly.

[28] The two approaches should yield comparable results. See La Ferrara and Marcellino (2000).

[29] This is a remark that also Sturm and de Haan (1995) made in relation to their own estimates for the Netherlands.

[30] Kopp (2005) built on Fernald (1999) and estimated a model where, given n countries, the difference between the TFP growth rates in each country and the average TFP growth rate, was regressed on the product between national vehicle intensity and growth in national road services and the product of overall vehicle intensity and overall growth in road services, and found that an increase in national road services would improve, ceteris paribus, national productivity growth relative to the productivity growth of the n country group. Kopps (2005) argues that his approach allows to deal with reverse causality issues because it is reasonable to assume that countries which use roads more intensively (relative to the average) should benefit more from their expansion. In other words, if governments were simply building roads as a by product of output expansion, there would be no reason to expect any particular relation between a country transport intensity and its relative productivity performance. Kopp (2005) also found a rate of return for road infrastructure capital of about 5 per cent.

[31] But see what we said above on reverse causality and simultaneity issues in panel data context.

However, a series of papers (Stephan, 2000, Cadot et al, 1999, Cadot et al, 2004 and Charlot and Schmidt, 1999) tried to deal with the existence of endogeneity of public capital using a simultaneous equation framework.

For instance, Kemmerling and Stephan (2002) built a political economy model in which a production function with public capital was estimated together with two equations explaining the investment decisions by German local authorities and the allocation of funds from higher tier governments in Germany. Estimating the model using appropriate econometric techniques, they found that the elasticity of output with respect to public capital was positive and significant (about 0.17, which would correspond to a rate of return of about 16 per cent).

A similar approach was followed by Cadot et al (1999 and 2004) for a panel of French regions: they in fact estimated a production function together with an equation to explain the infrastructure investment decisions and found positive and significant elasticities, in the order of about 0.08 and 0.10 (which would correspond to a rate of return of approximately 44 per cent). Interestingly, the estimates they obtained were very close to these obtained ignoring the endogeneity issue.

Charlot and Cadot (1999) took a similar approach and found large elasticities (about 0.3) of output with respect to public capital. However, the results do not appear to be particularly robust, because in a version of the model estimated by 3SLS the value of the elasticity falls and becomes insignificant.

It is interesting to note that the results reported in some studies seem to be characterised by significant variability across regions and across time.

For instance, the results for Italy provided by La Ferrara and Marcellino (2000) and Bonaglia et al (2000) masked quite different elasticities for sub regional aggregates (such as North, South, Centre) and across time. Public capital seems to have been more effective in stimulating growth in the south and the centre of the country rather than in the more developed north[32], and the negative elasticity found at the national level for the 1970-1994 period in Marcellino and La Ferrara (2000) seems to hold only for the 1970s, while in more recent years it appears to be large and increasing.[33]

Charlot and Cadot (1999) estimated the model explained above assuming a translog functional form for the production function, which allows them to compute the relevant elasticities for the French regions which made up their sample, and they found high values and substantial variability (0.17-0.51), with elasticities which tended to be higher in more developed regions. Another example is Kamps (2004a) who estimated a production function in first difference using a panel of 22 OECD countries: not only did he pool the observations together but he also estimated separate regressions for each country. While the panel regres-

[32] But see Percoco (2004) for a different result. Interestingly he obtained different results also for the whole sample, as he found a positive elasticity of output with respect to public capital, although the estimated methodology differed from that employed by both Bonaglia et al (2000) and La Ferrara and Marcellino (2000).

[33] However, to compute the estimates for sub regions or sub periods, the authors split the sample, thereby reducing substantially the degrees of freedom of the regressions.

sion yields an elasticity of about 0.22[34], the time series estimate show a large variability across countries: from negative (though insignificant) estimates for Portugal and Ireland, to positive, large and significant (Germany and The Netherlands, for instance).[35]

Finally, some studies have reported estimates using different aggregates for the public capital stock. For instance, Sturm and de Haan (1995) estimated a production function in first difference, using different aggregates to measure the stock of public capital, like the total public capital stock, buildings and infrastructure, only buildings and only infrastructure (land, road and water construction). While the estimates appear in general implausibly high, as noted by the same authors, infrastructure seems to play a far more important role in stimulating output growth than buildings.

Bonaglia et al (2000) report estimates for a production function where the stock of public capital is disaggregated into three components: transport, water and others (mainly communication and education) and found that the transport category has by far the largest positive (and significant) effect for the country as a whole and for the sub-regional aggregates (with the exception of the centre, where the elasticity was significantly negative). Similar results for Italy are reported in Picci (1999) (where core public capital seems to be more productive, with the exception of the North West of the country) and Destafanis and Sena (2004) (who estimated the relationship that exist between total factor productivity and the stock of public capital in a panel of Italian regions and found that public capital in general tends to increase total factor productivity and that the effect is much stronger for core infrastructure than for non core infrastructure).[36] [37] It is too early to draw robust conclusions, but the limited empirical evidence that we have reviewed seems to suggest that core infrastructure (of which transport infrastructure is a large part) is more productive than non-core infrastructure, as common wisdom would suggest.

We have mentioned in Section 1 the methodological problems that surround the definition of one of the few monetary aggregate for the stock of public capital (however broadly defined). Delgado and Alvarez (2000) is the only paper which does not rely on a monetary value for the stock of public capital. They have collected information on physical measures for some types of public infrastructure (e.g. km of high capacity roads, km of simple electrified railways, km of gas pipelines, km of non high capacity roads, km of double line electrified railways, etc) and used a principal component analysis technique to aggregate these physical measures into a single infrastructure indicator which they then inserted into an otherwise standard translog production function that was estimated for a panel of Spanish regions: the

[34] He assumes that country fixed effects have an impact on the level of output only, which amounts to assume that elasticities of public an private inputs are common across countries, which can be regarded as a quite restrictive assumption, especially in cross-country regressions, where market conditions, and levels of economic development can vary widely.

[35] We have to note that running the time series regression entails a heavy degrees of freedom loss. Furthermore, some results appear to be quite implausible, such as the 0.8 elasticity for Germany and the US and the 0.9 for the Netherlands.

[36] However, the authors do not reports standard errors for the estimates

[37] They also report the results form a Vector autoregressive model that suggests that core infrastructure and total infrastructure are weakly exogenous.

main result of their analysis was that the elasticity of output with respect to the composite infrastructure indicator was negative (-0.02).[38]

It is difficult to comment on the overall reliability and "quality" of the results. However, in general, we might observe that the largest results for the elasticity of output with respect to private capital could cast some doubts on the overall reliability of the econometric exercise that produced them. For instance, Sturm and de Haan (1995) observed that their "large" elasticity of public capital is associated to a really low or even negative elasticity of output with respect to private capital, a result which is difficult to reconcile with standard economic theory. In fact, if we make the standard assumptions that private firms combine capital and labour to maximize profits, we expect, as formally shown, for instance, in standard economic growth models a la Ramsey that the marginal product of capital will be equal to the real interest rate, which depends, among the other things, on the rate of time preference and the risk-profile of the investment. A negative of nearly zero elasticity of output with respect to private capital would therefore be difficult to reconcile with standard economic theory.

In Table 1 we have reported the elasticities of output with respect to private capital, labour and public capital for some of the studies we have discussed above.

It is difficult to identify a clear pattern between private and public capital elasticities from the results shown in Table 1. However, the two studies with the highest public capital elasticities tend to find private capital elasticities which are either negative (Sturm and de Haan, 1995) or substantially lower than public capital elasticities, while those studies which report the lowest public capital elasticity also find, in general, much higher private capital elasticities[39] We noted above that the finding of a negative or nearly zero elasticity of private capital is not easy to reconcile with neoclassical economic theory. In general, a natural expectation might be that private capital should command a higher return than public capital, unless there are serious shortages of public infrastructure in the economy, because it would seem reasonable to assume that the risk profile of private investments is generally higher than that of public investment. However, in financial economics it is not risk per se, but systematic risk (i.e. non-diversifiable risks, arising, for example, because of a correlation between the risks and the general economic cycle) that is the driver of returns. Following this insight, it might be expected that, in fact, public infrastructure expenditure returns should be greater than those from private capital — for example if transport-using sectors such as freight tended to produce high returns when the economy in general is doing well but low returns in recessions.

[38] No standard errors were reported by the authors.

[39] An exception is Cadot et al (2004) who find a private capital elasticity which is higher than that of public capital but who also find a perhaps unrealistic elasticity of labour which, according to standard marginal productivity theory, it should reflect the share of labour in total income.

Table 1: Elasticities of Output with respect to Public and Private Capital and Labour

	Public capital	Private capital	Labour
Bajo-Rubio and Sosvilla-Rivero (1993)	0.18	0.43	0.39
Sturm and de Haan (1995)	0.63 to 0.80	-0.61to 0.82	0.93 to
Picci (1999)	0.18 to 0.36	0.07 to .17	0.46 to .83
Stephan (20003)	0.38 to 0.65	0.10 to .30	0.26 to .50
Cadot et al (2004)	0.08	0.18	0.77
Kemmerling and Stephen (2002)	0.17	0.57	0.32
Percoco	0.14 to 0.18	0.16 to 0.28	0.62 to 0.72
Delgado and Alvarez (1999)	-0.03	0.63	0.25

4.6 The EU evidence: cost and profit functions

We have identified 14 studies that have provided empirical estimates of the effects of public infrastructure on GDP and productivity: with some notable exceptions, they all find that the stock of public infrastructure tends to reduce private sector costs. There appears to be substantial variability across studies, with some finding elasticities very close to zero, sometimes not even significant, with other studies finding elasticities in the order of about -0.05/-0.1 (which means that an increase of 1 per cent in the capital stock would lead, on average, to a reduction of private costs in the order of 0.05-0.1 per cent) and, finally, a minority finding cost elasticities of about 0.20.

Unfortunately, some studies do not report standard errors for the elasticity estimates, and therefore it is not possible to know whether, say, a negative elasticity was significantly different from zero. Furthermore, we have noted above that the finding of a negative elasticity (or a positive shadow price) is not sufficient to conclude the public capital is indeed optimally provided: in fact, the shadow price of public infrastructure should be compared with its social user cost: unfortunately, this has been done only in a few cases, perhaps reflecting the inherent difficulty of deriving robust measures of the social user cost. Furthermore, a few studies have reported only the elasticity of costs with respect to public infrastructure, rather than the shadow price, which could be used as a proxy for the gross rate of return of investments in public infrastructure.

All the studies that we have identified (with the notable exception of Lynde and Richmond, 1993 and Berndt and Hansson, 1992) used panel data on regional samples[40] (or on groups of

[40] In a few cases the relevant economic unit was the manufacturing sector(s) of the region while in others the focus was on the total private sector in the region.

manufacturing industries within a country), and this, combined with the flexible functional forms employed for the cost function, allows the estimation of cost elasticities and shadow prices of public infrastructure separately for each region (sector). While some papers have shown that the average elasticity for the whole sample was quite informative of the dynamics at regional (sector) level, others found that the value for the whole sample (i.e. the country value) masked quite different impacts of transport infrastructure at regional (sector) level.

Moreno et al (2003) estimated a variable cost function assuming that the private capital stock was a fixed input in the short run for a sample of 12 manufacturing industries, one for each of the 15 Spanish regions from 1980 to 1991. They found that the elasticity of variable costs with respect to the stock of public capital (defined as the stock of core public infrastructure) was negative (i.e. core infrastructure tends to reduce variable costs) but hardly statistical significant, with a similar pattern across regions. For the shadow price of public infrastructure, they found an average value of 0.004[41] (i.e. an additional 1000 pesetas would be worth, for the private sector, 4 pesetas or, putting it different, public infrastructure would have a gross rate of return of about 0.4 per cent). They also reported estimates for the elasticity of output with respect to public core infrastructure and they found a positive elasticity of about 0.03, much smaller than the "average" result from the production function approach. However, Moreno et al (2003) found that the effects of public core infrastructure on private sector costs are far from homogeneous at the sector level: for instance, electric machinery, food and drinks and textiles seems to be these that have gained most from public core infrastructure, while metallic minerals, chemistry and non metallic minerals and products these that gained less.

Similar results were found by Bosca et al (2002) who estimated a variable cost function using a panel of Spanish regions for the period 1980-1993.[42] They in fact found that the average elasticity of costs with respect to the public capital stock was about -0.03 and it was positive in 15 out of 17 regions. The elasticity of output with respect to public infrastructure was found to be 0.026 in the short run, very much in line with Moreno et al (2003). In the long run, private capital can be adjusted by firms: therefore Bosca et al (2002) report new estimates for the effects of the public capital stock assuming that the private capital stock was at its long run optimal level. They find very similar results, with the long run elasticity of costs to public capital being about -0.037 and that of output to the public capital stock about 0.035.

They also compared the shadow price of public infrastructure (or gross return) which (both in the short and in the long run) is positive in all regions, with an average value of about 0.20 (which means that one more peseta of investment in public infrastructure would tend to reduce private costs by about 0.20 pesetas). More importantly, Bosca et al (2003) compare the shadow price of public capital with a range of values for the user cost of public capital and find that the former was always higher than the letter, even if the difference narrowed over time, suggesting that the infrastructure gap in the Spanish economy had been falling over time.

[41] Not significantly different from zero.

[42] The study was based on figures for the total economic sector at the regional level.

Favourable evidence for a positive effect of public infrastructure for the Spanish case is also found in Zugasti et al (2001), who found positive shadow prices for the stock of core public infrastructure[43] estimating a variable cost function for a panel of 14 Spanish industries, observed over the period 1980-1991. The average shadow price (or gross return) was about 0.23 (in a range of 0.07-1.32). They also found an elasticity of output with respect to core infrastructure that provides an upper bound for the cost function studies, namely 0.24. The average value masks, however, significant variability across industries, with the construction sector gaining the most (0.64) and the sector of electric materials much less (0.07).

Canaleta et al (1998) estimate a total cost function using data on Spanish regions and three distinct sectors, agriculture, industry and services for the period 1964-1991. Their results are broadly similar to the papers surveyed above, with a slightly higher elasticity of costs with respect to public infrastructure (in absolute terms): interestingly, that elasticity is higher (in absolute terms), when a broad measure of capital stock is considered, while it turns out to be smaller when only public transport infrastructure is considered (in the case of agriculture it even turns out positive.[44] There is however some variation across sectors and regions, and depending on the infrastructure variable chosen, even if it is not immediate to identify a clear pattern in those differences.[45] The authors try to explore the theoretical possibility that transport infrastructure generates spillover effects, which would make the use of the stock of transport infrastructure in the single region not appropriate to capture the full benefits of transport infrastructure. They built a "new transport infrastructure" variable which, for a representative region A is given by the average stock of infrastructure in all other regions weighted by the share in the total flow of trade towards these other regions taken up by trade from region A. Accounting for spillover effects seems to matter, as they find a small increase in both cost and output elasticities, even if the increase is not particularly large.

The results for the Spanish case are somewhat supported by the existing empirical evidence for Greece. For instance, Rovolis and Spence (2002) estimated a total cost function for the manufacturing sector of Greek prefectures over the 1982-1991 period and found a negative (-0.06) elasticity of costs with respect to public infrastructure stock, with no significant variability across regions.[46] Though intimately related to the cost elasticity, the shadow price of public infrastructure does present some variability across prefectures, with those prefectures that are adjacent to the two large metropolitan areas having the highest shadow prices: in particular, the average shadow value was about 0.35, with a maximum value of 1.65 and a minimum level of 0.0004.

Mamatzakis (1999) estimated a total cost function for a panel of 20 2-digit large scale manufacturing industries in Greece over the period 1959-1990 and found that public infrastructure (defined as core infrastructure) tends to decrease total costs,[47] although there appears to be

[43] The values for the elasticities are not reported but they have by definition the opposite sign of the shadow price.

[44] Standard errors for the estimates are however not reported.

[45] A similar pattern is found also for the elasticity of output with respect to public capital.

[46] However, it should be noted that standard errors for the estimates of elasticities are not reported.

[47] No standard errors for the elasticities are shown.

large differences across sectors, with some displaying positive elasticities (chemicals, tobacco, textiles, footwear and wearing apparel). He also used the cost function estimates to decompose total factor productivity growth as explained in Morrison and Schwartz (1996) and found that core infrastructure contributed to only a small portion of total factor productivity growth in the Greek manufacturing sector, and at a declining rate.

Lynde and Richmond (1993) used time series data for the UK economy to estimate a cost function and used the results to decompose labour productivity growth into components attributable to the growth in the private capital to labour ratio, to the growth in the public capital to labour ratio and to a residual term (which captured the effects of technological change, scale economies and market power). The result was that the rate of growth of public capital to labour ratio added about 0.2 percentage points to the rate of growth of labour productivity (which was 3.15 per cent each year over the sample period) and that over the 1980s the contribution was actually negative.

Some evidence of a positive effect of public infrastructure in reducing private costs can be found, for West Germany, in a paper by Seitz and Licht (1995) who estimate a total cost function using a panel of regional manufacturing sectors, with labour and capital as the only production factor (and using value added, rather than gross output, as output)[48] and find a rather large elasticity of costs with respect to the stock of public infrastructure (-0.21)[49], with higher values (in absolute value) for regions that have largest areas (Nordrhein-Westfalen, Bayern and Baden-Wurttemberg)[50]

Less favourable results for the effect of public infrastructure reducing costs is that contained in La Ferrara and Marcellino (2000) who estimate a Cobb Douglas variable cost function for Italian regions over the 1970-1994 period and find a positive, but low elasticity of costs with respect to public capital (i.e. public capital would tend to increase costs). Across sub periods, they find that only in the 1970s the elasticity was positive, while in the subsequent period it was negative. However, also in the period 1980-1994, the shadow price of public infrastructure, though positive, was not high enough to cover its social user costs, suggesting that there was an overprovision of public capital. At the level of macro-regions, the centre performed better, followed by the South, where the elasticity was negative, but the shadow price of public infrastructure remained lower than its social user cost.[51][52] Other evidence in favour of overprovision of public infrastructure or, at least, of shadow prices than are not high enough to more than outweigh their social user cost is provided in Berndt and Hanssen

48 We can recall that the implicit assumption underlying the estimation of a value added production or cost function is that intermediate inputs are separable in the gross production function (Chambers, 1988).

49 No standard errors for the elasticities were provided.

50 Seitz (1994) presents empirical estimates of a cost function estimated with a panel of 31 2-digit manufacturing industries in West Germany and found very low shadow prices of public infrastructure (somewhat lower when core infrastructure was used rather than total infrastructure: the average value of the shadow price, in the case of core infrastructure, was 0.0036, which means than an extra 1000 DM would have brought about 3.6 DM of benefits for the firms.

51 However, the authors warn about the possibility that their measure of the social user costs could overestimate its true value.

52 Similar results are reported in Bonaglia et al (2000).

(1992), who estimate a labour requirement function[53] for the Swedish economy using data for the period 1964-1988 and show that while public infrastructure had been underprovided in the early years of their sample, in the later period public infrastructure was actually over-provided.

Demetriades and Mamuneas (2000) estimate a dynamic model or production based on an inter-temporal maximization framework using a panel of the manufacturing sector of the 12 OECD countries (the G7 countries plus Australia, Belgium, Norway, Sweden and Finland) over the 1972-1991 period. They assume that producers maximise the expected future values of profits taking the public capital stock as given. They solve the model in two stages: in the first, which corresponds to the short run, the private capital stock is assumed fixed for the existence of internal adjustment costs and, therefore, firms choose input and output levels to maximise variable profits. In the second stage firms choose their preferred level of private capital stock.

This specification of the model allows them to specify the effects of public capital on output both in the short and the long run. In the short run, public capital can increase output only directly, and not through its effects on the private capital stock, which is fixed: the empirical evidence presented by Demetriades and Mamuneas (2000) seems to suggest that public capital tends to increase output, with elasticities which varies form the 0.36 per cent in the UK to 2.06 per cent in Norway.[54] These elasticities do not vary much in the long run, when firms have fully adjusted their capital stock to their desired optimal level. Unlike other studies (see, for instance, Rovolis and Spence, 2003, Seitz, 1994, Mamatzakis, 2000, Seitz and Licht, 1995 Everaert and Heylen, 2004) Demetriades and Mamuneas (2000) found that public and private capital are substitutes, as labour and public capital (this is in agreement with the studies cited above). As in some of the cost function studies, Demetriades and Mamuneas (2000) compare rates of returns for public infrastructure (which are the equivalent of the shadow prices in the cost function framework and which they define as the amount that the manufacturing sector is willing to pay, in terms of increased profits, for an additional unit of public capital, at the optimal level of output, capital and labour) to its costs[55]: in the short run, rates of return (gross of depreciation) range from 11 per cent in the UK to 27 per cent in Italy, while in the long run they range from 29 per cent in the US to 39 per cent in Italy.[56] Comparing these figures with their estimates for the user cost of public capital, they conclude that, in the long run, public capital had been under-provided in all countries, but that the "public infrastructure gap" had been falling over time for all countries and that for some it was even closed at the end of the sample period. For instance, Belgium seems to have closed its underinvestment gap in the early 1980s, which is not surprising for the authors, given the extensive road investment projects that were undertaken in the previous decade.

[53] A labour requirement function is related to a variable cost function when labour is the only variable input.

[54] All the elasticities are statistically significant.

[55] Unlike some of the studies discussed above, they astray from complications arising from the absence of lump sum taxation.

[56] An interesting features of these figures is that countries with the lowest public capital to output ratios have the highest returns.

4.7 The EU evidence: VAR approach

An increasing number of studies have been recently published that use Vector Auto Regressive (VAR) models to explore the impact of public infrastructure on economic growth. VARs seem indeed to have become the standard time series approach in the public infrastructure-output growth literature, displacing the production function approach, which was more popular in the early 1990s.

Most of the studies have been conducted at national level only, with only one (Kamps, 2004b) dealing with an OECD sample, and another one with a group of 6 countries (Mittnik and Neumann, 2001).

Most of the evidence that we have been able to analyse seems to point towards the existence of a positive effect of public capital on output.

However, as we noted above, some studies suffer from methodological drawbacks (Kamps, 2004): some studies, like Ligthart (2000), specify VAR models in levels, based on the Sim's (1980) result that OLS estimates of VAR models in levels are consistent even when the variables are not cointegrated, neglecting that, unfortunately, the consistency does not carry through to the impulse response function, which is used to assess the long run impact of public capital on output. Other studies (like Pereira, 2005, Pereira and Roca-Sagales, 2001) test for cointegration using the Engle-Granger procedure which does not allow testing for the existence of more than a cointegration relation. Finally, the majority of studies do not report confidence intervals for the impulse response estimates, which is rather unfortunate, as it does not allow concluding whether a positive effect of public capital on output is significantly different from zero.

Kamps is one the most recent and comprehensive studies in the public capital/economic growth literature that relies on the VAR approach. He used a vector error auto regressive model for 22 OECD countries over the period 1960-2001 to test the relationship which exists between macroeconomic variables like output, private capital, employment and public capital. He found that, in the long run, the elasticity of output with respect to public capital was positive and significant for twelve countries, negative and significant for one and not significantly different from zero for the remaining nine.[57] It should be remarked that the elasticities that are in general estimated in VAR models differ from the production function elasticities, as they incorporate any feedback effect between the variables in the model, as opposed to the "ceteris paribus" elasticities which are estimated in production function studies. Furthermore, Kamps (2004)'s results[58] show that public capital reacts to GDP shocks, which suggests that public capital is endogenous.

Mittnick and Neumann (2001) estimated a vector error auto regressive model and found (for a group of six countries: Germany, Canada, Japan, France, UK, The Netherlands) positive but

[57] We might note that out of the 9 countries whose elasticity was not significantly different from zero, 8 had a positive value, which might suggest that the studies which fail to report confidence intervals could be misleading.

[58] See also Pereira and Roca (2001) and Pereira and Roca (2003) who report evidence consistent with Kamps (2004). However, see Mittnik and Neumann (2001) for a different result.

small elasticities of about 0.1 percent which were significantly different form zero only in the case of Germany and The Netherlands.

At a country level, there is a lot of empirical evidence for Spain. For instance, Pereira and Roca (1999, 2001 and 2003) found positive elasticities of output with respect to the public capital stock, although confidence intervals for the elasticities were not computed. According to the estimates presented in these papers, long run rates of return of public capital are about 5-8 per cent.[59] Higher rates of return for public investments in transport infrastructure are found in Pereira and Andraz (2005) for Portugal (15 per cent). Interestingly, they also examined the impact on output of narrower categories of transport investments, and found that investments in ports had the highest return, followed by national roads, municipal roads, airports and railways.

Mamatzakis (1999) for Greece and Flores de Frutos et al (1998) for Spain also concluded that the effect of public capital on output was positive. However, Sturm et al (1999) for The Netherlands and Litgarth (2000) for Portugal were not able to detect any positive impact of public capital on output.

Some additional interesting findings are reported in the series of papers by Pereira and Roca (1999, 2001 and 2003) who used the stock of transport and communication infrastructure as their measure for the public capital stock. In their 1999 paper they estimate a VAR model for the Spanish economy as a whole and, separately, for each region: while the average effect for Spain was positive (with a rate of return of about 6 per cent), the regional results suggest that there are strong disparities between regions. In particular, it was the most developed regions to gain the most from public capital investments in terms of output increase. In their 2001 paper, Pereira and Roca estimated a VAR model for the whole Spanish economy and, separately, for four distinct sectors (agriculture, manufacturing, construction and services). Again, while the aggregate result was positive, this concealed different dynamics at sector level, with the construction sector benefiting the most from public capital (followed by manufacturing and services) and with agriculture which was negatively affected by public capital investments. Finally, in their 2003 paper, they find some empirical evidence supporting the existence of spillover effects: they estimated a VAR model for the Spanish economy and, separately, for each of the regions. However, the aggregation for the Spanish economy of the regional results yielded a considerably smaller overall effect of public capital on output than the effect which was estimated from the aggregate model: they therefore re-estimate the regional VAR models with the capital stock of the other regions, as well as the other inputs and find out that the overall effect produced by aggregating the regional effects was very similar to the Spanish aggregate model, suggesting that regional studies that neglect spillover effects are likely to underestimate the effect of public infrastructure investments on economic growth.

This latter result, together with those of Cohen and Morrison (2003 a and 2003b) as well as Canaleta et al (1998) seems to suggest that the incorporation of spillover effects of transport

[59] These rates of return are computed from the elasticity figure and the public capital-output ratio to derive the long run impact (usually 20 to 25 years) of an additional unit of public capital on output and computing the annual rate of return that would produce that increase in output.

networks into economic growth models might be an important step for a better analysis of the effects of transport infrastructure on economic and productivity growth.

To the best of our knowledge, there is not any robust empirical evidence on both the existence and the magnitude of transport infrastructure spillovers on economic growth at the EU level. However, the fact that spillover effects have been identified in the US (as well as in two EU countries) might suggest that they could be important also for the EU a whole, even if their magnitude might be different. For instance, spillover effects might be more important between regions within a state than among countries within the EU, because of the greater economic integration between the regions of a single country. However, in a more "dynamic" perspective, the realisation of a fast network in, say, France, might have important spillover effects on the growth of, say, Spain and Italy, if, given the relative structure of the two economies, the new French network would lead to a strong increase in trade and a higher degree of specialisation in Spain and Italy.

4.8 The EU evidence: a summary

The empirical evidence for the EU countries that we have reviewed seems to suggest that public infrastructure capital does affect private output. Even if it is difficult to compare such different studies — for they differ not only for the approach they have chosen, but also for the sector and sample used in the analysis and for the definition of the public capital stock[60] — this main result does not seem to depend neither on the methodology or the nature of the sample (regions, rather than countries, total economy rather than manufacturing sector) used in the analysis.

However, different studies produce a wide range of estimates, with the production functions displaying, perhaps, the upper bound for the elasticity of output with respect to public capital. We have tried to highlight some of the limitations of the production function studies that we have reviewed, the most serious of which might be, perhaps, the inability of most studies to convincingly take into account the reverse causality between output and public capital (which is likely to be a serious concern if not properly taken into account, as the more recent time series work using VAR has shown that public capital and output are indeed jointly determined). However, even in the production function approach, a majority of studies seems to point towards elasticities of about 0.10-0.20, notably smaller than the 0.35 originally identified by Aschauer (1989).

The studies that have relied on behavioural approaches (i.e. cost and profit function) consistently point towards a positive role for public capital in reducing private sector costs. Even if it is difficult to find a consistent pattern across studies, it seems fair to conclude that, with some exceptions, there is evidence that, for the EU, cost function based studies seem to identify quite small elasticities of cost with respect to public capital. Although the elasticities as well as the returns identified in cost function studies are not directly comparable to these

[60] Furthermore, the output elasticity in production function studies is not directly comparable to the cost elasticities estimated by cost function models or to the long run elasticities implied by impulse response functions estimated by VAR models.

derived using a production function approach there seems to be some evidence that the former tend to be fairly smaller than the latter.

Furthermore, cost function studies show that aggregate results often exhibit show considerable variability across regions and across sectors, although a consistent pattern does not seem to have emerged yet: for instance, it is not clear whether more developed regions are more likely, on average, to gain from public capital or whether a particular sector is likely to benefit more from public infrastructure than others. A robust answer to this issue would require perhaps better information on the stock of public infrastructure than is provided by the use of monetary values: for instance, virtually all the studies are silent on very relevant issues such as the quality of the infrastructure stock, or the levels of congestion.

Finally, VAR studies seem to broadly confirm the main findings of the former two approaches. However, the fact that the large majority of studies we have reviewed do not report confidence intervals is an unappealing feature of this part of the literature review, because, as argued by Kamps (2004), it is often the case that positive elasticities are often not significant. However, the main message we can derive form the VAR literature is that the empirical evidence seems to support the idea that public capital has a positive impact on private output, with a magnitude which might be broadly put near the lower bound of the production function studies.

All in all, the empirical evidence for the EU supports the evidence we have discussed above for the US, and the conclusion that small but positive effects of public infrastructure exist is probably the most natural one to draw, as many of the drawbacks which characterised most of the early studies have been, at least in part, tackled by the subsequent literature.

Still, given the inability of most studies to control for important features of the capital stock like quality of the infrastructure and congestion, and the existence of large variations across countries and regions not immediate to rationalise, it would be hazardous to suggest some more precise quantification of the effects of public infrastructure on output and economic growth.

5 Literature Review: Conclusion

In the previous sections we have sought to provide a through discussion of the linkages between transportation infrastructure and economic growth. Not only have we extensively analysed the empirical economics literature for the EU and the US, but we have also attempted a critical evaluation of the insights offered by the theoretical literature on the effects that public capital in general and transport infrastructure in particular might have in fostering economic and productivity growth.

Early empirical studies were often *ad hoc*, as they were developed largely outside any robust economic model of the interactions which exist between transport infrastructure and economic activity. However, perhaps reflecting the debate which the original empirical work by Aschauer (1989a) raised, an increasing number of theoretical contributions that sought to better illustrate the relationship between transport infrastructure and economic and productivity growth finally started to appear in the 1990s, even if a substantial fraction of the empirical work in the field is still not focused on these new theoretical developments.[61]

We have seen that the theoretical literature has identified a set of channels through which transport infrastructure might affect economic and productivity growth. One of such channels is through classical endogenous growth models -whereby inputs have diminishing marginal returns but, together, they display constant returns- which can be used to show how there is a growth maximising level of transport infrastructure which depends on the interaction between the relative effects of transport infrastructure investment and the taxes levied to finance it.

We have also discussed how endogenous growth models could be used to model the effect of transport infrastructure on long run growth through its impact on the rate of technology innovation and diffusion.

Furthermore, transport infrastructure might favour long run output growth by allowing an increase in market size, which in turn might make it easier for private firms to exploit scale economies and specialisation economies. Finally, we have shown how some theoretical models introduce general equilibrium and imperfect competition, allowing transportation infrastructure to allow the development of industrial clusters and agglomeration economies.

Therefore, there appears to be in the theoretical literature a broad consensus on the mechanisms through which, at the microeconomic level, transport infrastructure might affect economic and productivity growth: transport infrastructure might reduce transportation costs, which allows reducing private sector costs and increasing specialisation and the degree of division of labour. In addition, transport infrastructure may bring about changes in factor markets and firm location decisions that allow the development of spatial clusters of economic sectors, which in turn affects innovation and allows further reduction in costs.

Furthermore, it seems clear from the literature that non-linearities in the effects of transport infrastructure on economic growth are important: for instance, additions to a not well developed transport network or new investments in a low quality stock or investments aimed to alleviate congestion problems eliminating bottlenecks would be likely to generate relatively larger benefits, ceteris paribus, than in the case of an already developed high quality transport network or a network with no congestion problems. However, the literature appears to be still in its infancy to be able to offer a robust explanation of the links between transport investment, the network dimension of transport infrastructure and economic growth.

We noted above as the theoretical and empirical literature developed quite independently. Therefore, while the former has sought to apply microeconomic considerations to model the transport infrastructure-economic growth relation, the latter –and especially the studies which adopted the production function approach- has mainly followed a "macroeconomic black box" approach which does not allow spelling out in some details the mechanisms that drive the effects of transport infrastructure on productivity growth. In other words, the em-

[61] This is not to say that the empirical contributions simply ignored the theoretical developments, as some were either based on theoretical models or incorporated some of the insights provided by the theoretical literature (such as geographic spillovers) into their empirical framework.

pirical literature, by large, describes the impact of public and transport infrastructure on economic and productivity growth at an aggregate level, but it does not allow researchers "to look" into the "black box", which is rather unfortunate, as, often, the aggregate impact of public infrastructure might be a poor proxy for the impact that specific transport projects might have on aggregate growth.

Having said that, the empirical evidence that we have surveyed for this report seems to suggest that public capital in general might have a positive effect on the level of economic activity, even if not as large as the early studies which employed production functions identified. In fact, both in the case of the US and the EU, there seems to be a tendency for production function studies to identify quite large returns for public capital and for transportation infrastructure in particular, even if probably not as large as the early studies suggested, probably because some of their most important methodological drawbacks had been somewhat taken into account by later studies.

Furthermore, the theoretical literature has made clear how the relationship between public capital and production is perhaps too complex to be tackled from the oversimplified perspective of the production function approach. The cost function approach –based on a behavioural model of production which allows to better identify the direct and indirect effect that public infrastructure might have on the cost structure and productivity growth of the private sector- as well as the studies that adopt a more "structural" approach –whereby infrastructure effects are incorporated into more general models of the economy- seem to back the theoretical insights that public capital and transport infrastructure might have a beneficial effect in fostering economic growth and the level of output, but they also seem to suggest that the returns of public infrastructure are positive, but lower than these identified by production function studies.

However, a precise quantification of the effects of public infrastructure on output and economic and productivity growth is more difficult to make, for a series of reasons.

First of all, some studies have suggested that there is a significant variability of infrastructure returns and elasticities across regions and sectors and that it is extremely difficult to rationalise this variability: in other words, there is not consistent evidence suggesting that some sectors or regions are more likely to gain (or to loose) more than others.

Second, there is some fairly robust empirical evidence that seems to support the insights offered by the theoretical literature that public infrastructure might have non-linear effects on the level of economic activity and growth: this is often picked up in cost and production function studies by positive -but declining over time- returns to public capital and transportation infrastructure (e.g. Demetriades and Mamuneas, 2000 for the OECD countries and Morrison and Schwarz, 1996 and Fernald, 1999 for the US[62]).

[62] Fernald (1999) argued that the construction of the Federal Highway Network in the US spurred economic growth in the subsequent years, leading to high returns of transport infrastructure, but that the returns subsequently fall: this could suggest, among the other things, that additional investments in secondary layers of the network could not be as highly productive as the construction of the main network.

However, empirical analysis of theoretical models which explicitly incorporate non-linearity between public infrastructure and output into their framework are perhaps still in their infancy, and therefore generalisations of findings of a few papers would be questionable.

Furthermore, the impact that quality and network aspects of transport infrastructure as well as congestion effects might play on "driving" the overall effect of public infrastructure on output, even if quite clear from a theoretical perspective, have not yet been investigated in much depth in the economic literature so far.

Having said that, the evidence of small albeit positive benefits -in terms of higher output and economic growth- stemming from public capital and, especially, from transport infrastructure-seems to find a broad support in the empirical literature, unlike what earlier literature reviews (e.g. Gramlich, 1994 or Sturm and de Haan, 1998) seemed to suggest.

There are some further few caveats worth noting.

The first is that there is some evidence in the literature which suggests that empirical works that have used samples at regional level have identified lower impacts of public and transport infrastructure on economic growth than studies based on aggregate national data, the reason being that the former neglect the spillover effects of public infrastructure across regions.

This could be one of the possible explanations for the lower estimates that are generally found in the cost function approach, which relied almost exclusively on regional level data, with respect to the time series studies which adopted a production function approach. Some studies (e.g. Cohen et al, 2003a, 2003b) have indeed identified the existence of spillover effects of transport infrastructure and have concluded that neglecting them would lead to underestimating the overall impact of transport infrastructure on private sector costs and productivity.

In second place, while many studies have reported rates of returns from public infrastructure investment, very few have actually compared them with the costs incurred by the governments.

In other words, it should be remarked that even if a positive rate of return is a necessary condition for public infrastructure investment to be "productive", it is not a sufficient condition for it to be also worthwhile.

In fact, it would first be necessary to compute a user cost of public funds which should consider depreciation, the opportunity costs and the marginal cost of public funds: if the user cost were higher than the rate of return, then public infrastructure investment would be consuming more resources than it would be generating. [63]

Furthermore, it should be observed that, even if the return of transport infrastructure were higher than its user cost, it would not necessarily follow that the government should invest in transport infrastructure. Given limited resources, the government might well decide to invest

[63] We can note that the few studies that have compared the return of public infrastructure with its cost have generally found that the rates of return were actually higher than the user cost, even if the difference was falling down over time

in other kinds of public investments. Put it simply, the gross rate of return of transport infrastructure should be compared to that of other types of public investment expenditures.

Unfortunately, the empirical literature that we have reviewed is not very helpful on this. There is some evidence that core infrastructure (which is closely related to the concept of transport infrastructure) seems to generate higher returns than other forms of public infrastructure, like offices and buildings. However, there does not seem to be, to the best of our knowledge, any robust theoretical and empirical attempt to compare returns to transport infrastructure to these of other non infrastructure public investments, such as public expenditure in education, R&D or health care.

6 Models of transport infrastructure and economic growth

6.1 Introduction

As discussed in the Main Report a new growth model has been developed and simulated. The model deals with the effects of transport infrastructure both on the production capacity of firms and on the utility of individuals. This latter aspect is the most innovative part of the model as this fact has not been considered in the economic literature that has been developed so far: the Barro (1990), Barro and Sala I Martin (1992) and Turnovsky (1997) models use a utility function that depends only on the level of consumption in each period. In these models therefore transport infrastructure influences utility only through the (positive) effects that it has on future productivity of capital and thus on increases in total production and consumption. However, it seems sensible to assume that the level of development of transport infrastructure has a direct effect on the utility of economic agents: roads, railways, harbours and airports are used for leisure activities as well as for production porpuses. In the model that we developed we have therefore taken into account this fact by inserting transport infrastructure directly in the utility function and assuming that it influences the labour supply decisions of agents.

After the leisure model is discussed a variant of the Barro and Sala I Martin (2004) (BSIM from now) model that takes into account the basic fact that transport infrastructure is subject to congestion, (i.e. for a given quantity of infrastructure the quantity available to a single individual declines as other individuals use the facility) has been developed for a simulation exercise.

In the following paragraphs we describe the main features of both models, leaving the discussion of the simulation results to the main report.

6.2 The different steps to construct the leisure model

The development of new models is by no means an easy task and it is therefore very useful to start from basic models that have been constructed and modify them to analyse the issues of interest. We base our analysis on a series of Ramsey-like growth models that have been developed in the past and for which very important analytical results are already known.

Before we turn to the description of the model we developed it is useful to spend a few words on the models upon which our analysis is based. Campbell (1994) provides a useful starting point as he describes the dynamic behaviour of a (stochastic) growth model under different assumptions on the form of the utility function and on the magnitude of the parameters in a discrete-time framework;

He starts from a very simple Cobb Douglas production function $Y_t = (A_t L_t)^{1-b} K_t^{\,b} = A_t^{1-b} K^b$ where *Y* represents output, *L* labour supply, *K* the amount of capital in the economy and *A* the Solow residual i.e. that part of product that cannot be attributed neither to capital nor to labour. Capital is accumulated according to the equation $K_{t+1} = (1-\delta)K_t + I_t$ where δ is the rate of depreciation and *I* the amount of investment. Individuals have a utility function of the form $\sum_{i=0}^{\infty} \beta^i \frac{C^{1-\gamma}}{1-\gamma}$ [64] where γ is the inverse of the elasticity of substitution of consumption and β is the discount factor that depends on the preferences of consumers. Defining the gross rate of return on investments as $R_{t+1} = b\left(\frac{A_{t+1}}{K_{t+1}}\right)^{1-b} + (1-\delta)$ Campbell proves that the growth rate of the economy (*g)* is given by $g = \frac{1}{\gamma}[\log(\beta) + \log(R)]$.

Since this value is constant the model has a steady state.

In the same paper it is also proved that if we modify the utility function so that agents can choose between consumption and leisure (and therefore the amount of time devoted to labour activities becomes an endogenous variable in the model) there would be no significant modifications in the result obtained above.

We now turn to the description of the various parts of the model that we use in the simulations.

6.2.1 The production technology

The model that we have developed is a continuous time extension of the one that we briefly described above. The production function is assumed to have an augmented Cobb Douglas form $Y = AK^b\left[(1-T)LN\right]^{1-b}$ where *N* represents the number of people[65] and we interpret *L* as the average share of time spent in working activities; *T* represents transport costs. In this model therefore transport costs reduce the effectiveness of labour: the same amount of labour is more productive if transport costs are lower. Since *L* represents the share of time devoted to working activities *T* can be interpreted as the time lost due to transport.

For practical purposes we can think of *T* as a combination of a two different parts i.e. the part of the workforce employed in the transport sector that could be employed in other ac-

[64] In his paper Campbell analyses a stochastic growth model and therefore the agents have their expectations on future consumption. In our model there is no uncertainty so that future consumption is non-stochastic. There is no need to include an expected value in the utility function.

[65] We include this parameter in the model for completeness, however for the rest of the discussion we assume that total population is normalised to 1.

tivities and the share of commuting time that is necessary to go to and come back from the workplace. The former component recognizes that the workers employed in the transport sector could be working in different sectors and therefore producing more consumption goods while the latter component simply states that the time spent commuting between the workplace and people's residences could be used in productive activities so that the overall productivity of the economy is reduced.

6.2.2 The utility function and the effects of transport infrastructure

As stated above, the most innovative part of our model is the recognition that transport infrastructure directly affects the utility of economic agents by its influence on leisure activities and therefore on the labour supply decisions of individuals. Sunday trips in the countryside, weekends in a historical place and holidays on the beach all require the use of transport infrastructure.

The utility function that we used has therefore transport costs as one of its arguments. It has the form $u(C,(1-L))=\ln(C)+\vartheta\frac{[(1-\tau)(1-L)]^{1-\gamma}}{1-\gamma}$ where *C* represents the level of consumption, *τ* transport costs (the leisure time that is lost due to the presence of transport costs) and *γ* the inverse of the elasticity of intertemporal substitution of leisure. We choose to use a function that has log utility for consumption and power utility for leisure for two reasons. Firstly, King, Plosser and Rebelo (1988) have shown that log consumption is required in order to obtain a constant labour supply on the balanced growth path and; secondly power utility for leisure has been widely used in the real business cycle literature.

The parameter *θ* weighs leisure with respect to consumption: the higher its value the more important leisure is for individuals.

The effects of transport costs on leisure are analogous, but not exactly equal, to those on labour productivity in the production function. We believe that it is useful to think of transport costs as a factor that reduces the time spent in leisure activities. We could think of many examples of transport costs influencing leisure activities: an inefficient airport that retards the departure for a week-end, the absence of motorways to reach a village in the countryside, the lack of train connections that makes it difficult to reach the ski resort and so on.

6.2.3 Capital and transport infrastructure accumulation

To study the dynamics of the economy described by the equations above we have to specify the law of motion of capital and transport infrastructure. We assume that capital and infrastructure depreciate respectively at rate δ_1 and δ_2 while investment in the two factors is represented by *I* and *IT*. We can therefore write:

$\dot{K} = I - \delta_1 K$ and $\dot{TI} = IT - \delta_2 TI$ where *TI* represents the stock of transport infrastructure and a dot over a variable indicates the time variation of the variable itself. To close the model we need to specify a relationship between the level of transport infrastructure and transport costs and a budget constraint. We assume a relationship of the form $T = TI^{-\phi}$, $\tau = TI^{-\psi}$.

and are therefore the elasticities of transport costs (respectively in the production and utility function) with respect to transport infrastructure.

While the budget constraint simply states that $Y = C + I + IT$, i.e. total output must be either consumed or invested in capital or transport infrastructure.

6.2.4 A few analytical results

Solving the dynamic maximisation problem that maximises the utility of an infinitely-lived individual subject to the constraints using the standard dynamic maximisation techniques yields the following first order conditions:

$$\frac{1}{C} = \lambda_k = \lambda_{TI}$$

$$-\vartheta(1 - TI^{-\psi})^{1-\gamma}(1-L)^{-\gamma} - \lambda_k \left[A\left(\frac{K}{L}\right)^b (1-b)(1 - TI^{-\phi})^{1-b} \right] = 0$$

$$\lambda_k = \lambda_{TI}$$

$$\dot{\lambda}_k = \rho\lambda_k + \lambda_k \left[\delta_1 - Ab\left((1 - TI^{-\psi})L\right)^{1-b} K^{b-1}\right]$$

$$\dot{\lambda}_{TI} = \rho\lambda_{TI} + \lambda_{TI}\left[\delta_2 - AK^b L^{1-b}(1 - TI^{-\phi})^b \phi TI^{-\phi-1} - \vartheta\psi(1-L)^{1-\gamma}(1 - TI^{-\psi})^{-\gamma} TI^{-\psi-1} \frac{1}{\lambda_{TI}} \right]$$

Where ρ represents the discount factor of future utilities and the two λ represent the costate variables associated to the laws of motion of *K* and *TI*. Investing in capital or in transport infrastructure must be equally productive in equilibrium (as stated by the third first order condition). We can calculate the steady state by differentiating the first of these equations to obtain

$$\frac{\dot{\lambda}_k}{\lambda_k} = \frac{\dot{\lambda}_{TI}}{\lambda_{TI}} = -\frac{\dot{C}}{C}$$

And using the first of the two Euler equations we get:

$$\frac{\dot{C}}{C} = -\rho + \left[-\delta_1 + Ab\left((1-T)L\right)^{1-b} K^{b-1}\right]$$

This represents the steady state growth rate of consumption. An economy with higher transport costs will grow less than an economy with lower transport costs. It is clear that with the model as such it won't be possible to obtain perpetual positive growth rates since we aren't assuming the existence of positive externalities of transport infrastructure in production and therefore the marginal product of capital tends to zero as the capital stock increases. However, the analysis of the model presented above offers very interesting insights on the effects of transport infrastructure on labour/leisure choice and on the transitional dynamics towards the steady state.

6.3 An endogenous growth model with congestion a la Barro and Sala I Martin

The structure of the BSIM model is, as usual, onein which infinitely-lived individuals maximize their total utility subject to a number of constraints. As we are not interested anymore in the dynamics of labour supply we assume that the (instantaneous) utility function takes the form $u(c) = \frac{c^{1-\eta} - 1}{1-\eta}$ [66] where η represents the intertemporal elasticity of consumption.

To model the fact that transport infrastructure is subject to congestion we write the production function as $Y = AK\left(\frac{TI}{Y}\right)^{\alpha}$ [67] . The term in parenthesis is the one that is necessary to model congestion: an increase in *Y* for given *TI* reduces the amount of transport infrastructure available to each producer and therefore reduces total output. The two accumulation equations for private capital and transport infrastructure are exactly the same as in the model that we used to model the effects of transport in the utility function: $\dot{K} = I - \delta_1 K$ and $\dot{TI} = IT - \delta_2 TI$. To close the model we need to specify the usual allocation equation as $Y = C + I + IT$.

In this formulation we are implicitly assuming that *TI* has to decline in relation to output in order for the congestion effect to take place. An alternative approach would be that of assuming that the ratio of interest is *TI/K*. The results would be essentially the same under both specifications[68].

Barro and Sala I Martin (1992 and 2004) model congestion in a particular way, i.e. the ratio between transport infrastructure[69] and output. In the general presentation of their research they assume a general functional form such as $f(G/Y)$ where G is the amount of public spending in the economy. They assume that *f* has a positive first derivative and a negative second derivative. What these assumptions mean is simply that an increase of *G* with respect to *Y* increases total output but the amount of the increase tends to zero as *G* grows.

An increase in *G* therefore implies an increase in total output, but an increase in total output also implies a more congested economy and a subsequent decrease in total output. It is therefore difficult to simulate numerically a model of this kind as the variable *Y* depends on its own value. In a number of alternative simulations that we tried a number of non-linearities with a high variability of the rates of growth emerged.

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[66] As we proved above this specification reduces to the logarithmic specification if the intertemporal elasticity of consumption tends to unity.

[67] The model is therefore part of the so called "AK" growth models. In this case the marginal productivity of capital is constant and therefore the model will be able to show endogenous and positive growth rates.

[68] For a discussion of the analytical properties of the BSIM model see Barro and Sala I Martin (1992).

[69] They think that also other publicly provided goods such as water systems, police and fire services and courts are subject to congestion and therefore use G as public expenditure.

It can be proved[70] that the optimal ratio *G/Y* in this model must satisfy the condition $\frac{f'(G/Y)}{f(G/Y)} = \frac{1}{1-(G/Y)}$. With the Cobb Douglas functional form that we used in the numerical simulations, that is equivalent to what Barro and Sala I Martin have used in their 1992 paper, the condition becomes: $\alpha\left(\frac{G}{Y}\right)^{-1} = \frac{1}{1-(G/Y)}$ [71]. This ratio is the one that maximises overall growth.

There are three solutions to this equation, namely $(G/Y) = \frac{\alpha}{\alpha+1}$ and $(G/Y) = \pm\infty$. Therefore it is optimal either to have a very low share[72] of public capital (or transport infrastructure in our case) or to have an infinitely high level of infrastructure. In the first case there would be congestion but the marginal product of infrastructure would be high. In the second case the marginal product would be negligible but there would be no congestion.

Of course the value that is economically more significant is the first one as it is one that can be calibrated. We tried to plug in an initial value of transport infrastructure that satisfied this condition as we thought that would be the one maximised growth and welfare. Unfortunately when such a value is used as the initial one there are numerical problems that emerge: the system is not capable of reaching a steady state.

In the alternative simulations that we have ran, by changing the initial value of transport infrastructure, in an attempt to replicate the results we obtained in our model, we noticed that as the value of the ratio (*TI/Y*) in steady state is closer to the optimal one then total welfare is maximised. Therefore we have a numerical confirmation of the analytical result of the BSIM model.

6.4 Calibrating the leisure model

The analytical results that we derived are useful as they provide an image of what long run dynamics we can expect from an economy described our model. However to have a clearer picture of the transition towards the steady state, to evaluate the effects of changes in the parameters, to make comparisons between economies that differ with respect to their initial values and to carry out scenario and sensitivity analyses it is necessary to use numerical simulations of this growth model. These simulations are as well very useful to understand the effects of policy changes and the data they generate can be analysed with statistical and/or econometric tools.

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[70] See Barro and Sala I Martin (2004) p. 225 for details.

[71] Starting from $f(G/Y) = (G/Y)^{\alpha}$ we get $f'(G/Y) = \alpha(G/Y)^{\alpha-1}$ and therefore $\frac{f'(G/Y)}{f(G/Y)} = \frac{\alpha(G/Y)^{\alpha-1}}{(G/Y)^{\alpha}} = \alpha(G/Y)^{-1}$

[72] The value of G with the parameters calibrated in our EU-15 and US model is .09.

6.4.1 Parameters calibration

There are many parameters that we need to calibrate in the model. The exponent *b* in the production function, and in the utility function, the discount factor , the depreciation factors δ_1 and δ_2, and the two elasticities *Φ* and .

6.4.2 Production function and utility function

The economic literature suggests that the value of *b,* that represents the share of capital in production, is around 0.35 (see, for instance, Kydland and Prescott, 1982). It is more complex to have a clear picture of what value should assume as it is much more difficult to measure. In addition much of the effort to estimate intertemporal elasticities has been made with regards to consumption so that the calibration of this parameter is very difficult. Hall (1988) suggests that the econometric studies point out a value of this parameter (in relation to consumption substitutability) that is close to zero and suggests an estimate of around 0.1. However Guvenen (2002) points out that the majority of macroeconomic studies use a value that is close to one to replicate the features of real economies and that the result of Hall could be driven by an omitted variable bias. Given the form of our utility function we have implicitly assumed that the intertemporal elasticity of consumption is equal to one[73].

For the intertemporal elasticity of leisure however there are reasons to believe that its value is much closer to zero: in this case household are indifferent to the timing of leisure. Therefore given that the level of consumption will grow over time they will be willing spend more time in leisure as the economy develops to keep their utility constant over time. The reduction of the amount of hours worked is an empirical characteristic of all industrialized economies. Therefore we calibrate the value of at 0.1.

The procedure to calibrate the weight of leisure in the utility function (*θ*) is not straightforward and, since it requires the calibration of and it will be described in the following paragraphs[74].

6.4.3 Depreciation rates

We use the depreciation rate that can be calculated starting from the data contained in Kamps (2004) as the baseline value for δ_1 and δ_2. For both the US and the EU-15 the value is very close to 0.05.

We have no data that refer specifically to the depreciation of transport infrastructure, however it is often assumed a 30 year period as the baseline for depreciation. Therefore while we stick to the calibrated value of 0.05 as the baseline value for our simulations but we also pro-

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[73] If we start from a utility function $u(C) = \frac{C^{1-\eta} - 1}{1-\eta}$ where is the intertemporal elasticity of consumption we can prove that $\lim_{\eta \to 1} \frac{C^{1-\eta} - 1}{1-\eta} = \lim_{\eta \to 1} \frac{\pm c^{1-\eta} \ln(C)}{\pm 1} = \ln(C) \cdot$

[74] Someone might argue that we need to calibrate the parameter *a* in the production function. However *a* is calculated at period 1 using the allocation and production equations and ensures that the first step of the model is consistent with the other initial values.

vide an analysis of the scenario where the depreciation rate is assumed to be 0.021 such that after 30 years the value of transport infrastructure would be 1/1000 of its initial value.

6.4.4 Elasticities of transport costs

Three parameters still need to be calibrated: the two elasticities of transport cost and the weight of leisure in the utility function. It is not possible to plug in directly the value of these parameters from the economic literature; however there is a way of estimating them using the conditions that are implicitly contained in our model.

Starting from the production function of the model it is possible to calculate the elasticity of output with respect to transport infrastructure:

$$Y = AK^b\left[(1 - TI^{-\phi})LN\right]^{1-b}$$

$$\frac{dY}{dTI} = AK^b(LN)^{1-b}(1-b)\left[1 - TI^{-\phi}\right]^{-b}\phi TI^{-\phi-1}$$

$$\frac{\frac{dY}{Y}}{\frac{dTI}{TI}} = (1-b)\phi TI^{-\phi}(1 - TI^{-\phi})^{-1}$$

Once we calibrate the initial value of the transport infrastructure, a thing that will be done in the section dedicated to the calibration of initial values, two unknowns remain in the equation: the first one is *Φ* and the second one is the value of the elasticity itself. We now have two alternative ways to estimate the value of *Φ*. The first possibility is plug into the equation a value of the elasticity and solve the equation numerically for *Φ*. In the Main Report] we showed that econometric estimates of $\frac{dy/Y}{dTI/TI}$ are around the value of 0.1 so that such a calculation is feasible. The second possibility stems from the interpretation that we suggested for transport costs as time subtracted from other productive activities. Once we have an estimate of this value we can simplify the equation and calculate *Φ*. We decided to exploit both these possibilities and used a two step iterative procedure to get a value for *Φ*. The first step estimates *Φ* using a value of the elasticity as close as possible to 0.1. We then use this estimate coupled with an estimate for the amount of time lost due to transport (that can be calculated via the formula $TI^{-\phi}$) and calculate the implied value *Φ* from the second possibility. We iterate this process modifying the elasticity so that the two estimates of *Φ* converge.

In the iterations we make sure that the estimated time spent in transport activities is not too different from empirical evidence.

According to the Labour Force Survey of Eurostat the average weekly working time for the EU-15 is 36.9 hours. A recent study of the Italian National Institute of Statistics (ISTAT 2006) suggests that the average time spent in travel is 1 hour and 37 minutes[75]. The estimate regards only Italian workers and it includes also time spent in travel for non labour activities. To estimate how much of this time is due to labour activities we calculate the ratio of (family

[75] The data is calculated from a survey of households who keep a diary of their activities for a randomly selected day. Given the level of aggregation that was randomly assigned to each household.

and non-family) labour to total non sleeping time and then allocate the travel time accordingly. This procedure yields to an estimate of 10% of time spent in travel for labour activities. To get an estimate of total time wasted we need to know the share of workers employed in the transport sector. In the Main Report and in Annex 7 we argued that it is roughly 4% for the EU-15 and USA. Therefore our estimate for total time "wasted" in transport activities is around 14%.[76]

For comparison, an alternative scenario, which uses the calculations from the ASTRA model, has been explored. In six European countries that represent 80% of the population of the EU15[77] the daily commuting time in 2003 was, on average 49 minutes per day. If we assume an 8 hour working day this gives us a slightly lower estimate of 9% commuting time that coupled with the share of people employed in transport activities would give us 13% of time wasted due to transport costs. Using this figure to estimate □ and then the elasticity of output with respect to transport infrastructure we would get a value of 0.94 which is slightly lower than what econometric estimates seem to suggest.

From a purely theoretical point of view this procedure could be replicated to get an estimate of   using the elasticity of utility with respect to transport. Unfortunately, there is no way to get an econometric estimate of the utility since it is not directly measurable. We are therefore forced to assume that the value of the two parameters is the same. In the simulations however we analyze the effects of changes in   on growth. The calibrated basic values for   and   are 0.91 and 0.73 respectively for the EU-15 and the US.

6.4.5 The weight of leisure

The last parameter that needs to be calibrated is θ i.e. the weight attributed to leisure in the utility function. Using the first two of the first order conditions of our model it is possible to prove that:

$$\vartheta = \frac{A\left(\frac{K}{L}\right)^{b}(1-TI^{-\phi})^{1-b}(1-b)}{C(1-L)^{-\gamma}(1-TI^{-\psi})^{1-\gamma}}$$

So that under the assumptions that we have made it is possible to get an estimate for this parameter. We only need to calibrate the initial values of the variables to analyse the dynamics of the model. The estimates obtained following this procedure are 2.6 and 2.5 for the EU-15 and the US respectively.

6.4.6 Initial values

Since we are interested in the analysis of the future possible paths of the European economy in comparison with the US we calibrated the model using the most recent data available for these economies. Given the data limitations of new member states of the EU we focused our analysis on the EU-15. There are two sources for the data: with regards to private and public capital we used the estimates contained in Kamps (2004); with regards to consumption ex-

[76] This figure does not include transport workers in the public sector, which clearly represent a sizeable share of workers in the transport sector.

[77] France, Italy, Germany, the Netherlands, Spain and the UK.

penditure the data come from the European Commission Annual Macroeconomic Dataset (AMECO). The base year is 2002 since that is the last year for which the Kamps estimates are available. All values are per worker.

Given the level of aggregation of the model and our interest in the effects of transport infrastructure our definition of the initial value of the variables is slightly different from the standard of economics textbooks. Capital is defined as the sum of private and public capital minus transport infrastructure capital. Consumption is the sum of private and public consumption and transport infrastructure is the value of infrastructure capital.

The value for initial capital per worker in the EU-15 and in the US is respectively 141.86 and 154.87 (thousands of €). To get to the initial value of investment the average 1994 – 2002 share of investment has been calculated and then this ratio applied to the estimated value of capital. In this way we should get a measure of investment that is independent of the cycle.

Initial consumption per worker is calibrated at 40.3 and 63.4 (thousands of €) respectively. The initial working time is calibrated at 0.333, as Prescott (1986) suggests that household spend one third of their time in market activities.

We only have to calibrate the initial value of transport infrastructure and investment in transport infrastructure to have all the data necessary for the starting point of our simulation. Unfortunately it is not easy to find a measure for aggregate transport infrastructure neither for the EU-15 nor for the US. There are data on the length of railways and roads, and on the number of airports and harbours. Unfortunately it is very difficult to aggregate the data into a single measure. We have therefore been forced to use an alternative approach. The Unification of accounts and marginal costs for transport efficiency (UNITE)[78] project at the University of Leeds provides estimates for the value of gross transport infrastructure in seven EU countries[79]. As a first step we calculated the ratio between the average value of transport infrastructure and the average public capital (from the Kamps dataset) in these countries. Then we applied this ratio to the total stock of public capital in the EU-15 and the US to get an estimate of the value of transport infrastructure. The results are 7.72 and 11.03 thousands of € per worker for the EU-15 and the US respectively. A procedure analogous to that used to estimate the level of investment in capital has been used to estimate the level of investment in transport infrastructure in the two economies. They are respectively 0.73 and 1.04.

6.5 The calibration of the BSIM model

The effort that we made when we calibrated the model in the previous section is useful also in the calibration in the BSIM model. All the initial values are the same since capital, consumption, transport infrastructure and investment in the two capital goods carry out directly. We can also use the same depreciation rates as they have been calculated from the data at our disposal. The only difference in the initial values that we have to take into account is that, given that output enters the production function, we need to specify a value for initial output. This value has been simply obtained summing initial consumption and initial investment

[78] See www.its.leeds.ac.uk/projects/unite for details.

[79] Belgium, Finland, Greece, Italy, Luxembourg, Portugal and Sweden.

in capital and transport infrastructure in order for the equations of the model to be consistent.

Unfortunately, we cannot use the same values that we used in the previous model for all the parameters for two reasons: the first one is that the production and utility function have different specifications, the second reason is that given this difference we have to modify the discount factor (*ρ*) in order to avoid that the system explodes with unreasonably high growth rates. The fact that the BSIM model is capable of generating constant positive growth rates due to the fact that the marginal productivity of capital is constant implies that consumption can grow very easily (more capital implies more output and therefore more consumption). Therefore if future consumption is weighed "too much" the optimal choice would be to consume very little in the first periods of the simulations and then consume a very large amount in the last few periods. Discounting the future consumption streams, i.e. stating that individuals prefer present consumption to future consumption, forces the system to have growth rates that are not unreasonably high.

We now turn to the calibration of the parameter *α.* in the production function. To do it we calculate the elasticity of output with respect to transport infrastructure in the new model:

$$\frac{dY}{dTI} = \frac{\alpha\left(\frac{TI}{Y}\right)^{-1}}{1+\alpha\frac{TI}{Y}\left(\frac{TI}{Y}\right)^{-1}} = \alpha\frac{\frac{Y}{TI}}{1+\alpha}$$

$$\frac{\frac{dY}{Y}}{\frac{dTI}{TI}} = \frac{\alpha}{1+\alpha}\left(\frac{TI}{Y}\right)^{-1}\frac{TI}{Y} = \frac{\alpha}{1+\alpha}$$

We claimed that the estimated value of the elasticity is 0.1 and we therefore we can calculate *α* and get the calibrated parameter as 0.1.

6.6 Dealing with infinite horizon

The model that we described assumes the existence of infinitely-lived individuals who maximise their utility. However, when running numerical simulations it is impossible to calculate anything for an infinite number of periods. For the model to be solved numerically we have to specify a finite time horizon so that the numerical calculations can be carried out. At this point however there is a further aspect that we have to take into account. If we impose a finite time horizon it is like saying to economic agents that the world is going to end at a certain date. Then it would be optimal for them to let all the capital and transport infrastructure depreciate by that date and consume the entire product so that their total utility is maximised. Notwithstanding its analytical correctness this is clearly a result that we need to avoid as we are interested in the dynamics of an economy that continues its existence, on the balanced growth path, even after the last period of analysis.

A simple procedure to solve the problem is described in Kalvelagen (2003) and implies giving an extra weight to the discount factor in the last period so that consumption remains at the same level after the last period of the simulations and that investment is at least replacing the depreciating stockafter the last period of the simulation. It is necessary to imply that the parameter β (equivalent to the one we described in the Campbell model) satisfies:

$\beta = (1-\rho)^{-t}$ for period t = 1…*(P-1)* where P represents the last period

$\beta = \rho^{-1}(1+\rho)^{1-P}$ for t = P.

In this way we are sure that after period P consumption remains stable and investment in transport infrastructure and capital ensure the replacement of the depreciating stock.

6.7 The simulation of the leisure model

In this section we report the path followed by the basic variables in the leisure mode to provide an easy way of comparing the EU15 and the USA economy.

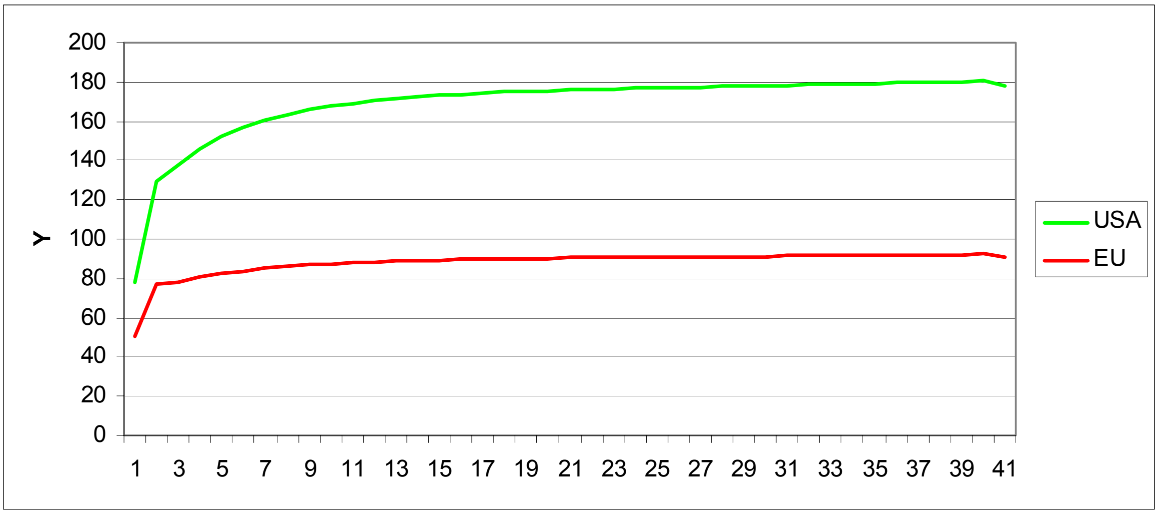

Figure 1: Simulated Output

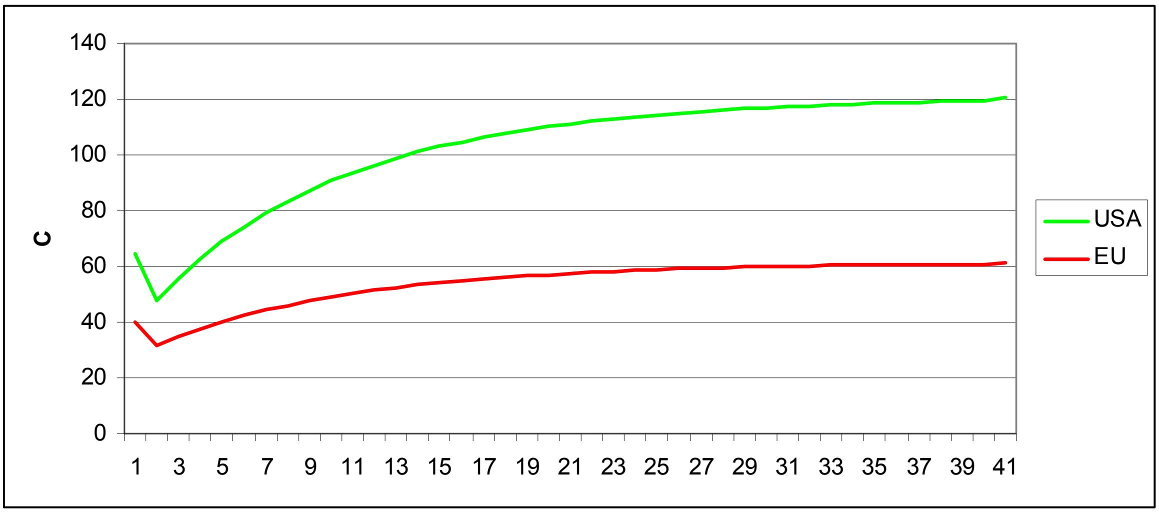

Figure 2: Simulated Consumption

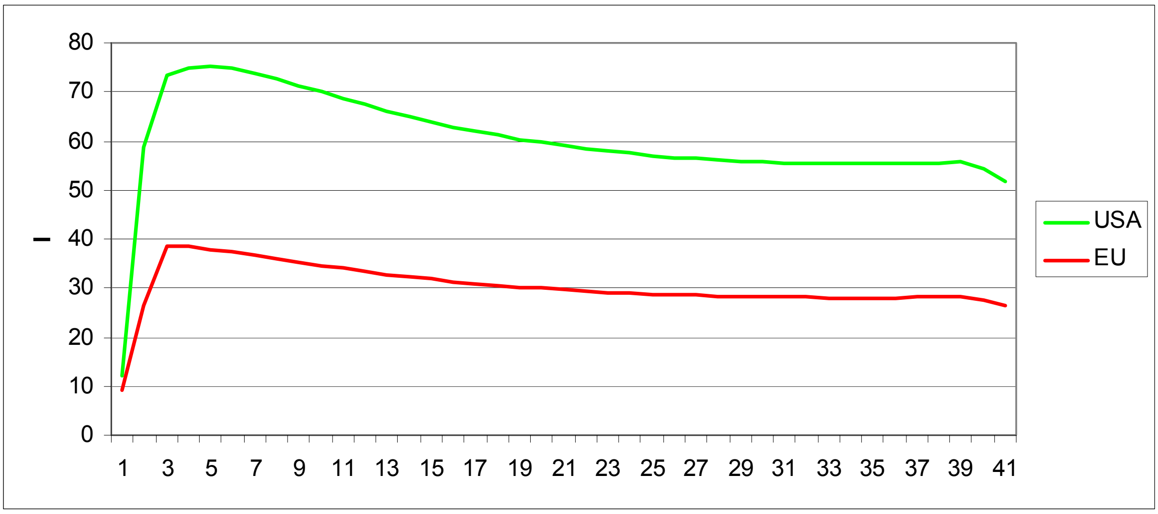

Figure 3: Simulated Investment

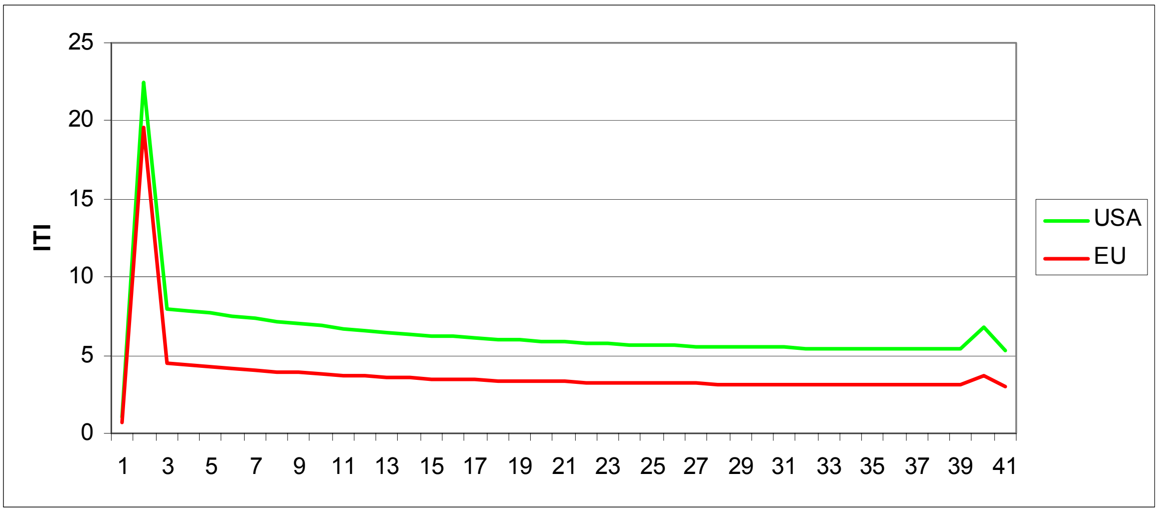

Figure 4: Simulated Investent in Transport Infrastructure

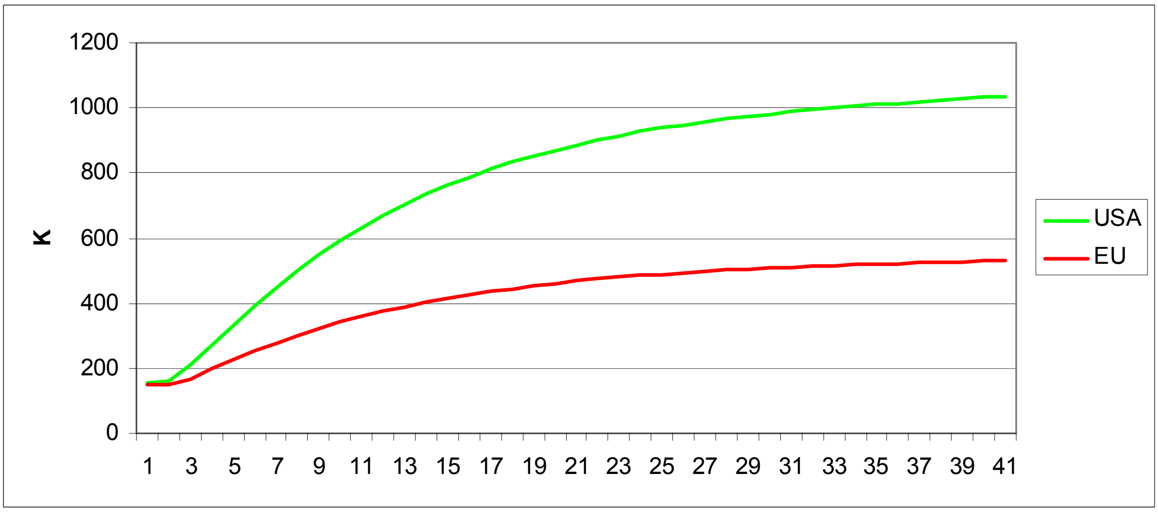

Figure 5: Simulated Capital Stock

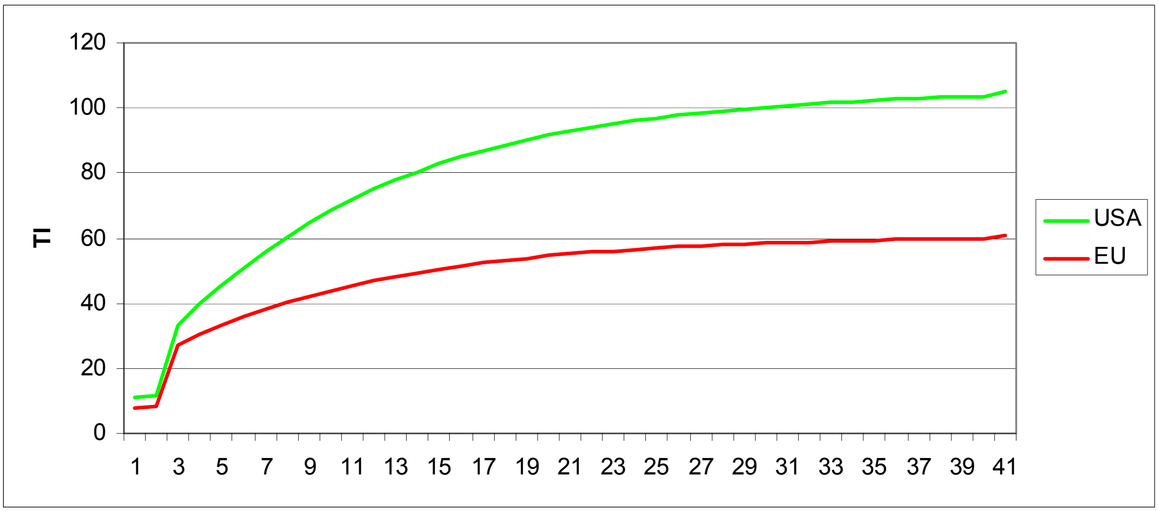

Figure 6: Simulated Transport Infrastructure Stock

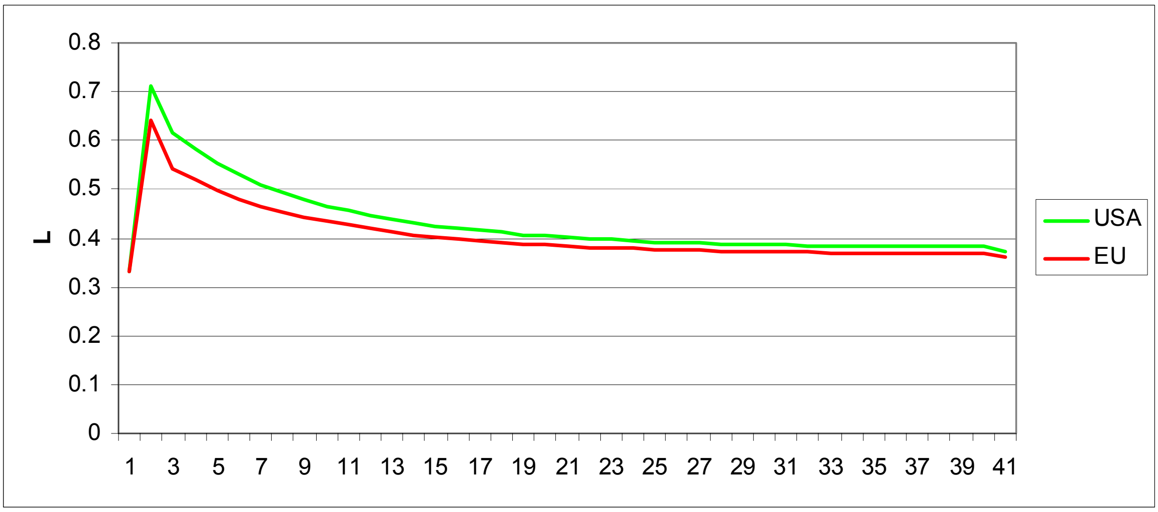

Figure 7: Simulated labour effort

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Box 1: Some useful Key words

Convoy kilometres	Convoy kilometres, in the context of this report, refers to output in the public transport sector defined in terms of the capacity provided for public transport, rather than the actual utilisation of the service.
Cost function	It is a function which relates costs of production to a set of input prices and output level. It results from th ecost-minimising behaviour of firms.
Diminishing eturns	A fall in the marginal product of an input that occurs as additional units of the input are added to production, holding all other inputs constant
Divisia index	The Divisia index is a weighted sum of growth rates, where the weights are the components' shares in total value.
Economies of scale	When an expansion in output leads to less than proportionate increase in costs, so that average costs per unit decrease
Economies of density	In a network industry, returns to density tells the increase in costs brought about by changes in output, keeping network characteristics (e.g. customers or network length) fixed.
Elasticity	Elasticity measures the percentage change that will occur in one variable in response to a one percentage change in another variable, holding all other things constant. Elasticity of substitution measures the elasticity of the ratio of two inputs to a production function with respect to the ratio of their marginal products. With competitive demands, this is also the elasticity with respect to their price ratio.
Homogeneity of degree N	A functiony is said to be homogenous of degree N when, if you scale all arguments in the function by a factor x, the value of the function is multiplied by x^N.
Marginal cost	The marginal cost is the change in cost that arises to produce an additional unit of output.
Marginal product	The change in output as one more unit of an input is added, holding all other inputs constant.
Optimisation problem	The optimisation problem for a firm usually involves profit maximisation: which is either to maximise production for a given level of costs, or minimise costs for a given level of output. An optimal level of inputs is chosen, given assumptions regarding the parameters of the production and cost function. For a consumer the optimisation problem involves maximising utility by choosing levels of consumption of goods, subject to a budget constraint.
Perpetual inventory method	It is one of the most widely used methods to build capital stock series from data on gross fixed capital formation and assumptions on the initial capital stock, scrap rates and (if the final objective is net, rather than gross, capital stock) depreciation rates.
Present value	The present value of a stream of monetary values adjusts the funds for time preferences by discounting appropriately (usually with the rate of interest)
Production function	A function that specifies the relationship between output

	and the inputs of production.
Public good	A good that has the property that one individual's consumption of it does not reduce others' ability to consume (non-rivalrous). It is also not possible to exclude some consumers from consuming the good once the good has been provided (non-excludable).
Returns to scale	In a production function framework, returns to scale tell, for a given increase in all inputs, the increase in output: there are increasing returns to scale when the increase in output is more than proportional than the increase in inputs.
Shadow price of public infrastructure	The shadow price of public infrastructure is measured as minus the derivative of the cost function with respect to the stock of public infrastructure, so that a positive value means that an extra unit of public infrastructure reduces private costs. The shadow price of public infrastructure might also be defined as the gross return of public infrastructure
Socially optimum	A socially optimum equilibrium is one where the net social benefits are maximised (this includes both private costs and benefits and externalities imposed on others)
Social user cost of public infrastructure	It might be defined as the sum of the depreciation rate, the opportunity cost of public capital and the shadow price of public funds.
Total factor productivity	Total factor productivity is a measure of the output of an industry or economy relative to the size of its factor inputs. A growth in TFP is the growth of real output beyond what can be attributed to increases in the quantities of labour and capital employed.
Tornqvist approximation	Tornqvist approximation is a discrete-time approximation to a Divisia index, in which averages over time fill in the quantities of capital and labour.
Utility function	A function that defines how the utility (well-being) of an individual changes with consumption of the goods, which can also be defined broadly to include leisure.

8 List of studies about networks and their growth impacts

The following lists present an overview on the different approaches of studies about networks and their growth impacts for the EU and the US. Three different major approaches have been identified:

- Production function approach.
- Cost function approach.
- Var approach.

Table 3. EU: Production function approach

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
La Ferrara, Marcellino	TFP, costs and public infrastructure: an equivocal relationship	Mimeo, Universita' Bocconi	Italian regions	TFP regression, production function and cost function	TFP regression: TFPg on Lg, Kg, KGg and fe. Production function: levels with fe. Cost function with fe. Endogenity in KG in the production function dealt with 2SLS.	1970-1994	Panel	regional industrial sector	Stock of public capital (mainly roads, railways, ports, water, communications, pipelines, sanitation, land)	TFP approach: for Italy elasticity of KG high (0.47) and significant. it is positive for South, insignificant for North. Prod function approach: elasticity of KG negative: across sub periods, this is true only in the 70s, in recent years it is positive and increasing; KG elasticity is higher in the south, followed by the centre. Cost function: KG does not reduce costs for Italy (with the exception of the 70s). In some areas it reduced costs, but there was overinvestment.

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
De Stefanis, Sena	Public capital and Total Factor Productivity: New Evidence from the Italian regions, 1970-98	Regional studies, 39, 5, 2005	Italian regions	TFP regression and non parametric methods	Estimation of cointegration relationship	1970-1998	Panel	total economy	Public capital stock, core infrastructure, non core infrastructure	TFP regression shows positive elasticities of KG for core infrastructure and total KG, especially in the NE, SW and SE. Statistical tests are used that seem to support the view that core infrastructure causes TFP growth. Non parametric estimates reinforce the econometric analysis' conclusions
Everaert, Heylen	Public cpaital and productivity growth: evidence for Belgium, 1953-1996	Economic modelling	Belgium	TFP regression	Engle Granger cointegrationn model to deal with non-stationarity of the data estimated with NLS	1953-1996	Time series	total economy	Public capital stock	Imposing constant returns to scale to all inputs, they find the elasticity of output to KG equal to 0.29 (which imply a rate of return to private investment of about 29%). Simultaneity dealt with using the Phillips-Hansen procedure that yield similar results. They also used an VECM to show that TFP does not cause KG.
Delgado, Alvarez	Public productive infrastructure and economic growth	ERSA 39TH Congress, 2000	Spanish regions	Production function with regional fixed effects	Translog production function in levels	1980-1995	Panel	Private output	Aggregation of physical measures for roads, high capacity roads, Ports, pipelines, electricity, number telephone lines, double line electricity railways, etc using principal component analysis	The elasticity of output with respect to KG is slightly negative (no standard error provided).

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
Bajo-Rubio, Sosvilla-Rivero	Does public capital affect private sector performance?	Economic Modelling, 1993	Spain	Production function with variables divided by K, taking productive capacity into account	Estimation of long run relationship using Phillips and Hansen methodology plus an ECM	1967-1988	Time series	total economy	Public sector capital stock	Elasticity of output to KG positive (about 0.18-0.20). Marginal productivity of public capital higher than that of private capital. The ECM results support these obtained from the estimation of the long run relationship.
Kamps	Is there a lack of public capital in the European Union?	Kiel Institute for World Economics, 2005	22 OECD countries (14 EU)	Production function in an endogenous growth framework	Growth rate regressed on public control variables, fixed and time effects and a function of private-public capital ratio estimated by NLS	1960-2001	Panel	Total economy	Net public capital stock	The elasticity of output to public capital is positive and significant both for the EU and the extended OECD sample (about 0.20). The data do not show any significant shortage or excess of public capital for most EU countries. There are some limitations in the study, such as assuming countries are in their steady state, the way public capital is financed, the limited number of control variable, the assumptions that capital is the only factor of production.

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
Kemmerling, Stephan	The contribution of local public infrastructure to private productivity and its political economy : evidence form a panel of large German cities	Public Choice, 113, 2002	87 German towns	Production function	Estimated with variables divided by labour with re and within a system (together with an equation for infrastructure investment function and an investment allocation function) by FIML	1980, 1986, 1988	Panel	manufacturing	Public infrastructure stock	Positive elasticity of KG (about 0.17), implying a rate of return of public infrastructure of about 16%. Private capital is more productive (33%).
Evans, Karras	Is government capital productive? Evidence from a panel of seven countries	Journal of Macroeconomics, 2, 16, 1994	Belgium, Finland, UK, Germany, Greece, US, Canada	Production function	First difference and TFP growth regressed on growth in public capital. Year and country effects plus AR(1) error	1963-88	Panel	total economy	Government net capital stock	In the first difference model, after accounting for time effects and country (random and fixed) effects, KG coefficient not significant. The TFP change regression on growth of public capital not significant (doubts endogenity fully taken into account).
Charlot, Schmitt	Public infrastructure and economic growth in France's regions	ERSA 39TH Congress, Dublin, 1999	French regions	Production function	Levels, fixed effects and endogenity correction attempted for some specifications of the model	1982-93	Panel	regional economy	Stock of public capital	CD with fixed effects found strong positive effects of GK on Y (similar to Aschauer, about 30%). A 3SLS (without fixed effect) shows a smaller unsigignificant value. A translog fixed effects find high positive effects of GK (no endogeneity correction). Sensitive to region and period

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
Stephan	Assessing the contribution of public capital to private production: evidence from the german manufacturing sector	International review of applied economics, 4, 17, 2003	German lenders	Production function	Levels and first difference. Fixed effects. Panel corrected standard errors to deal with group wise het, serial corr.	1970-96	Time series cross section	regional economy	Public gross stock of fixed assets at ground level (roads, highways, bridges, railways, waterway, dikes, ports)	Large elasticities (between 0.38 and 0.65 found) which imply rate of returns of between 26% and 72%, much higher than private capital, though declining through time. However, no attempt to control for endogeneity of inputs.
Picci	Productivity and Infrastructure in the Italian Regions	Giornale degli Economisti e annali di Economia, 1999	Italian regions	Production function	Level form. Time effects and fixed region effects	1970-1995	Panel	regional economies	Gross capital stock	Fixed effects estimates show large elasticity of KG (about 0.35) larger than private capital. If KG split into core and non core, core positive (0.50!), non core neg. A first diff model reduces KG elast to 0.18. a long difference regression still shows high elasticity. Elasticities tend to be lower in the more developed north. Core more productive than non core everywhere. No corrections for possible endogenity of inputs

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
Sturm, Dehan	Is public expenditure really productive? New evidence for the US and The Netherlands	Economic Modelling, 12, 1, 1995	US and Netherlands separately	Production function	Levels and first difference because of no stationarity and cointegration. No endogeneity correction attempted.	1949-1985 for the US; 1960-1990 for The Netherlands	Time series	Total economy	US: private non residential capital stock. The Netherlands: Buildings, infrastructure, sum of the two.	US: the appropriate specification (first diff) suggests positive KG elas but significant at only 10% (and counterintuitive results for labour and cap elas). The Netherlands: buildings not significant, infrastructure significant, total public capital significant and very large. Infrastructure elasticity ranges between 0.6 and 0.8.
Percoco	Infrastructure and economic efficiency in Italian regions	Networks and spatial economics, 4, 2004	Italian regions	Production function	Estimated in level, inefficiency in production assumed estimating a stochastic production frontier with ML, fixed effects considered and endogenity taken into account	1970-1994	Panel	total economy	Stock of roads, Railways, maritme infrastructure, communication	Elasticity of output with respect to KG is positive (about 0.10-0.20, depending on the specifications) and it seems highest in the north west. Railways seems the most important infrastructure type in stimulating technical efficiency
Kamps	New Estimates of Government net Capital Stocks for 22 OECD countries 1960-2001	IMF working paper, 04/67	22 OECD countries	Production function	first difference with fixed effects.	1960-2001	Panel	Total economy	Net public capital stock	The elasticity of output to KG is positive but reasonable (about 0.2).
Stephan	Regional infrastructure policy and its impact on productivity: a comparison of Germany and France	DIW Discussions papers, 2001	German and French regions	Production function	Estimated in levels with fixed effects, with an error term following an ARMA series, by ML	Germany: 1970-95; France: 1978-92	Panel	regional economy	Infrastructure stock	Cobb Douglas yileds an elasticity of about 0.08- 0.11

Author	Title	Source	Region	Methodology	Specification and estimation	Sample period	Sample type	Sector	Infrastructure variable	Main results
Cadot, Roller, Stephan	Apolitical economy model of infrastructure allocation: an empirical assessment	CEPR discussion papers, 2236, 1999	France regions	Production function	Production function estimated jointly with an equation to explain transport infrastructure	1985-1991	Panel	regional economy	Infrastructure capital stock	The elasticity is about 0.10
Bonaglia et al	Public capital and economic performance: evidence from Italy	Mimeo, Universita' Bocconi	Italian regions	TFP regression, production function and cost function	TFP regression: TFPg on Kg, KGg and fe. Production function: levels with fe. Cost function with fe. Endogenity in KG in the production function dealt with 2SLS.	1970-1994	Panel	regional economy	Stock of public capital (mainly roads, railways, ports, water, communications, pipelines, sanitation, land)	Conflicting results: the TFP regression shows positive effects of KG (K has negative effects). Production function: small and insignificant for Italy, driven by north west regions. Disaggregating KG seems to show, for Italy, that transport has a positive and significant effect. This is however not confirmed in a TFP regression framework. The cost function shows a negative elasticity of costs with respect to KG. Differences across regions: centre and south tended to show positive effects of KG.
Cadot, Roller, Stephan	Contribution to productivity or pork barrel? The two faces of infrastructure investment	DIW Berlin 458, 2004	French regions	Production function	Production function estimated jointly with an equation to explain transport infrastructure jointly estimated with FIML	1985-1992	Panel	regional economy	Infrastructure capital stock	Positive elasticity (about 0.08)

Table 4. EU: Cost function approach

Author	Title	Date	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Demetriades, Mamuneas	Intertemporal output and employment effects of public infrastructure capital: evidence from 12 OECD countries	2000	Economic Journal, 110, 2000	Australia, Belgium, Norway, Sweden, Finland, US, Canada, Japan, Germany. France, Italy, UK	Profit function plus other equations derived from producers intertemporal maximisation	Non linear SURE system (short run profit function, supply function and capital stock equations). Time effects plus state specific constants.	1972-91	Panel	Manufacturing	Government capital stock reconstructed using the series of gross capital formation by producers of government services (exclusive of military exp)	Public capital has a positive effect on output (from +0.36 to about +2%), labour and capital demand. In the short run, overinvestment of public capital only in Australia, Norway and US, optimal provision in Sweden and Finland, underprovision in the others. In the long run, underprovision everywhere, though declining in most countries. Countries with low KG to output ratios have the highest returns. Private capital more productive than public capital (except Sweden, Australia, Belgium and Finland)
Berndt, Hansson	Measuring the contribution of public infrastructure capital in Sweden	1992	Scandinavian Journal of Economics, 94, 1992	Sweden	Labour requirement function	Levels (all variables divided by output to reduce heteroskedasticity). Possible endogeneity of output tested and rejected	1964-1988	Time series	Total economy	Aggregate public infrastructure stock; core public infrastructure stock (roads, highways, mass transit, airports, water and sewer mains, railroads.	Public capital reduces variable costs (in their case labour), but there is an overprovision of public capital (assuming the benefits for consumers are zero, as common practice in this literature), in the late part of the sample.
Lynde, Richmond	Public capital and long run costs in UK manufacturing	1993	Economic Journal, 103, 1993	UK	cost shares derived from a cost function	Cost shares are estimated in levels, using the Philips and Hansen procedure to take into account their non stationary features	1966-1990	Time series	Manufacturing sector	Public capital stock (exclusive of dwellings)	They used the results to decompose the rate of growth of labour productivity into a term due to private capital/labour growth, public capital/labour growth and a residual. Changes in KG/labour ratio explained about 6% of rate of growth in labour productivity (as private capital to labour ratio), even if in the 1980s KG contribution was negligible.

Author	Title	Date	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Bosca et al	The effect of public infrastructure on the private productive sector of Spanish regions	2002	Journal of Regional Science	Spanish regions	Variable cost function, input demand equations and a short run pricing equation	Estimation using SURE	1980-1993	Panel	Private sector	Public capital stock	The shadow price of public capital is positive, implying a reduction of variable costs: the average value for the elasticity is -0.03 (declining over time), and it is positive in 15 out of 17 regions. The shadow KG is positive in 15 out of 17 regions (and large in some) even in the long run (when the private capital is adjusted to its long run equilibrium). The output elasticity of KG is about 0.02 and slightly higher in the long run. The actual KG was underprovided in the early period while the gap was nearly closed in 1993. KG and K complements
Moreno et al	On the effectiveness of private and public capital	2003	Applied Economics	Spanish regions	Variable cost function, cost shares plus regional and sectoral effects	Estimation using SURE and regional and sectoral effects	1980-1991	Panel	12 manufacturing industries	Stock of public core infrastructure	The elasticity of variable costs with respect to KG is negative (-0.02) but hardly significant. The average output elasticity is positive but low (0.02). Different sectors and regions showed rather different patterns, however. Electric machinery, food and drinks and textiles are these gaining most from KG. KG appears to be more important when private capital is scarce.

Author	Title	Date	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Rovolis, Spence	Duality theory and cost function analysis in a regional context: the impact of public infrastructure capital in the Greek regions	2002	Annals of regional Science, 36, 2002	Greece prefectures	Cost function plus cost shares.	estimation by SURE, fixed effects in both cost and input demand equations,	1982-1991	Panel	manufacturing	Infrastructure stock	KG reduces costs in all regions (the value is 0.06, although statistical significance not checked). KG is a substitute for labour and intermediate inputs and a complement for capital.
Seitz	Public capital and demand for private inputs	1994	Journal of public economics, 54, 1994	31 2-digit manufacturing industries	Cost function plus cost shares	estimation by SURE, fixed effects in both cost and input demand equations.	1970-1989	Panel	manufacturing	Total public capital stock/core infrastructure (Housing, Transport, communication, recreation) corrected for CU	The shadow value of public capital is positive (i.e. it reduces total costs) but very low: 1000DM of public capital would reduce total costs by about 2 DM (total GK) or 3.6 DM (core infrastructure). KG and K complements KG and labour substitutes.
Mamatzakis	Public infrastructure, private input demand, and economic performance in the Greek industry	1999	Mimeo, Queen Mary and Westfield College	20 2-digit manufacturing industries	Cost function plus cost shares	Estimation by SURE	1959-1990	Panel	large scale manufacturing	Core infrastructure	Public capital reduces total costs (elasticities between -0.02 to -0.78. and in most industries also marginal costs. KG is a complement to private capital, substitute for L. KG contributes positively for most of the industries to productivity growth (from -0.03% to + 0.53%), even if at a declining rate

Author	Title	Date	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Gil Canaleta et al	Public capital, regional productivity and spatial spillovers	1998	University of Navarra	Spanish regions	Cost function and, separately, a production function incorporating profit maximiasation restrictions	Estimation with sure and FE in both cost function and shares	1964-1991	Panel	Agriculture, industry and services	Stock of public capital or trasnport infrastructure	Elasticity of costs with respect to total KG is negative (about -0.14), while for transport capital is lower (in absolute value) and even positive for agriculture. Production elasticities are in general positive and reasonably low when transport is used, and higher when total KG is used. When they account for spillover effects (they use a weighted average of the other regions transport infrastructure weighted by shares in trade flows) the production elasticities tend to grow.
Seitz, Licht	The impact of public infrastructure capital on regional manufacturing production costs	1995	Regional Studies, 29, 3, 1995	German lenders	Cost function and factor shares	Estimation by SURE assuming fixed effects in the cost as well as factor share equations. Factor prices and output instrumented	1971-1988	Panel	Manufacturing sector at regional level	Public capital stock	KG complement to private capital and substitute to labour input. Elasticity of costs to public capital strongly negative everywhere (-0.2 on average), especially in regions with large areas.
Aviles Zugasti et al	The effect of public infrastructure on the cost structure of Spanish industries	2001	Spanish Economic review, 3, 2001	Spain	Variable cost function with factor shares	Estimation with sure and FE in the cost function. Endogeneity tests on public and private capital performed and rejected	1980-1991	Panel	19 industries	Stock of core public infrastructure	Positive shadow price of public capital, even if large variation across industries. The elasticity of output with respect to KG is positive and, on average equal to 0.24 (lower than that of private capital).Labour and intermediate materials are substitutes to KG in all industries.

Author	Title	Date	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Ferrara, Marcellino	TFP, costs and public infrastructure: an equivocal relationship	2000	Mimeo, Universita' Bocconi	Italian regions	TFP regression, production function and cost function	TFP regression: TFPg on Lg, Kg, KGg and fe. Production function: levels with fe. Variable cost function with fe. Endogenity in KG in the production function dealt with 2SLS.	1970-1994	Panel	regional industrial sector	Stock of public capital (mainly roads, railways, ports, water , communications, pipelines, sanitation, land)	TFP approach: for Italy elasticity of KG high (0.47) and sig. it is pos for South, insignificant for North. Prod function approach: elasticity of KG negative: across sub periods, this is true only in the 70s, in recent years is pos and increasing; KG elasticity is higher in the South, followed by the centre. Cost function: KG does not reduce costs for Italy (with the exception of the 70s). In some areas it reduced costs, but there was overinvestment.
Everaert, Heylen	Public capital and long term labour market performance in Belgium	2004	Journal of policy Modelling, 26, 2004	Belgium	Dynamic structural model	ECM joint estimation of factor demand equations, wage equation, domestic and external demand	1968-1996	Time series	total economy	Public capital stock	The elasticity of costs to public capital is negative and significant (-0.28, which implies one more euro of public capital reduces total costs of 0.24 euros). Private and public capital are complements and public capital and labour substitutes.
Bonaglia et al	Public capital and economic performance: evidence from Italy	2000	Mimeo, Universita' Bocconi	Italian regions	TFP regression, production function and cost function	TFP regression: TFPg on Kg, KGg and fe. Production function: levels with fe. Variable cost function with fe. Endogenity in KG in the production function dealt with 2SLS.	1970-1994	Panel	regional economy	Stock of public capital (mainly roads, railways, ports, water, communications, pipelines, sanitation, land)	Conflicting results: the TFP regression shows positive effects of KG (K has negative effects). Production function: small and insignificant for Italy, driven by north west regions. Disaggregating KG seems to show, for Italy, that transport has a positive and significant effect. This is however not confirmed in a TFP regression framework. The cost function shows a negative elasticity of costs with respect to KG. Differences across regions: centre and south tended to show positive effects of KG.

Table 5. EU: VAR approach

Author	Title	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Pereira, Roca	Public capital formation and regional development in Spain	Review of Development Economics, 3, 3, 1999	Spain	VAR	VAR in first difference	1970-1989	Time series	total economy	Public capital stock in transport and communication infrastructure	Employment and private capital elasticity with respect to public capital stock is 0.4, while output elasticity is 0.38 (a one additional peseta of public capital raises output by 4.38 pesatas in the long run, which implies a rate of return of 6%). Effects of public capital uneven in the regions, with the most developed ones gaining the most. However, confidence intervals not reported
Pereira, Roca	Infrastructure and private sector performance in Spain	Journal of Policy Modelling, 23, 2001	Spain	VAR	VAR in first difference	1970-1993	Time series	total economy and 4 sectors (agriculture, manufacturing, construction, and services) separately	Public capital stock in transport and communication infrastructure	Public capital stock not an exogenous variable. Elasticities of employment, private capital and output are positive (0.49, 0.52 and 0.31, implying marginal products of 3.28, 10.18, 5.5 (and a rate of return of 7.7%). Elasticities tend to be negative for agriculture, and positive for the other sectors, with construction benefiting the most (the output elasticity is 1.23 for cons., 0.81 for manufacturing and 0.37 for services). Marginal products suggest that manufacturing takes the 41.5 of the effects of public capital on output, services 37 and construction 22. However, confidence intervals not reported
Pereira, Roca	Spillover effects of public capital formation: evidence from the Spanish regions	Journal of Urban Economics	Spain and Spanish regions	VAR	VAR in first difference	1970-1995	Time series	total economy	Public capital stock in transport and communication infrastructure	Public capital not exogenous in the model. Elasticity of output is positive in Spain using aggregate data (0.52, which implies a marginal product of about 2.9 and a rate of return of 5.5%). The regional analysis show some dispersion and the aggregate effects over all regions account for only 44% of the total effect derived in the aggregate model. Considering also the capital installed in other regions alters the results significantly: the public capital in the region affects positively output, as capital installed outside does. This shows that spillovers effects tend to be important, especially for peripheral regions. However, confidence intervals not reported

Author	Title	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Pereira, Andraz	Public investment in Transportation Infrastructure and Economic performance in Portugal	Review of Development Economics, 9, 2, 2005	Portugal	VAR	VAR in first difference	1976-1998	Time series	total economy	Public investment in transportation infrastructure as a whole and disaggregated (national roads, municipal roads, highways, ports, airports, railways)	Public investment exogenous, while this is not the case for some sub-categories. Public investment raises private investment (elasticity 0.64) employment (elasticity 0.08 which implies 230 additional jobs created out of one million euros in public investment in transport infrastructure) and output (elasticity 0.18 which implies a rate of return of 15.9%). At disaggregated level the results are confirmed: in particular, public investment in national roads have the largest effect on both output, employment and private capital; public investments in airports are the least effective
Ligthart	Public capital, and output growth in Portugal: an empirical analysis	IMF working papers, 11, 2000	Portugal	VAR	Levels and first differences and VAR	1965-1995	Time series	total economy	Equipment and transport material, construction, core infrastructure	Positive elasticity (about 0.20-0.35) for the production function, core infrastructure the most important. However, VAR models suggest that the KG effect on output is insignificant
Kamps	The dynamic effects of public capital: VAR evidence for 22 OECD countries	Kiel working paper 1224, 2004	22 OECD countries	VAR	VAR estimated with Johansen ML procedure	1960-2001	Time series	total economy	Public net capital stock	For most countries (13) the long run elasticity of output to KG is positive and significant at the 68% level, for two is negative, and for the others is not significantly different from zero.
mittnik, Neumann	Dynamic effects of public investment: Vector autoregressive evidence from six industrialized countries	Empirical economics, 26, 2001	Canada, France, UK, Japan, The Netherlands, Germany	VAR	VECM estimated with Johansen ML procedure	Canada: 1955-94; France: 1970-94; UK: 1962-93; Japan: 1955-94; The Netherlands: 1977-94; Germany: 1960-89. Quarterly data	Time series	Total economy	Public investment	The long run elasticity of output to public investment is small. Positive, but in general insignificant (with the exception of Germany and The Netherlands). Public investment does not in general seems to be driven by GDP.
Sturm, Jacobs, Groote	Output effects of infrastructure investment in The Netherlands 1853-1913	Journal of Macroeconomics, 2, 21, 1999	The Netherlands	VAR	VAR	1853-1913	Time series	Total economy	Transport infrastructure capital formation	Positive effects in the short run, insignificant in the long run

Author	Title	source	Region	Methodology	specification and estimation	sample period	sample type	sector	Infrastructure variable	results
Flores de Frutos, Garcia, Perez	Public capital and economic growth: An analysis of the Spanish economy	Applied Economics, 30, 8, 1998	Spain	VAR	VARMA in first differences	1964-1992	Time series	national economy	Infrastructure capital stock	Positive effects on output
Mamatzakis	Testing for the long run relationship between infrastructure and private capital productivity a time series analysis for the Greek industry	Applied Economics Letters, 6, 4, 1999	Greece	VAR	VECM	1959-1993	Time series	national economy	Public capital stock	Public capital exogenous, positive effects of KG on output
Everaert	Balanced growth and public capital: an empirical analysis with I(2) trends in capital stock data	Economic Modelling, 20, 2003	Belgium	VAR	VECM estimated with Johansen ML procedure	1953-1996	Time series	national economy	Public capital stock	Positive elasticity of output (about 0.14)

Table 6. US: various approaches

Author	Title	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Aschauer, D.A.	Is public expenditure productive?	Journal of Monetary Economics, 1988	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.	University of California at Irvine. Working Paper, 1996	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.	Journal of Regional Science, 1998	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.	Journal of Urban Economics, 2003	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.	Mimeo., 2003	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

Author	Title	Source	Region	Methodology	Specification	Sample Period	Sample type	Infrastructure Variable	Results
Duggal, V., Saltzman, C., and Klein, L.	Infrastructure and productivity: a nonlinear approach.	Journal of Econometrics, 1999	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.
Evans, P. and Karras, G.	Are government activities productive? Evidence from a panel of U.S. states.	The Review of Economics and Statistics, 1994	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?	The American Economic Review. 1999	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.	The Review of Economics and Statistics, 1996	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.

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Haughwout, A.	Public infrastructure investment, productivity, and welfare in fixed geographic areas.	Journal of Public Economics, 2002	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.	The Review of Economics and Statistics, 1994	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.
Holtz-Eakin, D. and Shwartz A.E.	Infrastructure in a structural model of economic growth.	Regional Science and Urban Economics, 1995	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.	Regional Science, 1997	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.

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Morrison C. and Schwartz, A.E.	State infrastructure and productive performance.	The American Economic Review, 1996	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.	The Review of Economic and Statistics, 1994	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.	US Department of Transportation, 1998	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.
Pereira, A.	On the effects of public investment on private investment: What crowds in what?	Public Finance Review, 2001	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.

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Pereira, A. and Andraz J.	On the impact of public investment on the performance of U.S. industries.	Public Finance Review, 2001	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.	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.	Journal of Economic Growth, 2001	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	US 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.