No 154 **Discussion Papers** **September 1995**

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A Cost Function/Cost Share Approach for Norway, 1971-1991

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Abstract
An issue of major concern to politicians and policy-makers around the world today is whether transport infrastructure investments, such as those in roads and airports, generate enough economic benefits to justify their very large price tag. Beginning in the mid 1970s, nearly all OECD countries experienced a sustained decline both in public investment and in private sector output. Since infrastructure comprises the vast majority of public capital in these countries, this led many economists to conclude that underinvestment in infrastructure was largely responsible for the low growth rates in output and productivity which were experienced by these countries. In our paper, we discuss the findings in the literature with respect to both econometric and modeling deficiencies. Based on these criticisms, we develop a cost function modeling approach which includes public transport infrastructure capital, perform an econometric analysis and discuss several of our estimates of infrastructure productivity effects. The paper concludes that, in nearly all production sectors (except oil/agriculture), the public transport infrastructure investments made in Norway over the last 20 years significantly reduced private production costs and altered demand for private inputs. However, we find such effects to be statistically insignificant at the aggregate level.

Keywords: Infrastructure, public transport investment, economic growth

JEL classification: C32, E62, H54, R42

Acknowledgement: We would like to thank Erling Holmøy for his helpful comments on earlier drafts. Financial support from Norges Forskningsråd through the Society, Environment and Energy program (SAMMEN) is also gratefully acknowledged.

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1 Introduction

An issue of major concern to politicians and policy-makers around the world today is whether transport infrastructure investments, such as those in roads and airports, generate enough economic benefits to justify their very large price tag. Beginning in the mid 1970s, nearly all OECD countries experienced a sustained decline both in public investment and in private sector output. Since infrastructure comprises the vast majority of public capital in these countries, this led many economists (such as Aschauer (1989) and Munnell (1990 a,b)) to conclude that underinvestment in infrastructure was largely responsible for the low growth rates in output and productivity which were experienced by these countries. Our aim in this paper is to investigate how transport infrastructure capital, the majority of which is publicly owned in most countries, enters into the private production process. We hope to find out whether or not there is a clear and discernible link between this particular type of public infrastructure and private production costs in Norway.

One widely used definition of infrastructure is as the real fixed capital stock which is owned by the public sector. This is a rather vague definition, but it permits easy measurement. An alternative, and better definition from a theoretical standpoint, is that infrastructure includes all the various networks of capital intensive natural monopolies, such as highway and utility systems. This is often called the 'core' infrastructure because it is considered most likely to enhance private sector production. While this 'core' definition is more precise than the 'public ownership' one and captures that infrastructure can be both publicly and privately owned, it is notoriously difficult to measure (see Gramlich, 1994). Furthermore, available national accounts data rarely distinguish between private infrastructure capital and other types of private capital. For these reasons, we must follow convention and define transportation infrastructure according to the 'public ownership definition', i.e. as the real fixed public capital stock in air, rail, road, sea, and communication activities.

Even though it is intuitively obvious that production would be impossible without public infrastructure, classical production theory, oddly, has typically ignored this variable, focusing instead on only those variables internal to the firm, like private capital and labor. Traditionally firms are assumed to choose the optimal amount of private inputs given private input prices, a predetermined level of output, and various exogenous environmental factors - such as technological change. Public transportation infrastructure capital, like technological change, can be thought of as one of those environmental factors which are external to the firm's decision making process yet nonetheless influence its production possibilities, and thus, indirectly, its cost structure.

According to Meade (1952), public capital affects output in two ways. One way is as an environmental variable, as just discussed, which can boost private input productivity. The other way public capital affects output is more directly as an input which contributes independently to a private firm's production. Public capital can stand in its own right in the production function, even though it is not a 'choice' variable of the firm. (In the simplest case, think of plane plus pilot plus public airport services as producing air travel services.) The important distinction is that public infrastructure capital is different from traditional inputs because it is not purchased by the firm like private inputs are. Instead, changes to the stock are usually determined externally, via the political process. Assuming that the individual firm has no influence in this process, public infrastructure capital should be considered as an exogenous, unpaid factor of production which affects the firm's variable costs.

A review of the literature

A brief review of the literature demonstrates that economists are widely divided over whether or not public infrastructure investment generates economic returns, in terms of higher output or increased productivity. The controversy is not about *if* public capital belongs in the production (or cost) function, but rather *how* the function should be estimated. Important issues to consider are which functional form is appropriate and whether the data used are stationary, i.e. give reliable results.

It should be noted at this point that there is an important distinction between the *stock* of infrastructure capital and the *flow* of services from that stock. It is the amount of *services* which a firm receives from the infrastructure stock which influences a firm's cost structure, rather than the total infrastructure capital network which exists. Unfortunately, it is impossible to accurately measure the amount of infrastructure services which a firm uses. For example, it is hard to measure which parts of a national highway system a firm actually uses, how intensely it uses these routes, and how to account for variations in road quality or congestion levels. The second-best solution, now standard in most of the recent literature, is to multiply the infrastructure capital stock by a capacity utilization index in order to reflect that firms utilize the available infrastructure stock to different degrees, depending on the level of activity in their industry. Thus in boom periods, the firm's demand for public transport infrastructure services will be relatively high, reflecting that the demand for the firm's own products is large, whereas in recessions situation is obviously reversed.

Assuming Cobb Douglas production technology, constant returns to scale over all inputs[1], and using time series data, Aschauer (1989) performs a straightforward least squares regression of total private business economy value-added per unit of private capital on the private labor-capital ratio, the net (of depreciation) public capital (nonmilitary) stock to private capital

[1] CRTS over all inputs is tested and accepted by Aschauer.

stock ratio,[2] capacity utilization in the manufacturing sector, and on time as a proxy for technological change. Using annual US data from 1949-1985,[3] he finds that the elasticity of output with respect to 'core infrastructure', is .24 and is highly significant.[4] This means that a 1% increase in the public 'core' public infrastructure capital stock would generate a .24% rise in output. The estimated elasticity of output with respect to private capital is .26. Therefore, in Aschauer's model, public 'core' infrastructure capital appears to have almost the same impact on private sector output as private capital does. He concludes that the government should take advantage of this large stimulative effect by increasing public investment in infrastructure. Aschauer's work prompted many other economists to investigate whether the economic returns to infrastructure were really as dramatic as he claimed.

Using a similar approach, Ratner (1983) had earlier estimated an aggregate Cobb Douglas production function, assuming constant returns to scale technology. Ratner's model was slightly different from Aschauer's model, where capacity utilization enters additively to the estimated equation, as an independent variable. In his original study, Ratner finds an elasticity of private US business sector output with respect to public (infrastructure) capital of .06 over the period 1949-1973. Tatom (1991) reestimates Ratner's model using revised levels data for this period and finds that the elasticity of output with respect to public (infrastructure) capital is .28. Tatom argues, however, that Ratner's findings (as well as his own reestimation) are invalid due to the nonstationarity of the data[5]. Therefore, Tatom reestimates the model (for the same period) after first differencing the data, which makes each of the variables stationary (he also includes a term for the price of energy relative to the price of business sector output). Once the variables are first differenced, the impact and statistical significance of public capital fall dramatically. When Tatom uses the first differenced data for just 1949-1973, the public capital coefficient changes sign to negative and becomes statistically insignificant. He also reestimates the model to include the period 1949-1985 and finds that the elasticity of output with respect to public capital still is statistically insignificant. In addition, when Hulten and Schwab (1994) reestimate Aschauer's equations using first differenced data instead of the levels, they also find that the coefficient on public capital becomes statistically insignificant. They note that, "with slightly different statistical

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[2] Here, the stock of public capital is used here as a proxy for the flow of services from public capital since the services are assumed to be proportional to the stock. The capacity utilization index comes in additively.

[3] A detailed discussion of the international literature is presented in APPENDIX C.

[4] Aschauer defines 'core' public infrastructure as highways, mass transit, airports, utility (electric, gas, water) systems, and sewers. So defined, 'core public infrastructure' comprises 55% of the total nonmilitary public capital stock.

[5] By stationarity, it is meant that the main properties of the variable, such as its mean, variance, and covariance with its lagged variables do not depend on the absolute value of time, but rather on the time *between* periods. For example, after a random shock we would expect the mean of a stationary variable to return to its original long run trend. For a non stationary variable, however, temporary shocks become permanent ones. The problem with macroeconomic time series, in particular, is that they not only usually follow a trend (e.g. the means rise over time), but often even when the trend is removed, they remain non-stationary. For more on time series analysis see, for example, Harvey (1990), Kennedy (1992) and Granger and Newbold (1986).

approaches (i.e. whether or not the data are first differenced), the same data could lead us to conclude that additional investment in infrastructure could have either a dramatic impact or virtually no impact on the private economy." This underscores the main point here, that obtaining non-spurious results hinges on whether stationary data are used.

Economists are not only divided over econometric issues concerning data stationarity, they are also divided on how to model the link between infrastructure public capital and output. Most studies of the effects of infrastructure capital on output use the Cobb Douglas single equation aggregate production function specification. This is probably due to its simplicity, especially with relatively few inputs, and to the fact that current research is often compared to earlier work, which usually employed Cobb Douglas aggregate production functions. Another modeling dilemma concerns whether to use a single equation approach or a simultaneous equation estimation.

The main problem with the Cobb Douglas production function is the relationships that it presupposes between the inputs. The elasticity of substitution between the different inputs are constant and equal to one which means *ex ante* that private capital, public capital and labor are all assumed to be substitutes. By choosing this form, then, one has already decided <u>beforehand</u> that higher investment in public capital leads to higher marginal and average productivity of the other inputs. The Cobb Douglas form, therefore, is too restrictive because it does not leave room for the possibility of complementarity between the inputs.[6]

A related problem with the Cobb Douglas production function is that is presumes that all inputs are variable in the production process at all times.[7] A more realistic assumption, of course, would be to model only some factors (such as material inputs and labor) as variable in the short run, while inputs such as private and public capital would be fixed. The translog functional form could incorporate these changes.[8]

A drawback of using a single equation estimation relates to the problem of correlation versus causality. Two time series which are dominated by strong, similar trends , like output growth and infrastructure investment, will no doubt be correlated, but this does not necessarily imply that one variable indeed *caused* the other. The problem here is to determine which variables are exogenous and which are endogenous. It is very likely the case, for example, that the production function is part of a system of simultaneous equations and, therefore, that the right hand side variables (inputs in the standard production function estimates, like Aschauer's) like

[6] Private and public capital are found to be complements in most of the literature, especially in the manufacturing sector. See, for example, Seitz (1994), and Berndt and Hansson (1991).
[7] The problems with using the Cobb Douglas functional form are discussed in greater detail in Berndt and Hansson (1991).
[8] The translog cost function was first introduced in Christensen, Jorgenson, and Lau (1973).

labor input and capacity utilization are actually endogenously determined. If so, then OLS yields biased and inconsistent estimates. Since the endogenous variables are jointly determined in a simultaneous equation system, causality is not implied by correlation when looking at just one equation (such as the production function) in isolation. In addition, a single equation approach also seems to be inadequate due to the unique nature of public infrastructure capital and the multi-dimensional way that it affects production.[9]

Taking advantage of duality principles, Lynde and Richmond (1992) look at the effects that public capital has on US private sector (nonfinancial) production costs. Following the 'ownership' definition of infrastructure, they measure public capital as the net stock of nonmilitary fixed government-owned capital. Under perfect competition, the individual firm minimizes private production costs by choosing the optimal level of labor services and private capital services given the level of public capital services which are provided by the government at no cost to the firm[10]. Lynde and Richmond use a translog cost function and estimate only the set of cost share equations for the period 1958-1989. They find a negative and significant infrastructure coefficient in the labor cost share equation which implies that an increase in the provision of public capital services leads to a fall in the cost share of labor. When Lynde and Richmond calculate the *overall* effect of public infrastructure capital on the demand for labor (i.e. after also taking the productivity effect into account), they find that labor and public capital are substitutes. They also find that private and public capital are complements. The results also suggest that the marginal product of public capital is falling over the period. That is, an increase in public capital services leads to an increase in its shadow cost share. Nonetheless, they find that the marginal product of public capital was <u>not</u> driven below zero. In short, although Lynde and Richmond take a different methodological approach than Aschauer and Ratner, they also conclude that public capital is a significant determinant of US manufacturing sector costs. They do not, however, discuss the stationarity of their data.

The Norwegian case

In contrast to the analytical studies performed thus far, most of which look at the impact of aggregate public infrastructure investment (i.e. which also includes utilities, sewers, schools, etc) on the manufacturing sector, we are interested in the effects of one particular type of public infrastructure, namely transport infrastructure. This variable is particularly interesting to focus on because it is reasonable to assume, for example, that expenditure on a better highway system will have more of a direct effect on the economy than, say, building a hospital will. Public transport infrastructure capital is also arguably an important type of public infrastructure to study because it accounts for such a large part of the total public

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9 The deficiencies of single equation models in this context are detailed in Hulten (1993).

10 See Appendix C.

capital stock and public investment in most OECD countries. In 1991, for instance, Norway's public transportation infrastructure capital stock was NOK 307.3 billion (1991 prices), which was about 45% of the total Norwegian real fixed public capital stock (Statistics Norway, 1994).

Figure 1

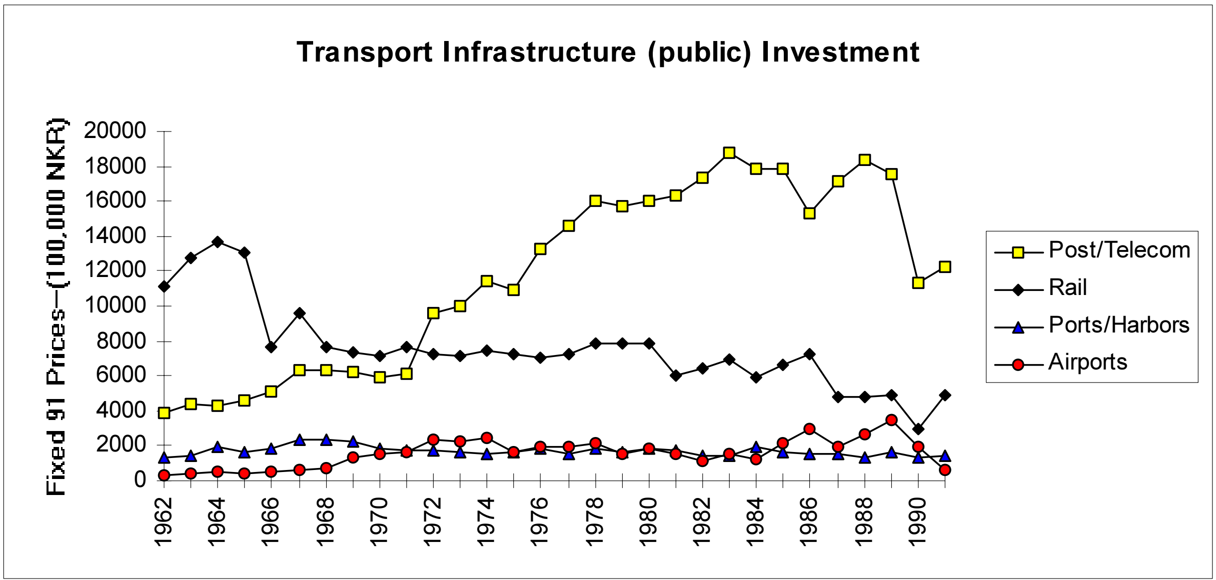
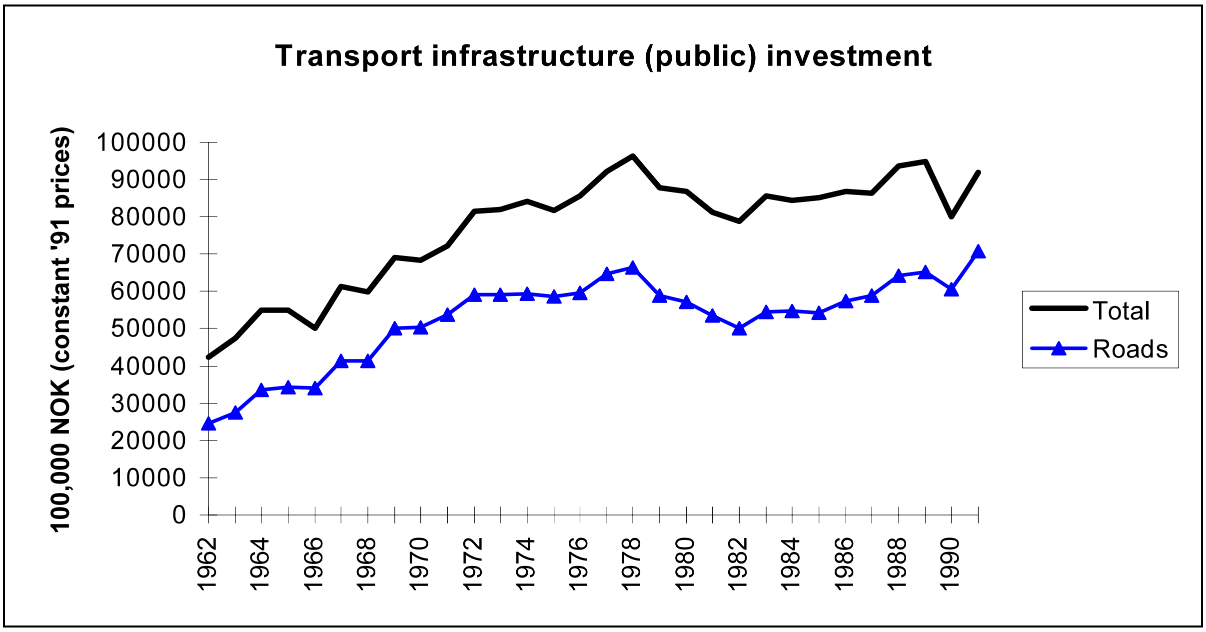
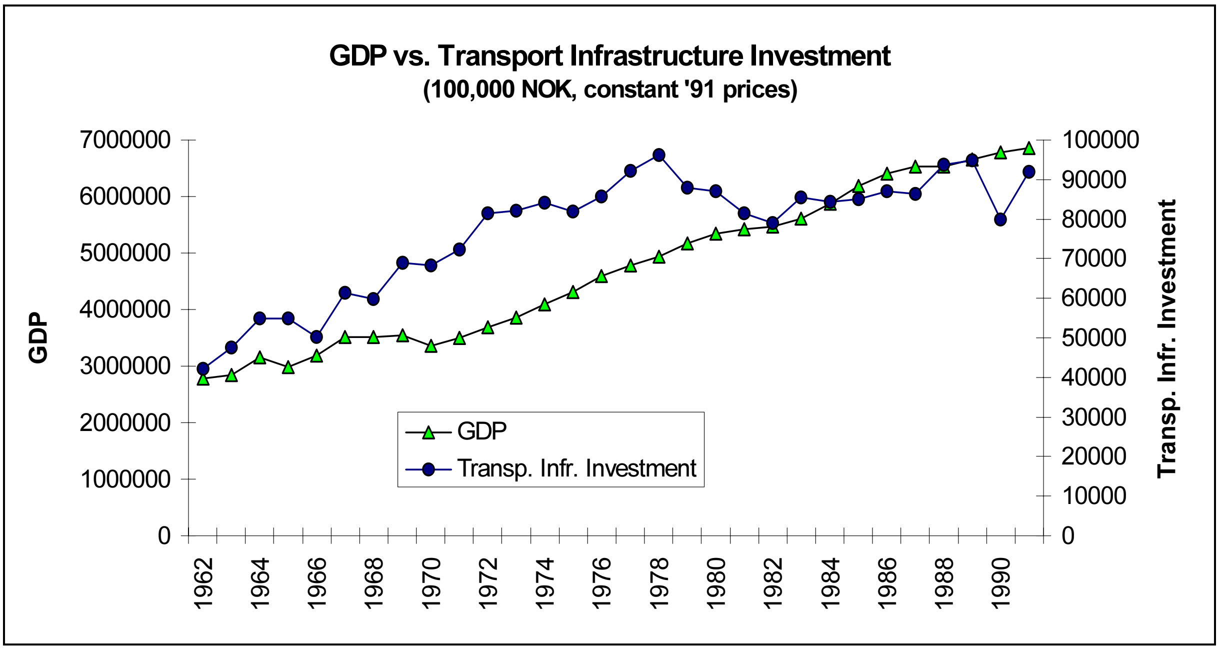


Figure 2



The same year, total investment in Norwegian public transportation infrastructure was NOK 9.2 billion (1991 prices), which was approximately 1.3% of GNP or about 7% of total national gross fixed capital formation (Statistics Norway, 1994). The most dramatic *change* in transport infrastructure investment levels occurred in the post/telecommunications sector, as Figure 1 shows. However, Figure 2 reveals that by far the majority of all public transport infrastructure investment went to the road sector. For instance, road investment accounted for 73% of total public investment in transport infrastructure in 1991. This means that, for Norway, when we analyze the effects of public transport infrastructure investment on the private production process, we are primarily talking about the impact of spending on roads (including tunnels and bridges).

Figure 3



Norway stands out as an interesting case study for two main reasons. First, Norway was one of the only OECD countries which did not experience a sustained decline in its public transport infrastructure investment after 1975 (OECD, 1960-1990). As can be seen in Figure 3, both Norwegian GDP and public transport infrastructure investment rose steadily between 1962 and 1991. This then raises the question: is there a connection between Norway's steadily increasing investment in transport infrastructure and the similarly steady growth in its GDP?

A second interesting feature of Norway is its geography combined with its political objectives as a welfare state. Norway is a long, thin country which contains many small coastal islands and which is criss-crossed by fjords all up and down the coast. There is, therefore, a high demand by rural inhabitants for transport infrastructure, especially for bridges, tunnels, and roads, in these isolated regions.[11] While it seems clear that providing a better transportation infrastructure network to these people would increase their welfare, it is less clear whether connecting these regions is justifiable on economic grounds--that is, whether the construction of a better public transport infrastructure network results in a 'payoff' in the form of lower private production costs in the affected regions. Identifying a clear and discernible relationship between such public transport infrastructure investment and private sector cost reduction is, therefore, of clear importance.

Using a cost function/cost share approach, we seek to model the impacts, if any, that public transport infrastructure capital has on Norwegian private sector (variable) costs. We use annual time series data for the period 1971-1991 and examine private production costs at both the aggregate and sectoral level. The paper is further structured as follows: In section 2, the results of our Norwegian estimations, including elasticity estimates, are reported at the aggregate and dissagregate level. Section 3 concludes with some final comments.

2 Estimations

As noted earlier, most studies about the role of public capital in the production process employ the broad 'public ownership' definition of infrastructure capital and focus on the United States economy. We use Norwegian time series data and focus on a particular type of public infrastructure capital-- *transportation* infrastructure (which is represented by G in our model). We assume a translog cost function and estimate a set of cost share equations simultaneously, making sure to use stationary data. The production and cost functions contain the same information according to duality principles, but we use the latter specification because it allows us to explicitly include input price effects and their impact on factor utilization.[12] After obtaining results for the aggregate Norwegian economy, we re-run the regressions at the sectoral level, to examine the impact of public transport infrastructure capital on sectoral production.

[11] However, this is not necessarily reflected by a high willingness of inhabitants to pay for the services from these types of transport capital.

[12] For a discussion on duality and on measuring infrastructure benefits see Diewert (1986).

2.1 The Translog Aggregate Cost Function and Estimated Cost Share Equations for the Norwegian Economy

Suppose that, in a perfectly competitive market, each industry has a simple, well-behaved (variable) private cost function[13] which depends on private input prices (p_K, p_L, p_M), gross output level (Y), the amount of public transport infrastructure capital services available (G),[14] and time (as a proxy for technological change). The three private input quantities- services of capital (K), labor (L), and intermediates (M) - are determined conditional on the predetermined (by the government) public input, namely public transport infrastructure capital services, which is available at zero cost to firms in this simple model. G is thus modeled as an exogenous unpaid factor of production which can indirectly influence the cost function by altering the production environment. Total cost is defined by

$$(2.1) \qquad C(p_K, p_L, p_M, Y, G, t) = \min_{K,L,M} p_L L + p_K K + p_M M \qquad s.t.\ \ \mathrm{Y = f(K, L, M, G, t)}$$

where f(.) is a production function. We assume that $f_K > 0$, $f_L > 0$, $f_M > 0$, $f_t > 0$ and $f_G \geq 0$. [15]

Using Shephard's lemma, the optimal conditional factor demands can be expressed as

$$(2.2a) \qquad L^* = \frac{\partial C}{\partial p_L} \quad ,$$

$$(2.2b) \qquad K^* = \frac{\partial C}{\partial p_K} \quad ,$$

$$(2.2c) \qquad M^* = \frac{\partial C}{\partial p_M} \quad .$$

Recalling that under perfect competition, $\lambda^* = q$ (output price) and using the envelope theorem, the following relations can be shown to hold

$$(2.2d) \qquad \frac{\partial C}{\partial y} = q \quad ,$$

$$(2.2e) \qquad \frac{\partial C}{\partial G} = -q f_G \quad .$$

13 Properties of the well-behaved cost function C(·) include that it is continuous, twice differentiable, concave in input prices, non-decreasing in output level and linearly homogenous in input prices.

14 Here, the transport service is assumed to be proportional to the stock of transport infrastructure capital multiplied with a capacity utilization index.

15 The $f_G \geq 0$ assumption is equivalent to requiring that the cost function be nonincreasing in G, which is discussed below (free disposal assumption).

By imposing a free disposal assumption, we rule out *a priori* the possibility that increasing the amount of public infrastructure capital can increase costs. Thus, we assume that an increase in G enables the firm to produce a given level of output with fewer labor, private capital, and/or intermediate inputs *ceteris paribus*. This assumption requires that $f_G \geq 0$ (on the production side) or, equivalently, that $C_G \leq 0$ (on the cost side) and which then implies $s_G \leq 0$.

An alternative way of expressing the shadow price of public transport infrastructure capital is in terms of the adjustment costs of labor, private capital, and intermediates:

$$(2.3) \qquad \frac{\partial C}{\partial G} = p_L(\frac{\partial L^*}{\partial G}) + p_K(\frac{\partial K^*}{\partial G}) + p_M(\frac{\partial M^*}{\partial G}), \quad which \ \leq 0, by\, assumption\,.$$

This shows that an exogenous change in the *transport* infrastructure capital stock can affect the private production costs by altering both the productivity of and the cost minimizing conditional demands for the private factors.[16] Only if these effects go in the "right" direction (for example, if all private inputs were substitutes with respect to public transport infrastructure capital), will an increase in public capital services unambiguously reduce private production costs. This would obviously be a legitimate argument for increasing infrastructure investment. Ascertaining the production relationships between all of the factors, i.e. whether they are complements or substitutes, is therefore of key importance.

We use a translog cost function of the form

$$\begin{aligned} &\ln C = \beta_0 + \sum_i \beta_i \ln p_i + .5 \sum_i \sum_j \beta_{ij} \ln p_i \ln p_j + \beta_Y \ln Y + .5\beta_{YY}(\ln Y)^2 + \sum_i \beta_{Yi} \ln p_i \ln Y \\ (2.4) \quad &+\beta_G \ln G + .5\beta_{GG}(\ln G)^2 + \sum_i \beta_{iG} \ln p_i \ln G + \beta_{YG} \ln Y \ln G + \beta_t \ln t + .5\beta_{tt}(\ln t)^2 \\ &+\sum_i \beta_{it} \ln p_i \ln t + \beta_{Yt} \ln Y \ln t + \beta_{Gt} \ln G \ln t \qquad\qquad i,j = K, L, M \end{aligned}$$

Substituting from (2.2(a-e)), the cost shares can be written as

$$(2.5a) \quad s_L^* = \frac{p_L L^*}{C^*} = \frac{\partial \ln C}{\partial \ln p_L} \geq 0 \qquad \text{(cost share of labor)} \ ,$$

$$(2.5b) \quad s_K^* = \frac{p_K K^*}{C^*} = \frac{\partial \ln C}{\partial \ln p_K} \geq 0 \qquad \text{(cost share of private capital)} \ ,$$

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[16] For example, increased investment in airports might mean that an air courier firm could deliver its packages faster. Per unit costs would fall, but there might also be an indirect effect on the demand for labor and private capital. The total number of pilot hours worked could fall (less need for overtime) and the planes would perhaps require less frequent repairs. The individual firm therefore, adjusts its private input decisions according to whether each private input substitutes or complements public capital services.

(2.5c) $s^*_M = \frac{p_M M^*}{C^*} = \frac{\partial \ln C}{\partial \ln p_M} \geq 0$ (cost share of intermediates) ,

(2.5d) $s^*_Y = \frac{qy}{C^*} = \frac{\partial \ln C}{\partial \ln y} > 0$ (cost flexibility) ,

(2.5e) $s^*_G = \frac{-qf_G G}{C^*} = \frac{\partial \ln C}{\partial \ln G} \leq 0$ (shadow cost share of public capital) .

However, because the private factor cost share equations must sum to one only two of the private input share equations are independent

(2.6) $s^*_K + s^*_L + s^*_M = 1$.

If f(.) is homogeneous of degree one in K, L, M, G (i.e. constant returns to scale), then it can also be shown by Euler's Theorem, (2.5d), and (2.5e) that

(2.7) $s^*_G + s^*_Y = 1$.

Letting the measured equivalents of the cost minimizing cost shares (*) equal S_L, S_K, S_Y and S_G, our set of simultaneous equations is thus comprised of two of the S_L, S_K, S_M equations and either the S_G or S_Y equation. We (arbitrarily) choose to estimate the S_K ,S_M and S_Y equations. The unrestricted cost share equations are then

(2.8) $s_K = \beta_K + \beta_{KK} \ln p_K + \beta_{KL} \ln p_L + \beta_{KM} \ln p_M + \beta_{KY} \ln Y + \beta_{KG} \ln G + \beta_{KT} \ln t$,

(2.9) $s_M = \beta_M + \beta_{MK} \ln p_K + \beta_{ML} \ln p_L + \beta_{MM} \ln p_M + \beta_{MY} \ln Y + \beta_{MG} \ln G + \beta_{MT} \ln t$,

(2.10) $s_Y = \beta_Y + \beta_{YK} \ln p_K + \beta_{YL} \ln p_L + \beta_{YM} \ln p_M + \beta_{YY} \ln Y + \beta_{YG} \ln G + \beta_{YT} \ln t$.

The producer's choice of inputs determines the cost level at the same time, and therefore equations (2.4), (2.8), (2.9), and (2.10) comprise a set of simultaneous equations. However, to maximize the degrees of freedom in the regressions, we estimate only the share equations (2.8), (2.9), and (2.10), since they will yield all the parameters in which we are interested. Full Information Maximum Likelihood (FIML) estimation is used.

Conditions and Restrictions

To ensure that the cost function is consistent with economic theory, some conditions must be imposed on the parameters of the share equations. Neo-classical theory maintains that the cost function must be symmetric and linearly homogeneous in input prices. For symmetry to hold, we require $\beta_{ij} = \beta_{ji}$. and $\beta_{iy} = \beta_{yi}$ for *i, j = K, L, M, Y, G*. By Euler's Theorem, the linear homogeneity of the cost function implies that the share equations be homogenous of degree 0 in input prices. The relevant conditions affecting the share equations are then $\beta_{iK} + \beta_{iL} + \beta_{iM} = 0$ for $i=K, L, M, Y, G$. In order for the CRTS restriction to hold, the share equations must be homogeneous of degree 0 in Y and G, (i.e. $\beta_{iY} + \beta_{iG} = 0$ for $i = K, L, M, Y, G$).

The Data

To test for stationarity, we use Augmented Dickey-Fuller (ADF) t-tests to check for unit roots in the levels variables. A unit root here corresponds to a zero coefficient on the lagged levels variable, Z_{t-1} (coefficient β in Test A, Appendix A) and indicates a non stationary data series. The critical values are found in the Dickey-Fuller tables, which cover estimations with a drift and with a drift and time trend.[17] As can be seen in the results table, for none of the levels variables is this β coefficient significantly different from zero.[18] Thus, none of the variables we use are stationary in levels.

We then perform the same tests on the first differences of the variables and report the results under Test B, Appendix A. The coefficient estimates for ΔZ_{t-1} (again called β) are now all significantly different from zero. Therefore, all of the first differenced variables are stationary, I(1), perhaps some with a drift.[19] Since all of the variables are of the same order of integration, we can proceed with the analysis using these first differenced variables and can interpret the estimates in the conventional manner.

In accordance with the literature, the price of private capital is constructed using the user cost of capital formula originally developed by Jorgenson (1963)[20]

$$(2.11) \qquad p_K = p_J(r+\delta) \quad .$$

That is, it equals the price index of new investment (p_J) multiplied by the sum of the interest rate (r) and the physical capital depreciation rate (δ). The interest rate is proxied by the rate of return in the manufacturing sector and equals the operating surplus divided by the real capital stock in that sector. The depreciation rate, δ, is assumed to be .05.[21] This specification implies that the capital can be resold at the end of each period at no cost, and that corporate taxes are not taken into consideration at this stage of the analysis.

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17 See Table 8.5.2 in Fuller (1976).

18 The relevant ADF critical t-statistics here at 5% (reported for n=25) are approximately -3.6 when the constant and a trend are significant, -3.0 with only a constant, and -1.95 if neither the constant nor the trend are included.

19 While, admittedly, this may not be the best or only way to make the data stationary, we feel it is better than not taking account of the non-stationarity at all. A better method, beyond the scope of this paper, might be to find cointegrated relationships among the variables.

20 For example, Seitz (1994), Nadiri and Mamuneas (1991), Lynde and Richmond (1992) all use this type of specification for the user cost of capital. An alternative specification based on interest rates which include tax rates is formulated in Biørn (1983). Biørn and Fosby (1980) also discuss the relationship between the capital depreciation structure and the user cost of capital.

21 At the next stage of investigation, a unique depreciation rate will be calculated for each sector.

2.2 Aggregate Estimation Results

Regression results (symmetry and homogeneity assumed):

Log Likelihood=229.30

() indicates coefficient restricted a priori

(2.12)
$$\underset{}{s_K} = \underset{(-.513)}{-.003} + \underset{()}{.117 \ln p_K} \underset{(-4.59)}{- .046 \ln p_L} \underset{(-3.61)}{- .071 \ln p_M} \underset{(-4.47)}{- .146 \ln Y} \underset{(1.03)}{+ .114 \ln G} \underset{(.047)}{+ .001 \ln t}$$

$R^2 = .662 \quad SER = .192$

(2.13)
$$s_M = \underset{(.412)}{.002} \underset{(-3.61)}{- .071 \ln p_K} \underset{(-4.78)}{- .093 \ln p_L} \underset{()}{+ .164 \ln p_M} \underset{(3.86)}{+ .162 \ln Y} \underset{(-.262)}{- .020 \ln G} \underset{(-.220)}{- .004 \ln t}$$

$R^2 = .496 \quad SER = .013$

(2.14)
$$s_Y = \underset{(.261)}{.002} \underset{(-4.47)}{- .146 \ln p_K} \underset{()}{- .016 \ln p_L} \underset{(3.86)}{+ .162 \ln p_M} \underset{(-.014)}{- .014 \ln Y} \underset{(.049)}{+ .007 \ln G} \underset{(-.285)}{- .009 \ln t}$$

$CR^2 = .643 \quad SER = .022$

Our model yields estimates which are of plausible magnitudes and sign, although they do not imply much of a role for public transport infrastructure capital at the aggregate level. Using the likelihood ratio (LR) test we find that the hypothesis of constant returns to scale over K, L, M, and G is not consistent with the aggregate data (LR=26.6, $\chi^2_{(3)}(.05) = 7.82$) and is therefore not imposed. For the most part, the price and output coefficients are significant, and the goodness-of-fit statistics of the restricted regressions are acceptable. For the s_K equation (2.12), the estimated cost share elasticities, which measure the response of the cost shares to a change in input prices, are of the anticipated sign and are significant. According to the results, a 1% increase in the price of private capital leads to a .12% increase in that factor's cost share, while increases in the other private input prices lead to a decrease in s_K. The output coefficient in the same equation is negative and significant, and implies that a 1% increase in the output level reduces private capital's cost share by .14%, which is referred to as a negative bias of scale. Next, the infrastructure coefficient estimate suggests that infrastructure capital services do not affect the cost share of private capital at the aggregate level. The insignificant time trend in the s_K equation indicates that technological progress also does not meaningfully influence the cost share for private capital, *ceteris paribus*.

Equation (2.13) similarly confirms that increases in the prices of private capital and labor reduce the cost share of intermediates. The bias of scale is again significant, but here positive, which means that the cost share of intermediates rises with an increase in the output level. Lastly, infrastructure capital services and time again do not significantly affect the equation.

The cost flexibility (s_Y) equation contains basically the same information as in the private input cost share equations. In particular, the bias of scale effects are the same as discussed in (2.12) and (2.13) due to symmetry conditions. The aggregate cost flexibility is also estimated to be independent of the output level, the amount of transport infrastructure services available, and time.

The total elasticity of the demand for private inputs with respect to transport infrastructure capital is the sum of the *productivity effect* (s_G) and the *factor bias effect* ($\frac{\beta_{iG}}{s_i}$ for i = K, L, M). Whether or not public capital and each private inputs are substitutes or complements depends on the relative signs of these two terms. This elasticity can be calculated at the sample means according to

$$\text{(2.15)} \qquad \xi_{iG} = s_G + \frac{\beta_{Gi}}{s_i} \qquad i = K, L, \mathrm{M} \quad .$$

However, our results suggest that there is no significant productivity effect or factor bias effect from the provision of public transport infrastructure capital at the aggregate level within the estimation period.

Conclusions from Aggregate Estimations

To summarize, our aggregate estimation yields the following main results about the Norwegian economy during the sample period 1971-1991:

1. Constant returns to scale (over K,L, M, G) at the aggregate level is not consistent with the data at the 95% significance level.
2. No significant productivity effect or bias effects from transport infrastructure capital are found.

Our results controvert those of the studies which conclude that public infrastructure capital plays an important role in private production.[22] This difference in findings could be due to our focus on the aggregate level,[23] our use of a specific type of public infrastructure variable (transport), and/or our use of stationary data. Having found no evidence of productive effects from public transport infrastructure capital at the aggregate level, we now turn towards

22 For example, Nadiri and Mamuneas (1991) for the US manufacturing economy.
23 Most other studies analyze only the manufacturing sector.

sectoral estimations in the hope that they will provide more insight as to how/whether public transport infrastructure capital affects private production/cost relationships.

2.3 Disaggregated Estimation Results

Oil production contributes an increasing share to Norwegian GDP (aggregate) after the late 70s. Whereas oil revenues were negligible in 1971, by 1991 they accounted for 14.5% of GDP. However, the petroleum sector, as well as several other sectors, does not depend to a great degree on public transport infrastructure capital. Conversely, it is reasonable to expect that the road transport sector, for instance, would be heavily dependent upon the provision of a good highway system. Therefore, it was our aim that by disaggregating the data, we might be able to uncover the various degrees to which public transport infrastructure capital services can affect private sectoral costs. By dividing the economy into six major production sectors, we hope to find sector-specific infrastructure effects which were not revealed at the aggregate level. This is particularly important since different industries require different kinds and amounts of public transport infrastructure capital in the production process.[24] We first divide the economy as follows into six major sectors, based on our *a priori* beliefs as to their relative dependence upon transport infrastructure capital:

Sector A *(a priori belief about G dependency level: medium)*

- Construction, excluding oil well drilling
- Finance and Insurance
- Wholesale and Retail Trade
- Other private services
- Defense
- Central and Local Govt.: Education and Research
- Central and Local Govt.: Healthcare and Veterinary Services
- Other Central and Local Govt. services

Sector B *(a priori belief about G dependency level: low)*

- Agriculture
- Fishing and Fisheries
- Forestry
- Dwelling Services
- Ocean Transport
- Production and Pipeline Transport of Oil and Gas
- Oil and Gas Exploration and Drilling

Sector C *(a priori belief about G dependency level: medium-high)*

- Manufacture of Pulp and Paper Products
- Manufacture of Industrial Chemicals
- Petroleum Refining
- Manufacture of Consumer Goods
- Manufacture of Wood, Chemical, and Mineral Products
- Manufacture of Metals
- Manufacture of Metal Products and Equipment
- Building of Ship and Oil Platforms

Sector D *(a priori belief about G dependency level: low)*

- Production of Electricity and Gas

Sector E *(a priori belief about G dependency level: high)*

- Road Transport

[24] While we have not disaggregated public transport infrastructure capital by type in this analysis, we hope to do so at the next stage of investigation.

Sector NV *(a priori belief about G dependency level: high)*
Air Transport, Rail Transport, Sea Transport, Post and Telecommunications

Again, before estimating we check that the sectoral data are also stationary. The results of these tests are reported in Appendix B. Once more, none of the levels variables are stationary, but all of the first differenced variables are, as was the case for the aggregate variables. Using the first differenced sectoral data, we then perform the disaggregated estimations. The hypothesis of constant returns to scale is consistent with the data in only one of the six sectors: the manufacturing sector (sector C). Thus, only for this sector is the restriction imposed on the parameters. For the other four sectors, the data reject this hypothesis and no CRTS restrictions are imposed on the equations.[25]

We use the same set of simultaneous equations as before. The LHS variables, therefore, are now the sectoral cost shares, instead of their aggregate counterparts. As for the exogenous variables, the input prices are now sectoral, as is (gross) output level. Public transport infrastructure capital services, however, is not a sectoral variable because we assume that all of the available infrastructure services are at the disposition of any industries which want to use them (i.e. G is a pure public good such that consumption of services are non-rival and non excludable). Letting h be an index running over the 6 production sectors, we estimate the following set of equations (results follow in Table 1):

Unrestricted share equations (symmetry and homogeneity assumed):

(2.16) $s_{Kh} = \tilde{\beta}_K + \tilde{\beta}_{KK} \ln p_{Kh} + \tilde{\beta}_{KL} \ln p_{Lh} + \tilde{\beta}_{KM} \ln p_{Mh} + \tilde{\beta}_{KY} \ln Y_h + \tilde{\beta}_{KG} \ln G + \tilde{\beta}_{KT} \ln t$

(2.17) $s_{Mh} = \tilde{\beta}_M + \tilde{\beta}_{MK} \ln p_{Kh} + \tilde{\beta}_{ML} \ln p_{Lh} + \tilde{\beta}_{MM} \ln p_{Mh} + \tilde{\beta}_{MY} \ln Y_h + \tilde{\beta}_{MG} \ln G + \tilde{\beta}_{MT} \ln t$

(2.18) $s_{Yh} = \tilde{\beta}_Y + \tilde{\beta}_{YK} \ln p_{Kh} + \tilde{\beta}_{YL} \ln p_{Lh} + \tilde{\beta}_{YM} \ln p_{Mh} + \tilde{\beta}_{YY} \ln Y_h + \tilde{\beta}_{YG} \ln G + \tilde{\beta}_{YT} \ln t$

where

(2.19) $C_h = p_{Kh} K_h + p_{Lh} L_h + p_{Mh} M_h$

(2.20) $s_{Kh} = \dfrac{p_{Kh} K_h}{C_h}$

(2.21) $s_{Mh} = \dfrac{p_{Mh} M_h}{C_h}$

(2.22) $s_{Y_h} = \dfrac{q_h Y_h}{C_h}$ *h=1, ..,6*

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[25] The relevant LR statistics here are:
$\chi^2_A = 17.32, \chi^2_B = 16.02, \chi^2_C = 6.46, \chi^2_D = 198.68, \chi^2_E = 16.00, \chi^2_{NV} = 13.67,$ while the critical test statistic is $\chi^2_{(3)}(.05) = 7.82$.

Table 1 - Sectoral Estimation Results (1971-1991)

Sector Coefficient	Sector A	(t stat)	Sector B		Sector C		Sector D		Sector E		Sector NV	
					CRTS							
B_K	-0,005	-(2,47)	-0,007	-(1,01)	-0,0002	-(0,286)	-0,003	-(0,43)	0,007	(2,77)	-0,006	-(2,62)
B_{KL}	-0,093	-(19,88)	-0,026	-(4,39)	-0,029	-(4,36)	-0,053	-(7,97)	-0,079	-(6,03)	-0,054	-(6,33)
$B_{KM}=B_{MK}$	-0,085	-(12,60)	-0,261	-(4,28)	-0,036	-(4,67)	-0,160	-(7,44)	-0,130	-(6,21)	-0,052	-(5,86)
$B_{KK}=-B_{KL}-B_{KM}$	0,178	*	0,287	*	0,065	*	0,213	*	0,209	*	0,106	*
$B_{KY}=B_{YK}$	-0,217	-(20,01)	-0,122	-(2,67)	-0,039	-(2,83)	-0,252	-(9,87)	-0,121	-(4,96)	-0,145	-(4,21)
B_{KG}	0,227	(8,86)	-0,022	-(0,21)	0,039	*	0,288	(3,04)	0,241	(6,36)	0,161	(5,56)
B_{KT}	0,003	(0,44)	0,024	(0,89)	-0,004	-(1,06)	0,003	(0,10)	-0,022	-(2,17)	0,001	(0,11)
B_M	0,002	(1,15)	0,004	(0,58)	-0,002	(1,22)	0,004	(0,44)	-0,001	-(0,17)	0,007	(3,09)
B_{ML}	-0,074	-(2,88)	-0,020	-(1,30)	-0,066	-(2,96)	-0,033	-(2,01)	-0,030	-(0,67)	-0,228	-(5,22)
$B_{MM}=-B_{ML}-B_{MK}$	0,159	*	0,281	*	0,102	*	0,193	*	0,160	*	0,280	*
$B_{MY}=B_{YM}$	0,233	(7,76)	0,146	(3,12)	-0,102	*	0,296	(6,70)	0,068	(1,17)	0,246	(5,57)
B_{MG}	-0,106	-(4,01)	0,061	(0,56)	-0,077	-(3,07)	-0,244	-(1,96)	-0,073	-(1,12)	-0,003	-(0,10)
B_{MT}	-0,004	-(0,53)	-0,011	-(0,40)	-0,010	-(1,22)	-0,013	-(0,38)	-0,005	-(0,29)	-0,018	-(2,65)
B_Y	-0,001	-(0,26)	0,024	(1,33)	-,005	-(1,68)	0,007	(0,71)	0,005	(0,86)	0,015	(1,43)
$B_{YL}=-B_{YK}-B_{YM}$	-0,016	*	-0,024	*	.141	*	-0,044	*	0,053	*	-0,101	*
B_{YY}	0,238	(4,06)	0,147	(1,10)	-,001	(0,010)	0,316	(3,28)	0,082	(1,00)	0,363	(2,31)
B_{YG}	-0,191	-(4,39)	-0,488	-(1,70)	,011	*	-0,163	-(1,14)	-0,212	-(2,07)	-0,103	-(0,81)
B_{YT}	-0,018	-(1,63)	-0,034	-(0,46)	0,005	(0,530)	-0,003	-(0,08)	-0,003	-(0,10)	-0,062	-(2,01)
LOG L	257,356		186,741		259,717		203,39		208,777		229,347	
RSQ1	0,969		0,772		0,964		0,814		0,968		0,932	
RSQ2	0,899		0,696		0,447		0,541		0,731		0,855	
RSQ3	0,958		0,446		0,405		0,748		0,717		0,721	
SER1	0,006		0,023		0,002		0,021		0,008		0,006	
SER2	0,005		0,024		0,006		0,027		0,012		0,004	
SER3	0,009		0,066		0,007		0,031		0,020		0,023	
DW1	2,10		1,08		2,26		2,03		1,98		2,18	
DW2	1,93		1,07		2,58		2,00		2,22		2,13	
DW3	1,69		1,70		2,48		2,16		2,41		2,50	

*=restricted a priori

nob = 21, novar = 15

Referring to Table 1 and looking first at the private capital (sectoral) share equation coefficients, the estimates appear to be of reasonable signs and magnitudes. All of the $B_{KL}/B_{KM}/B_{KK}$ estimates are highly significant and reflect that private input prices are the most important determinant of private input cost shares. We find that there are significant negative biases of scale for private capital (B_{KY}) in all sectors. Thus, as is the case at the aggregate level, the cost share of private capital decreases with increases in the level of output. Interestingly, the public capital coefficient estimates in the s_K equation (B_{KG}) are significant in all sectors except B (agriculture/oil), which we had anticipated would not be heavily dependent upon G. In the other five sectors, this bias effect of public capital is positive, which means that increasing the availability of public transport infrastructure capital services raises the cost share of private capital. Lastly, technological change appears to be factor neutral (i.e. it does not affect private factor cost shares) in all sectors except sector E (road transport), where technological progress is found to reduce private capital's cost share.

For the intermediate input cost share equation, all of the estimated price coefficients are significant, except for labor price in sectors B (agriculture/oil) and E (road transport). The bias of scale estimates (B_{MY}) are positive and significant, except for again in sector E. Thus, increases in output raise the cost share of intermediate inputs in the other five sectors. Next, the public transport infrastructure capital coefficient estimates are significant in two sectors-- A and C (services and manufacturing). Contrary to our aggregate results, here we find that increasing the availability of public transport infrastructure capital services significantly reduces the cost share of intermediate inputs. Also noteworthy is that the time coefficient is significant in the non-road sector (E), which suggests that the intermediate input cost share falls over time due to technological progress.

Turning next to the sectoral S_Y equations, we find that cost flexibility is significantly increasing in the level of output in sectors A, D and NV (services, electricity/gas, and non-road transport). The public transport infrastructure capital coefficient estimates are negative and significant in sectors A and E (services and non-road transport), which implies that a 1% increase in public transport infrastructure capital services leads to a .19% decrease in cost flexibility in sector A, and a .21% reduction in S_Y in sector E. Lastly, the negative time trend is again significant in the non-road sector (E), which means that cost flexibility in that sector falls over time. Using symmetry relations (B_{YG}=B_{GY}), we can also infer that increasing the output level reduces the shadow cost share of public transport infrastructure capital, i.e. S_G falls. This means that the marginal product of public capital (f_G) rises with the output level, according to equation (2.5e).

Using equation (2.15) which calculates the total elasticity of the (conditional) demand for private inputs with respect to the public input (ξ_{iG}) as the sum of a productivity effect (s_G) and a factor bias effect, we find the following relationships between the variables.

Table 2 - Summary Statistics from Sectoral Regressions

Sector	s_G	$Bias_{LG}$	$Bias_{KG}$	$Bias_{MG}$	ξ_{LG}	ξ_{KG}	ξ_{MG}	Conclusions
A-Svcs.	0	-.306	.966	-.286	-.306	.966	-.286	L,G substitutes K,G complements M,G substitutes
B-Agric. /Oil	0	0	0	0	0	0	0	no effect of G on prvt. factor demand or productivity
C-Manuf.	-.04	-.165	.506	-.111	-.205	.466	-.151	L,G substitutes K,G complements M,G substitutes
D-Electr. /Gas	0	-.005	.679	-.528	-.005	.679	-.528	L,G substitutes K,G complements M,G substitutes
E-Road Transp.	-.02	-.691	.873	0	-.711	.853	-.02	L,G substitutes K,G complements M,G substitutes
NV-Non-Road Tr.	-.013	-.328	1.14	0	-.341	1.13	-.013	L,G substitutes K,G complements M,G substitutes

Examination of the Table 2 estimates reveals some interesting information about the relationships between the private and public variables. Most striking is that public transport infrastructure capital has no measurable impact whatsoever in the agriculture and oil sector (B). For all of the other sectors, we find a complementary relationship between private capital and public transport infrastructure. The other two private inputs, labor and intermediates, are found to be substitutes with the public input in all of these sectors. The productivity effect of public transport infrastructure capital is negative (i.e. cost reducing) in the manufacturing, road and non-road transport sectors (C, E, and NV)). We estimate that a 1% increase in public transport infrastructure capital services reduces manufacturing (variable) costs by .04%, road transport costs by .02%, and non-road transport sector costs by .01%. Thus, in these sectors the mean marginal product of public transport infrastructure capital services is positive. In the other three sectors, where no significant productivity effect was found, the total impact of G on private factor demand is just the bias effect. Note that in all cases, the bias effects are much stronger than the productivity effects.

Conclusions from Sectoral Estimations

The most important findings at the sectoral level are:

1. The hypothesis of constant returns to scale is rejected for all sectors except manufacturing (C). This is consistent with the literature, where many of the econometric studies which focus solely on the manufacturing sector find constant returns to scale (for example, Lynde and Richmond (1992)).
2. Public transport infrastructure capital is not estimated to have any effect on the agriculture/oil sector (B). This is consistent with our *a priori* expectations.
3. Public transport infrastructure capital and private capital are found to be complements in all sectors (except sector B). This shows the importance of disaggregation. Labor and intermediates are estimated to substitute for public transport infrastructure capital in all sectors (except B). These production relationships findings are basically undisputed in the literature, with the exception of Nadiri and Mamuneas (1991).
4. Public transport infrastructure capital is only found to be cost reducing in 3 sectors: manufacturing, road, and non-road transport, with this productivity effect being strongest in manufacturing.
5. In all sectors (except B), the bias effect is much greater than the productivity effect, indicating that the main influence of public transport infrastructure capital comes via its effect on private factor demand.

The only comparisons that can be made with the literature are for the manufacturing sector.[26] Our elasticity estimates for this sector of ξ_{LG} = -.205, ξ_{KG} = .466, and ξ_{MG} = -.151 are in accordance with the literature. For example, Lynde and Richmond (1992) find for UK manufacturing that ξ_{LG} = -.45 and ξ_{KG} = .71, Berndt and Hansson (1991) obtain ξ_{LG} = -.60 and ξ_{KG} = .86 for Swedish manufacturing, and Seitz (1994) estimate that ξ_{LG} = -.138 and ξ_{KG} = .361 for German manufacturing (the latter two studies use 'core' infrastructure as their G variable, which is dominated by transport infrastructure capital in both countries). Like Seitz's results, our elasticity estimates fall on the low end of the literature's range.

3 Final Conclusions and Direction for Further Study

In conclusion, our results indicate that during the sample period public transport infrastructure investment reduced costs in several sectors and significantly altered the demand for private inputs. (The main exception to these findings is the oil/agriculture sector.) The influence of public transport infrastructure investment appears to come primarily through a bias effect, rather than through a productivity effect.

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26 As noted earlier, the literature focuses almost exclusively on the manufacturing sector.

Our clear finding that public transport infrastructure capital and private capital are complements supports the «public capital hypothesis», which suggests that public capital raises the marginal productivity of private capital and must be in place before private investment can take place. A good public transport infrastructure network is a vital factor of production because it provides a conducive environment for private production. In this regard, infrastructure is a necessary prerequisite for production and growth, even though its quantitative effects may be quite small. In the case of our sample period, we found that public transport infrastructure capital has a positive (mean) marginal product in the manufacturing, road, and non-road transport sectors, and that its provision led to significant, but relatively small cost savings there.

We have shown that, almost without exception, studies like Aschauer's which flaunt seemingly significant and large public capital estimates have not checked their data for non stationarity, thus invalidating their conclusions (assuming they used nonstationary data, which most time series data are). While we feel confident that the cost function/cost share is the best approach to the question of returns to public capital, there still remains possible econometric problems to grapple with such as endogeneity of public capital, omitted variables, and reverse causation. Furthermore, due to infrastructure's unique nature, accurate measurement of its services will always be difficult. In particular, we need a better way to measure the flows of services from the infrastructure stocks, in order that the degree of utilization efficiency of the infrastructure network can be taken into account.

In future research work, many interesting extensions and improvements to our model could be made by: (a) including corporate taxation, i.e. how firms indirectly pay for the transport infrastructure services they use via the taxes they pay to the government, (b) modeling infrastructure as an impure public good, trying to capture congestion effects, (c) including other environmental externalities, (d) disaggregating public transport infrastructure capital by type (i.e. road, rail, etc.), and (e) focusing on the regional level to see whether infrastructure investment in the rural, 'political-motivated' road and tunnel projects generate less private cost reductions than the same level of infrastructure investment would generate in an urban area.

APPENDIX A

				Tests for Stationarity						*Approx. ADF Critical Values*
										no const, no t = -1.95
1972-1991										const, no t = -3.0
Test A: Levels of Variables (Z)				$\Delta Z = \alpha + \beta Z(-1) + \delta T + \varepsilon \Delta Z(-1)$						const, t = -3.6
(t stat)										
Z		α	β	δ	ε		**CRSQ**	**SER**	**DW**	**conclusion**
ln (PL)		-2.320	-0.321	0.008	0.513		.437	.025	1.79	**non stationary**
		-(2.75)	-(2.77)	(2.55)	(3.02)					
ln (PK)		-2.840	-0.843	-0.057	0.142		.238	.161	1.96	**non stationary**
		-(2.30)	-(2.44)	-(2.14)	(0.53)					
ln (PM)		-0.008	-0.059	0.002	0.298		.283	.033	1.96	**non stationary**
		-(0.04)	-(0.49)	(0.16)	(1.15)					
ln (Y)		4.480	-0.261	-0.010	.579		.258	.031	2.03	**non stationary**
		(1.93)	-(1.94)	-(1.72)	(2.68)					
ln (G)		7.120	-0.460	-0.016	0.537		.199	.041	1.66	**non stationary**
		(2.03)	-(2.05)	-(1.79)	(2.07)					
SK		0.147	-0.658	0.000	0.406		.243	.025	1.88	**non stationary**
		(2.93)	-(2.98)	-(0.28)	(1.81)					
SM		0.309	-0.639	0.001	0.365		.229	.014	1.91	**non stationary**
		(2.87)	-(2.90)	(1.16)	(1.60)					
SY		0.364	-0.365	0.001	0.286		.065	.032	1.98	**non stationary**
		(2.03)	-(2.02)	(0.83)	(1.20)					
1973-1991										
Test B: First Differences of Variables					(ΔZ)		$\Delta^{**}2Z = \alpha + \beta\Delta Z(-1) + \delta T + \varepsilon \Delta^{**}2 Z(-1)$			
								where	Δ**2	is the 2nd difference
Δ	Z	α	β	δ	ε		**CRSQ**	**SER**	**DW**	**conclusion**
Δ	ln (PL)	0.025	1.910	0.000	-0.313		.737	.029	1.99	**stationary**
		(1.12)	(4.72)	-(0.29)	-(1.37)					
Δ	ln (PK)	0.191	0.973	-0.006	-0.273		.310	.187	2.07	**stationary**
		(1.63)	(2.99)	-(0.82)	-(1.07)					
Δ	ln (PM)	0.151	1.450	-0.005	-0.285		.822	.028	2.58	**stationary**
		(4.48)	(4.47)	-(3.70)	-(1.41)					
Δ	ln (Y)	-0.054	1.640	0.002	-0.188		.708	.033	2.17	**stationary**
		-(2.29)	(4.07)	(1.32)	-(0.80)					
Δ	ln (G)	-0.078	1.770	0.003	-0.438		.629	.040	2.46	**stationary**
		-(2.82)	(4.99)	(1.79)	-(1.89)					
Δ	SK	-0.003	1.540	0.000	-0.413		.551	.029	2.32	**stationary**
		-(0.18)	(4.45)	(0.13)	-(1.74)					
Δ	SM	0.002	1.440	0.000	-0.354		.525	.017	2.25	**stationary**
		(0.23)	(4.17)	-(0.14)	-(1.47)					
Δ	SY	0.009	1.320	0.000	-0.190		.492	.036	2.10	**stationary**
		(0.44)	(3.46)	-(0.27)	-(0.72)					

APPENDIX B

Tests for Stationarity

1972-1991

Test C: Levels of Variables (Z) $\Delta Z = \alpha + \beta\, Z(-1) + \delta\, T + \varepsilon\, \Delta\, Z(-1)$

Z	α	β	δ	ε	CRSQ	SER	DW	conclusion
ln(PL.A)	-1,390	-0,199	0,003	0,445	,554	,013	1,74	non stationary
	-(2,42)	-(2,45)	(2,00)	(2,47)				
ln(PK.A)	-2,450	-0,725	0,049	0,512	,284	,130	1,78	non stationary
	-(2,87)	-(2,81)	(2,64)	(2,23)				
ln (PM.A)	-0,129	-0,119	0,007	0,477	,315	,025	1,71	non stationary
	-(0,53)	-(0,82)	(0,63)	(1,83)				
ln(Y.A)	11,380	-0,690	-0,029	0,780	,619	,018	2,18	non stationary
	(2,96)	-(2,97)	-(2,90)	(2,92)				
SK.A	0,126	-0,559	0,000	0,374	,197	,027	1,78	non stationary
	(2,61)	-(2,71)	(0,43)	(1,67)				
SM.A	0,278	-0,758	0,000	0,515	,334	,012	1,75	non stationary
	(3,46)	-(2,48)	(0,29)	(2,38)				
SY.A	0,565	-0,559	-0,002	0,400	,204	,032	1,76	non stationary
	(2,71)	-(2,74)	-(1,32)	(1,77)				
ln(PL.B)	-0,867	-0,099	0,008	0,234	,234	,038	1,36	non stationary
	-(0,79)	-(0,90)	(0,67)	(1,12)				
ln(PK.B)	-2,560	-0,696	0,056	0,538	,305	,125	1,79	non stationary
	-(2,95)	-(3,10)	(2,78)	(2,41)				
ln (PM.B)	0,089	-0,029	-0,003	0,145	,316	,049	2,20	non stationary
	(0,49)	-(0,30)	-(0,35)	(0,58)				
ln(Y.B)	2,090	-0,147	0,003	0,171	,143	,112	2,06	non stationary
	(0,92)	-(0,95)	(0,56)	(0,65)				
SK.B	0,522	-1,040	-0,005	0,548	,490	,030	2,26	non stationary
	(4,46)	-(4,34)	-(3,74)	(2,67)				
SM.B	0,430	-0,919	0,001	0,464	,432	,028	2,20	non stationary
	(3,61)	-(2,83)	(1,34)	(2,18)				
SY.B	0,233	-0,311	0,009	0,265	,021	,078	2,16	non stationary
	(1,82)	-(1,76)	(1,64)	(1,07)				
ln(PL.C)	-3,540	-0,494	0,014	0,390	,307	,031	1,92	non stationary
	-(2,95)	-(2,97)	(2,77)	(2,01)				
ln(PK.C)	-2,580	-0,833	0,040	0,524	,331	,117	1,87	non stationary
	-(3,21)	-(3,34)	(2,90)	(2,31)				
ln (PM.C)	-0,044	-0,093	0,003	0,212	,130	,044	1,91	non stationary
	-(0,19)	-(0,64)	(0,32)	(0,80)				
ln(Y.C)	4,930	-0,307	-0,016	0,600	,272	,036	1,72	non stationary
	(2,08)	-(2,10)	-(1,93)	(2,83)				
SK.C	0,034	-0,468	0,000	0,237	,107	,010	1,82	non stationary
	(2,10)	-(2,29)	(0,28)	(1,03)				
SM.C	0,303	-0,456	0,001	0,170	,072	,007	1,89	non stationary
	(2,12)	-(2,10)	(1,89)	(0,69)				
SY.C	0,419	-0,395	-0,001	-0,013	,053	,008	1,92	non stationary
	(1,79)	-(1,79)	-(1,60)	-(0,05)				

ln(PL.D)		-2,410	-0,385	-0,003	0,278		,188	,056	1,90	**non stationary**
		-(2,38)	-(2,40)	-(1,35)	(1,28)					
ln(PK.D)		-2,640	-0,786	0,052	0,542		,331	,128	1,79	**non stationary**
		-(3,17)	-(3,32)	(2,93)	(2,43)					
ln (PM.D)		-1,230	-0,600	0,059	0,722		,240	,070	2,02	**non stationary**
		-(2,59)	-(2,81)	(2,71)	(2,41)					
ln(Y.D)		4,330	-0,317	-0,013	0,533		,152	,052	1,96	**non stationary**
		(1,81)	-(1,84)	-(1,49)	(1,83)					
SK.D		0,173	-0,384	-0,001	0,263		,076	,040	1,87	**non stationary**
		(1,99)	-(2,08)	-(0,65)	(1,12)					
SM.D		0,142	-0,354	0,002	0,243		,053	,034	1,92	**non stationary**
		(2,07)	-(1,94)	(1,12)	(1,01)					
SY.D		0,339	-0,747	0,007	0,498		,275	,046	1,66	**non stationary**
		(2,55)	-(2,77)	(2,94)	(1,99)					
ln(PL.E)		-2,240	-0,302	0,009	0,682		,302	,035	1,51	**non stationary**
		-(2,05)	-(2,04)	(2,30)	(2,99)					
ln(PK.E)		-2,890	-0,874	0,056	0,597		,382	,121	1,88	**non stationary**
		-(3,42)	-(3,57)	(3,14)	(2,67)					
ln (PM.E)		-0,006	-0,055	0,001	0,324		,230	,036	1,66	**non stationary**
		-(0,02)	-(0,38)	(0,12)	(1,17)					
ln(Y.E)		2,370	-0,186	0,001	0,564		,370	,051	1,61	**non stationary**
		(1,30)	-(1,33)	(0,25)	(2,38)					
SK.E		0,150	-0,501	-0,001	0,353		,161	,034	1,83	**non stationary**
		(2,39)	-(2,51)	-(0,80)	(1,56)					
SM.E		0,198	-0,624	0,003	0,218		,154	,019	1,98	**non stationary**
		(2,55)	-(2,50)	(2,12)	(0,88)					
SY.E		0,483	-0,799	0,008	0,532		,364	,026	2,05	**non stationary**
		(3,41)	-(3,47)	(3,62)	(2,41)					
ln(PL.NV)		-0,705	-0,108	-0,001	0,063		,422	,020	2,01	**non stationary**
		-(0,92)	-(0,99)	-(0,28)	(0,27)					
ln(PK.NV)		-2,750	-0,806	0,054	0,547		,349	,123	1,82	**non stationary**
		-(3,31)	-(3,45)	(3,08)	(2,49)					
ln (PM.NV)		0,002	-0,049	0,001	0,281		,296	,026	1,88	**non stationary**
		(0,01)	-(0,45)	(0,16)	(1,08)					
ln(Y.NV)		12,850	-8,890	-0,053	0,549		,370	,033	2,31	**non stationary**
		(3,66)	-(3,38)	-(3,61)	(2,50)					
SK.NV		0,069	-0,463	0,000	0,378		,167	,017	1,75	**non stationary**
		(2,36)	-(2,47)	-(0,58)	(1,73)					
SM.NV		0,127	-0,401	0,002	0,627		,399	,008	2,27	**non stationary**
		(2,85)	-(2,86)	(2,80)	(3,21)					
SY.NV		0,672	-0,540	-0,001	0,217		,147	,035	2,00	**non stationary**
		(1,71)	-(1,81)	-(0,55)	(0,71)					

1973-1991										
Test D: First Differences of Variables				(ΔZ)		$\Delta**2Z = \alpha + \beta\Delta\ Z(-1) + \delta\ T + \varepsilon\ \Delta**2\ Z(-1)$				
							where	Δ**2	is the 2nd difference	
Δ	Z	α	β	δ	ε		**CRSQ**	**SER**	**DW**	**conclusion**
Δ	ln(PL.A)	0,023	1,900	-0,002	-0,287		0,813	0,014	1,83	**stationary**
		(1,52)	(4,54)	(0,00)	-(0,27)					
				-0,930	-1,140					
Δ	ln(PK.A)	0,110	1,660	-0,003	-0,461		0,608	0,150	2,29	**stationary**
		(1,19)	(4,79)	-(0,42)	-(1,95)					
Δ	ln(PM.A)	0,116	1,840	-0,003	-0,421		0,835	0,021	2,47	**stationary**
		(4,30)	(5,41)	-(3,31)	-(2,05)					
Δ	ln(Y.A)	-0,042	2,060	0,000	-0,446		0,731	0,026	2,45	**stationary**
		-(2,37)	(5,36)	(0,40)	-(1,97)					
Δ	SK.A	-0,009	1,620	0,001	-0,430		0,584	0,03	2,38	**stationary**
		-(0,51)	(4,71)	(0,55)	-(1,86)					
Δ	SM.A	0,005	1,740	0,000	-0,516		0,649	0,013	2,54	**stationary**
		(0,69)	(5,45)	-(0,78)	-(2,43)					
Δ	SY.A	0,007	1,640	-0,001	-0,432		0,602	0,036	2,36	**stationary**
		(0,35)	(4,80)	-(0,59)	-(1,88)					
Δ	ln(PL.B)	0,137	1,710	-0,004	-0,254		0,793	0,036	1,62	**stationary**
		(2,57)	(4,99)	-(1,86)	-(1,27)					
Δ	ln(PK.B)	0,126	1,740	-0,003	-0,480		0,632	0,143	2,28	**stationary**
		(1,40)	(4,98)	-(0,45)	-(2,07)					
Δ	ln(PM.B)	0,202	1,000	-0,009	-0,062		0,803	0,044	2,35	**stationary**
		(3,89)	(3,08)	-(3,50)	-(0,30)					
Δ	ln(Y.B)	-0,082	0,862	0,006	0,183		0,562	0,113	1,90	**stationary**
		-(1,16)	(2,34)	(1,23)	(0,73)					
Δ	SK.B	0,013	1,470	-0,002	-0,448		0,581	0,04	2,49	**stationary**
		(0,53)	(4,63)	-(0,88)	-(2,00)					
Δ	SM.B	-0,021	1,390	0,002	-0,413		0,570	0,036	2,47	**stationary**
		-(0,97)	(4,40)	(1,13)	-(1,85)					
Δ	SY.B	0,018	0,962	0,001	0,135		0,469	0,087	1,95	**stationary**
		(0,34)	(2,51)	(0,23)	(0,51)					
Δ	ln(PL.C)	0,040	1,600	-0,001	-0,313		0,600	0,036	2,11	**stationary**
		(1,48)	(4,25)	-(0,47)	-(1,32)					
Δ	ln(PK.C)	0,093	1,600	-0,002	-0,462		0,588	0,140	2,34	**stationary**
		(1,09)	(4,69)	-(0,39)	-(1,94)					
Δ	ln(PM.C)	0,165	1,380	-0,006	-0,320		0,758	0,036	2,55	**stationary**
		(4,65)	(4,48)	-(3,47)	-(1,58)					
Δ	ln(Y.C)	-0,072	1,900	0,002	-0,389		0,751	0,035	2,36	**stationary**
		-(2,90)	(5,20)	(1,31)	-(1,79)					
Δ	SK.C	-0,005	1,440	0,000	-0,372		0,522	0,011	2,26	**stationary**
		-(0,76)	(4,19)	(0,74)	-(1,52)					
Δ	SM.C	0,007	1,110	0,000	-0,210		0,436	0,008	2,11	**stationary**
		(1,59)	(3,48)	-(0,72)	-(0,91)					
Δ	SY.C	0,000	0,888	0,000	-0,085		0,310	0,009	1,91	**stationary**
		(0,01)	(2,65)	-(0,46)	(0,51)					

Δ	ln(PL.D)	0,017	1,250	-0,001	-0,052		0,441	0,067	1,79	**stationary**
		(0,42)	(2,71)	-(0,51)	-(0,19)					
Δ	ln(PK.D)	0,107	1,710	-0,002	-0,502		0,624	0,149	2,35	**stationary**
		(1,16)	(5,03)	-(0,36)	-(2,18)					
Δ	ln(PM.D)	0,120	1,700	-0,002	-0,396		0,524	0,083	1,70	**stationary**
		(1,82)	(3,36)	-(0,43)	-(1,30)					
Δ	ln(Y.D)	-0,080	1,440	0,003	-0,221		0,592	0,057	1,73	**stationary**
		-(1,79)	(2,97)	(1,12)	-(0,81)					
Δ	SK.D	-0,025	1,350	0,001	-0,206		0,518	0,044	2,09	**stationary**
		-(0,92)	(3,66)	(0,73)	-(0,82)					
Δ	SM.D	0,030	1,300	-0,001	-0,221		0,512	0,037	2,05	**stationary**
		(1,32)	(3,64)	-(0,96)	-(0,90)					
Δ	SY.D	-0,021	1,680	0,003	-0,576		0,652	0,048	2,17	**stationary**
		-(0,73)	(5,31)	(1,33)	-(2,63)					
Δ	ln(PL.E)	0,013	2,170	0,001	-0,411		0,699	0,038	1,90	**stationary**
		(0,51)	(4,69)	(0,48)	-(1,50)					
Δ	ln(PK.E)	0,125	1,690	-0,004	-0,496		0,627	0,147	2,41	**stationary**
		(1,36)	(4,98)	-(0,60)	-(2,14)					
Δ	ln(PM.E)	0,155	1,690	-0,005	-0,404		0,848	0,027	1,91	**stationary**
		(5,05)	(5,68)	-(4,13)	-(1,50)					
Δ	ln(Y.E)	-0,065	2,020	0,005	-0,417		0,786	0,05	2,28	**stationary**
		-(1,90)	(5,00)	(1,98)	-(1,76)					
Δ	SK.E	-0,012	1,560	0,001	-0,370		0,558	0,038	2,28	**stationary**
		-(0,54)	(4,45)	(0,39)	-(1,53)					
Δ	SM.E	0,009	1,170	0,000	-0,278		0,393	0,022	2,17	**stationary**
		(0,69)	(3,40)	-(0,28)	-(0,11)					
Δ	SY.E	0,001	1,560	0,001	-0,406		0,590	0,033	2,30	**stationary**
		(0,03)	(4,49)	(0,69)	-(1,73)					

APPENDIX C

In this appendix, we describe the Lynde and Richmond model in more detail for comparative purposes.

The Lynde and Richmond Model

Taking advantage of duality principles, Lynde and Richmond (1992) look at the effects that public capital has on US private sector (nonfinancial) production costs. Following the 'ownership' definition of infrastructure, they measure public capital as the net stock of nonmilitary fixed government-owned capital. Under perfect competition, the individual firm minimizes private production costs by choosing the optimal level of labor services (L) and private capital services (K) given the level of public capital services (G), which are provided by the government at no cost to the firm. Thus the optimization problem is

(1) $$C(p_L, p_K, y, G, t) = \min_{L,K} p_L L + p_K K \qquad \text{s.t. } y = A(t)\, f(L, K, G) \;,$$

where A(t) represents technological change, which is assumed to progress with time $(A'(t) > 0)$, and y is (value-added) output.

Using the envelope theorem then yields the *shadow price* of public capital

(2) $$\frac{\partial C}{\partial G} = -\lambda\, A(t)\, f_G \;,$$

where λ is a Lagrange multiplier. (2) reflects the willingness to pay for an additional unit of public capital services or, equivalently, the private production cost savings which result from the provision of an additional unit of public capital.

Public capital's 'shadow cost share' can therefore be expressed as

(3) $$s_G = \frac{-qA(t) f_G G}{C(\cdot)} \;,$$

which is analogous to the standard private cost share expressions: $s_i = \dfrac{p_i i}{C} \;\; for \;\; i = K, L$.

Since perfect competition is assumed, λ equals the price of output, q. The cost function, C(.), is homogeneous degree 1 in p_L and p_K and, under constant returns to scale (CRTS), also in y and G. Equation (3) shows that if the marginal product of public capital is positive (f_G>0), then public capital 'subsidizes' production (i.e. has a negative shadow price), and thus s_G must be negative.

Lynde and Richmond use a translog cost function and estimate only the set of cost share equations using the iterated Zellner SURE (Seemingly Unrelated Regressions) estimation method for the period 1958-1989. We report below Lynde and Richmond's estimates under price homogeneity, CRTS, and symmetry. (Note that they include a dummy variable, DUM, to account for an outlying data point in 1974.)

$$s_L = \frac{\partial \ln C}{\partial \ln p_L} = .127 + .161 \ln p_L - .161 \ln p_K + .159 \ln y - .159 \ln G - .004t - .298 DUM \tag{4}$$

(7.31) (43.75) (–43.75) (11.85) (–11.85) (–22.44) (–25.32)

$R^2 = .993 \quad DW = 1.39$

$$s_G = \frac{\partial \ln C}{\partial \ln G} = .368 - .159 \ln p_L + .159 \ln p_K - .342 \ln y + .342 \ln G + .009t + .268 DUM \tag{5}$$

(5.67) (–11.85) (11.85) (–3.75) (3.75) (7.36) (6.83)

$R^2 = .919 \quad DW = 1.46$

The negative and significant infrastructure coefficient in the s_L equation implies that an increase in the provision of public capital services leads to a fall in the cost share of labor. When Lynde and Richmond calculate the *overall* effect of G on the demand for labor (i.e. after also taking the productivity effect into account), they find that labor and public capital are substitutes. They also find that private and public capital are complements. The infrastructure coefficient in the s_G equation is significant and positive, suggesting that the marginal product of public capital is falling over the period. That is, an increase in public capital services leads to an increase in its shadow cost share (by (3), for s_G to be rising, the marginal product of capital must be falling). Nonetheless, they find that the marginal product of public capital was not driven below zero, since s_G is negative over the whole sample period. In short, although Lynde and Richmond take a different methodological approach than Aschauer and Ratner, they also conclude that public capital is a significant determinant of US manufacturing sector costs. They do not, however, discuss the stationarity of their data, which is where our study deviates from theirs.

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