

MEASURING THE CONTRIBUTION OF PUBLIC INFRASTRUCTURE CAPITAL IN SWEDEN

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I. Introduction

Although much attention in macroeconomics has been focused on the effects of government spending on private sector output and productivity growth, and even though private sector capital accumulation has long been studied in terms of its effects on economic growth and productivity, surprisingly little consideration has been given to the corresponding effects of public infrastructure capital stock formation. By public infrastructure capital stocks, we refer to the highways, airports, mass transit facilities, water supplies, sewer systems, police and fire stations, courthouses and public garages, etc., that provide an environment in which private production is facilitated.

As David Aschauer [1989] and Alicia Munnell [1990a,b], among others, have recently emphasized, this relative neglect of public infrastructure capital is particularly startling, for the amount of such infrastructure capital is substantial, both absolutely and relatively.¹ Munnell [1990a, Table 3], for example, reports that in 1987 in the United States, the value of the total private (nonfarm business plus farm) capital stock was \$4.1 trillion dollars, while the total non-military public infrastructure capital stock was \$1.9 trillion -- about 46% of the private sector stock. For Sweden, our estimate of the private business sector capital stock in 1988 is 817 billion SEK, while that for the public infrastructure capital stock is 355 billion SEK -- about 43% of the private sector stock. In both countries, infrastructure capital is substantial.

Government investments in long-lived capital equipment and buildings undoubtedly provide valuable infrastructure services for the private business sector, as well as for individual consumers. The construction of new roads,

or the maintenance and upkeep of existing highways, for example, can have a substantial impact on the time required to transport goods and services, and to conduct other business affairs. Thus it is reasonable to expect that public sector infrastructure capital formation has a significant impact on the performance and productivity of the private sector.²

Table 1

Growth Rates of Real Private and Real Public Capital Stocks
in Sweden and in the United States, Selected Time Periods

	Average Annual Growth Rate of Capital Stock		
	<u>1960-88</u>	<u>1960-73</u>	<u>1974-88</u>
Private Business Sector:			
Sweden	3.8%	4.7%	3.0%
United States	3.4%	4.3%	3.1%
Core Infrastructure:			
Sweden	2.6%	4.1%	1.3%
United States	2.6%	4.1%	1.4%
Core Infrastructure Excluding Electricity:			
Sweden	2.3%	4.8%	0.0%

Note: Data for Sweden computed by authors. For the United States, data are averages of values reported by Alicia Munnell [1990a], Table 4, p. 15.

In this context, it is of interest to examine relative growth rates of capital accumulation in the private and public sectors of Sweden and the United States. As is shown in Table 1, surprisingly similar trends have occurred in these two countries since 1960, with both revealing a rather sharp slowdown in public infrastructure capital formation in the 1970's. More specifically, over the 1960-88 time period, the annual average growth rate (AAGR) of real capital stocks in the private sector was 3.8% in Sweden and

3.4% in the US; the 1974-88 AAGR for Sweden (3.0%) and the US (3.1%) were both less than that from 1960-73 (4.7% for Sweden and 4.3% for the US).

Since 1973, however, growth of the public infrastructure capital stock has lagged considerably behind that in the private sector, both in the US and Sweden. While the AAGR from 1960-73 for core infrastructure capital (highways, airports, mass transit, electric and gas plants, telecommunications, water supply facilities and sewers) was substantial at 4.1% in both countries, growth fell sharply to 1.3% (Sweden) and 1.4% (US) from 1974 to 1988. And if one excludes electricity generation and distribution investments from the core capital, in Sweden the growth rate of infrastructure capital since 1974 is 0.0% -- zero.

The rough coincidence of this slowdown in public infrastructure capital formation with the much-discussed decline in productivity growth in both these countries is striking. A "back of the envelope" calculation reveals further that the simple correlation between annual multifactor productivity growth in Sweden's private business sector and the growth rate of its public infrastructure capital stock from 1961 to 1988 is 0.55, while that between productivity growth and the growth rate of this infrastructure stock lagged one year is 0.65. Is there in fact a relationship between public infrastructure capital formation and the productivity growth slowdown in Sweden? Or, as has been conjectured by Charles Schultze [1990], is this correlation simply a temporal coincidence, without any cause-effect implications?

Our purpose in this paper is to examine how one might evaluate and measure the contribution of public infrastructure capital on private sector output and productivity growth. We do this by specifying and implementing empirically a number of alternative econometric models using annual data for Sweden from 1960 to 1988.

The outline of this paper is as follows. In Section II we begin by summarizing and critiquing the theoretical framework and empirical results reported in several recent studies of public infrastructure capital formation based on US data. In Section III we provide an alternative theoretical framework, using modern duality theory. Then in Section IV we discuss measurement issues and econometric implementation. In Section V we report empirical results for the total private business sector in Sweden, and in Section VI we focus on the manufacturing sector only. Finally, in Section VII we present a summary of our findings and provide suggestions for future research.

II. Brief Review of Literature

The literature on modeling the contribution of public infrastructure capital to economic growth is substantial; much of it is in the context of regional economics and economic development.³ A common specification in this literature is that of a production function relating value-added output Q to the quantities of labor input L , private capital input K_p , and public infrastructure capital K_i :

$$Q = F(L, K_p, K_i). \quad (1)$$

In an early theoretical article, James E. Meade [1952], develops a specification in which it is assumed that F is homogeneous of degree one in all inputs L , K_p and K_i . Since by assumption K_i affects Q , and since it is exogenous to the firm but does not directly receive a factor payment from the firm, Meade calls this specification an "unpaid factor" model. Another specification considered by Meade is one where F is homogeneous of degree one in only the private inputs L and K_p , and in which the marginal product of the public infrastructure capital is positive; Meade calls this an "atmosphere"

model. In this atmosphere model, returns to scale over all inputs are typically increasing, although they are constant over private inputs. A third possibility, of course, is one in which no constraints are placed on the homogeneity of the F function, implying no restrictions on returns to scale.⁴

At this point it is worth remarking that relatively few empirical studies have been reported in the literature that incorporate public infrastructure capital K_I as an input into production or cost functions. An implication of this is that in most studies the K_I measure is an omitted variable, and that therefore the resulting estimates of private returns to scale may suffer from an omitted variable bias. What the sign of this bias is cannot be stated in general, for it depends on the specific representation of the production or cost function. An intriguing question that emerges, however, is whether the recent spurt of literature on economic growth emphasizing the existence of increasing returns to scale for private inputs, is based in large part on such an omitted variable bias.⁵

Although most of public infrastructure literature is theoretical, a number of econometric studies have been undertaken. Among the more recent analyses, those by David A. Aschauer [1989] and Alicia H. Munnell [1990a,b] are of particular interest to us. We now briefly summarize their findings.

Aschauer assumes that the production function in (1) is Cobb-Douglas, and he estimates parameters for all three of the returns to scale specifications noted above. Moreover, he adds to the estimating equation a time counter variable "t" to incorporate the effects of disembodied technical progress, and a capacity utilization variable CU. For his specification with no constraints placed on returns to scale, Aschauer estimates parameters of the equation

$$\ln Q - \ln K_p = a_0 + a_1 \cdot \ln L + a_2 \cdot \ln K_p + a_3 \cdot \ln K_I +$$

$$a_4 \cdot \ln CU + a_5 \cdot t + u \quad (2)$$

where \ln is the natural logarithm, u is a traditional stochastic disturbance term, and the degree of returns to scale over all inputs is equal to $a_1 + a_2 + a_3 + 1$. Aschauer also derives and estimates a productivity equation having the form

$$\ln A = b_0 + b_1 \cdot \ln L + b_2 \cdot \ln K_p + b_3 \cdot \ln K_i + b_4 \cdot \ln CU + b_5 \cdot t + v \quad (3)$$

where A is the normalized level of multifactor productivity computed from a Divisia index of growth in output Q minus growth in the private inputs L and K_p , and v is a random disturbance term. Note that Meade's unpaid factor and atmosphere models are testable special cases of (2) and (3).

Aschauer's measure of K_i is the net stock of non-military public structures and equipment, which is based on values presented in a US Department of Commerce publication, Fixed Reproducible Tangible Wealth 1925-85; K_i includes federal, state and local capital stocks of equipment and structures. Annual data on US private business sector output Q , hours L , private capital K_p , and multifactor productivity A are obtained from the US Department of Labor publication, Monthly Labor Review, while the capacity utilization measure is from the Federal Reserve Bulletin and is restricted to the manufacturing sector of the US economy. Based on this 1949-85 annual data, Aschauer reports results of estimating equation (2) as:

$$\begin{aligned} \ln Q - \ln K_p = & -5.60 + 0.29 \cdot \ln L - 0.44 \cdot \ln K_p + 0.36 \cdot \ln K_i & (4) \\ & (10.90) \quad (3.04) & \quad (7.95) \quad (9.79) \\ & + 0.45 \cdot \ln CU + 0.010 \cdot t & \quad R^2 = 0.977 \quad \text{SER} = 0.0078 \\ & (11.31) \quad (4.46) & \quad \text{DW} = 1.74 \end{aligned}$$

where absolute values of t -statistics are in parentheses, SER is the standard error of the regression and DW is the Durbin-Watson test statistic. Note that the 0.36 coefficient on $\ln K_i$ is positive and statistically significant, and that it implies that if public infrastructure capital were increased by 1%,

ceteris paribus, the private business sector output would increase by 0.36%. Estimated returns to scale are 1.21, but the null hypothesis of constant returns to scale in all inputs (Meade's unpaid factor model) cannot be rejected at usual significance levels. The implied elasticity of output with respect to labor is 0.29, while that with respect to private capital is 0.56 (-0.44 + 1); the relative values of these two elasticities differ considerably from the "conventional wisdom", in which the ratio of the L to K_p output elasticities is typically 3:1, not 1:2.⁶

A related set of empirical efforts have been reported by Alicia Munnell. As in Aschauer, in Munnell [1990a] it is assumed that the production function is Cobb-Douglas, but CU rather than $\ln CU$ is added as a regressor, and the t variable is not included. When no constraints are placed on returns to scale, Munnell's estimating equation is of the form

$$\ln Q - \ln L = c_0 + c_1 \cdot \ln L + c_2 \cdot \ln K_p + c_3 \cdot \ln K_1 + c_4 \cdot CU + \epsilon \quad (5)$$

where ϵ is a random disturbance term that follows a first-order autoregressive (AR1) process. Returns to scale over all inputs equal $c_1 + c_2 + c_3 + 1$.

Munnell considers two alternative measures of non-military K_1 , both based on the same data sources employed by Aschauer. One is what she calls the "core infrastructure" capital, and it consists of highways, airports, mass transit facilities, electric and gas plants, water supply facilities and sewers; a second measure is more general, and it includes not only the core infrastructure capital, but also non-military public buildings such as schools, hospitals, police and fire stations, courthouses, garages and passenger terminals, and those used in conservation and development. In 1987, about 63% of the total non-military public capital consisted of core infrastructure, education, hospital and other buildings constituted about 28%, and conservation and development structures provided the remaining 9%.

Using 1949-1987 annual data for the US private nonfarm business sector and the total nonmilitary public capital measure for K_I , Munnell reports estimates of (5) as:

$$\ln Q - \ln L = 4.45 - 1.02 \cdot \ln L + 0.64 \cdot \ln K_P + 0.31 \cdot \ln K_I + 0.66 \cdot CU, \quad (6)$$

(7.3) (4.4) (4.1) (3.2) (5.8)

having an R^2 of 0.998, a SER equal to 0.0099, and an estimate of the first-order autocorrelation coefficient equal to 0.74, with a t-statistic of 4.7. Very similar results were obtained when the K_I measure was confined to the core infrastructure capital. Specifically, Munnell reports estimates as:

$$\ln Q - \ln L = 4.37 - 1.06 \cdot \ln L + 0.62 \cdot \ln K_P + 0.37 \cdot \ln K_I + 0.68 \cdot CU \quad (7)$$

(6.9) (4.5) (4.0) (3.9) (5.8)

with an R^2 of 0.998, SER = 0.0096 and an estimate of $\rho = 0.67$, with a t-statistic of 3.9. Hence the two estimates of the elasticity of output (or, average labor productivity) with respect to K_I range from 0.31 to 0.37, very close to the 0.36 estimate reported by Aschauer. Although point estimates of returns to scale over all inputs are 0.92 for the more inclusive measure of K_I and 0.93 for core infrastructure, the null hypothesis of constant returns to scale is not rejected at usual significance levels. The implied elasticities of output with respect to labor input in (6) and (7) are -0.02 and -0.06, respectively, while those with respect to private capital input are 0.64 and 0.62; the negative values for the labor elasticity are of course unreasonable, and the relatively large value for the private capital output elasticities is at sharp variance with conventional wisdom.

More reasonable results are obtained in Munnell [1990b], where the underlying data are pooled cross-section annual time series for the 48 continental states over the 1970-1988 time period. The K_I data is "core infrastructure" state and local capital and it includes cumulated and depreciated government capital outlays defined as direct expenditures for the

construction of buildings, roads and other improvements, including additions, replacements, and major alterations to fixed works and structures, whether contracted privately or built directly by the government; these outlays encompass highways, sewage and water supply facilities, but exclude all federal government, and in particular, all military expenditures.

Munnell estimates an equation similar to (6) with the state's unemployment rate replacing the CU variable and with the dependent variable being $\ln Q$ rather than $\ln Q - \ln L$:

$$\ln Q = d_0 + d_1 \cdot \ln L + d_2 \cdot \ln K_p + d_3 \cdot \ln K_1 + d_4 \cdot UN + \nu, \quad (8)$$

and with the three alternative returns to scale specifications. In the unrestricted version analogous to (4), returns to scale are equal to $d_1 + d_2 + d_3$. Munnell reports OLS estimates of the unrestricted equation as follows:

$$\ln Q = 5.75 + 0.59 \cdot \ln L + 0.31 \cdot \ln K_p + 0.15 \cdot \ln K_1 - 0.007 \cdot UN \quad (9)$$

(39.7) (43.2) (30.1) (9.0) (4.7)

where t-statistics are in parentheses; the R^2 is 0.993, and the standard error of the regression is 0.088. The implied elasticity of output with respect to infrastructure capital is 0.15, which is positive and statistically significant, but is considerably smaller than the 0.31 - 0.39 estimates reported in the studies by Munnell [1990a] and Aschauer [1989] discussed above, each of which employed national data. Note that the estimated returns to scale from this model are $0.59 + 0.31 + 0.15 = 1.05$, which implies increasing returns to scale. When Meade's "atmosphere" returns to scale restrictions are imposed ($d_1 + d_2 = 1$), the fit is only marginally affected (the R^2 falls to 0.992 and the SER increases to 0.090), but when Meade's "unpaid factor" returns to scale constraints are introduced ($d_1 + d_2 + d_3 = 1$), the goodness of fit declines considerably (the R^2 is 0.990, but the SER increases to 0.102). Munnell reports similar findings when the infrastructure

capital is disaggregated into stock of highways, stock of water and sewer systems, and stock of other state and local public capital (primarily buildings). Finally, the value of the elasticity of output with respect to labor input (0.59) relative to that with respect to private capital (0.31) is more in line with the conventional wisdom, although the 0.59/0.31 ratio is still less than 3:1.

One implication of the use of the Cobb-Douglas functional form in these studies is that the L , K_I and K_P inputs are assumed to be substitutable inputs, implying that increases in K_I are by *assumption* specified to increase the average and marginal productivity of the labor and private capital inputs. In an effort to gain more information about substitutability relationships among inputs, Munnell estimated parameters of a translog production function, a functional form more general than the Cobb-Douglas. Although she does not report estimates of substitution elasticities, she interprets OLS parameter estimates of the translog model as implying that K_P and L are strongly substitutable inputs, that K_P and K_I are weakly substitutable, and that K_I and L are complementary (although the relationship is not statistically significant).

The studies by Aschauer and Munnell generate provocative and intriguing findings, but they suffer from a number of serious drawbacks. First, in the literature on cost and production, the highly restrictive Cobb-Douglas functional form is hardly ever employed anymore, and instead more flexible functional forms are used. Second, there is a serious issue of what is endogenous and what is exogenous, and the extent to which the production function estimates -- Cobb-Douglas or translog -- suffer from a simultaneous equations bias. Specifically, the right-hand variables in the various equations estimated by Aschauer and Munnell include measures of labor input

(hours paid) and utilization (either capacity utilization or state unemployment rate), and strong arguments have been made that in this type of a context such variables should be treated as endogenous, not exogenous; in such a case estimation by OLS produces biased and inconsistent parameter estimates.⁷ Third and finally, although this approach provides one measure of the impact of K_i on private sector costs and productivity, it does not provide a framework in which one can begin to assess whether the amount of K_i is insufficient or excessive.

A more appropriate approach, we believe, is to follow developments of the last two decades in modern duality theory and to specify a variable cost function dual to a production function -- a cost function that reflects the optimizing behavior of individual firms.⁸ In the present context, for example, one can specify a variable cost function for the private sector in which firms are envisaged as attempting to produce a given level of output at minimum private variable cost, conditional on quantities of fixed inputs such as K_i and perhaps K_p , where private variable costs include labor, and perhaps energy and other non-energy intermediate materials. In the next section, we outline this alternative theoretical framework, and show how it permits us to measure benefits of public infrastructure capital, or more precisely, how to obtain measures of the shadow value of this capital.

III. An Alternative Theoretical Framework

In the economic theory of cost and production, the notion of a production function plays a central role. Essentially, a production function is an engineering notion revealing the maximum possible output Q that can be produced within a time period, given quantities of the inputs x_1, x_2, \dots, x_n . A useful way of viewing the production function relationship is to think of it

as a book whose pages contain alternative blueprint designs for combining inputs to produce output level Q . Clearly, the production function and the book of blueprints must be consistent with laws of nature and other engineering relationships. While laws of nature are by definition stable and do not change over time, our understanding and discovery of these laws, as well as our ability to exploit technological possibilities, has improved with time. One way of accounting for such advances in the state of technical knowledge, therefore, is to think of them as adding new pages to the book of blueprints. For such reasons, often a time counter variable " t " is included in the production function relationship.

Economic content can be added to the notion of a production function if one assumes that firms optimize. In particular, assume that the prices of inputs purchased by the firm are given (call these prices p), and that conditional on the level of output Q and other environmental factors beyond the firm's control, called Z (including the state of technical knowledge t , but also other variables), firms choose quantities of the inputs so as to minimize the private costs of producing output Q . Given standard continuity and regularity conditions on the production function, according to modern duality theory there exists a cost function dual to the production function, having the general form

$$C = g(Q,p,Z) \tag{10}$$

where C is the total private cost of purchasing the input quantities x_j at prices p_j . The dual cost function is increasing in Q and in p , and is homogeneous of degree one in p .

When private firms optimize, they take into account the environment in which they operate. One of these environmental variables is the state of technical knowledge, which, although typically exogenous to the firm, affects

its production possibilities. Another environmental variable affecting production relationships but exogenous to the firm is the amount of available public infrastructure capital K_1 . Since both the t and K_1 variables affect the production function, they also influence cost relationships. It is therefore useful to specialize the Z inputs in the dual cost function (10) and to re-write it as

$$C = g(Q, p, K_1, t). \quad (11)$$

Among the n inputs, it is often the case that some inputs (such as private capital stocks of structures and equipment) are fixed in the short-run, while other inputs (labor hours, energy, non-energy intermediate materials) are variable. In this case, in the short-run firms optimize by choosing those quantities of variable inputs that minimize total variable input costs C_v , given Q , p_v , K_1 , t and K_p , where K_p is the private firm's capital stock, p_v is the set of input prices for the variable inputs, and C_v is the sum of short-run costs over the variable inputs. Following Paul A. Samuelson [1953], one can specify a short-run or variable private cost function, written as

$$C_v = h(Q, p_v, K_p, K_1, t). \quad (12)$$

A concept that will be of particular use to us in this paper is the notion of the shadow value of the public infrastructure capital stock K_1 . Holding other things fixed, one can assess the impact on the private firm's costs of there being an exogenous increase in the amount of available public infrastructure capital, i.e., one can compute the marginal benefits to the private sector (in terms of reduced costs) of there being an increase in K_1 . For the total private cost function (11), define the shadow value of infrastructure capital B_1 as

$$B_1 = - \partial C / \partial K_1 > 0, \quad (13)$$

and for the variable private cost function (12), define the corresponding shadow value B_{vi} as

$$B_{vi} = - \partial C_v / \partial K_i > 0. \quad (14)$$

For the private sector firm minimizing short-run variable costs, there is also a shadow value relationship involving its private capital stock.

Accordingly, define the shadow value of private capital B_{vp} as

$$B_{vp} = - \partial C_v / \partial K_p > 0. \quad (15)$$

If the private sector firm were in long-run equilibrium with respect to its private inputs, then the marginal benefits of K_p would just equal its marginal costs. Call the ex ante one-period price of private capital PK_p . Then at this long-run equilibrium point, the optimal amount of private sector capital K_p^* is that amount at which marginal benefits equal marginal costs, i.e.,

$$K_p = K_p^* \Leftrightarrow B_{vp} = PK_p. \quad (16)$$

Factors affecting the optimal provision of public (rather than private) infrastructure capital K_i are more complex, and may involve normative issues of equity; for a discussion of issues underlying the optimal amount of public goods, see the chapters of modern public finance textbooks, such as that by Joseph Stiglitz [1986]. In the case of pure public goods, one could define total marginal benefits of K_i capital as the sum of the B_{vi} shadow values over all private sector firms, plus the sum of corresponding marginal benefits over all final consumers; call this social or total marginal benefit of K_i capital B_{is} . Alternatively, if there is no congestion in the consumption of public goods, the total marginal benefit could be the largest benefit accruing to any one or set of consumers, rather than the sum over all consumers. One rather simple notion of the optimal provision of K_i capital is that amount of infrastructure capital K_i^* for which social marginal benefits B_{is} just equal

marginal costs PK_1 , where PK_1 is the one-period social price of public infrastructure capital K_1 , i.e.,

$$K_1 - K_1^* \Leftrightarrow B_{1S} - PK_1. \quad (17)$$

One other result from duality theory will also be of importance to us. By assumption, private sector firms choose quantities of variable inputs so as to minimize private variable costs, given the constraints expressed in (12). It turns out that the optimal, variable cost-minimizing quantities of the variable inputs x_v^* simply equal the derivative of (12) with respect to p_v , i.e.,

$$x_v^* = \partial C_v / \partial p_v. \quad (18)$$

This empirically useful result is typically known as Shephard's Lemma; for a discussion and derivation, see W. Erwin Diewert [1974].

In order to implement this theory of cost and production empirically, and to estimate shadow values of private and public capital in Sweden, we must gather appropriate data and specify mathematical functions for the cost functions (11) and (12). To this we now turn our attention.

IV. Data and Econometric Implementation

The production and input data used in this study consist of prices and quantities for variable inputs (labor - L, energy - E, non-energy materials - M), quantity estimates of the private sector capital stock K_p and the public infrastructure capital stock K_1 , ex ante one-period or rental prices for private (PK_p) and public infrastructure (PK_1) capital, and output quantity Q.

For this initial empirical analysis, we have employed data at two levels of aggregation. First, for the private business sector, the measure of output Q is value-added in constant 1985 prices; in this case, L is the only variable input. For the manufacturing sector, we also compute as a measure of output a

gross output series (sales plus net changes in inventories, adjusted for inflation). When output is value added, the only variable input is L, and with gross output, the variable inputs are L, E, M, and, in some cases, K_p .

For both the private business and the manufacturing sectors, the labor quantity measure L is total hours worked, while P_L is total compensation to employees plus employers' contributions to social security, all divided by L; further details on data sources and construction procedures for the labor data are given in Hansson [1991c].

For manufacturing, the energy quantity index E is a Divisia quantity index covering 18 different types of energy (mineral coal, coke, charcoal, fuel wood, other types of fuel wood, propane and butane gas, petrol, paraffin oil, diesel oil, four types of heating oils, town gas, and electricity). The aggregate energy price index is then computed as total energy costs divided by E. Non-energy intermediate materials are total intermediate materials minus energy; total payments to non-energy intermediate materials in current and constant currencies are computed by reversing the double deflation procedure involving value-added and gross output. Further details on the E and M data for the manufacturing sector are provided in Hansson [1991c].

Aggregate capital input for the private sector K_p is computed as a Divisia quantity index of machinery and buildings stocks, with the share weights employing ex ante rental prices of capital, calculated according to the formula $w_k = q_k(r + \delta_k)$, where q_k is the investment deflator for the k^{th} capital good, r is the five-year government bond yield, and δ_k is the constant rate of depreciation for the k^{th} type of capital asset. Note that at this stage of our research, corporate taxes are not included in the rental price measure.⁹ Capital stocks for buildings and machinery are computed separately using the perpetual inventory method, with depreciation rates set to equal

those reported by Hulten and Wykoff [1980,1981].¹⁰ For the manufacturing sector, gross investment series are available back to 1870, but for the entire private business sector¹¹, consistent series are available only since 1950. For the non-manufacturing sectors, 1950 benchmark capital stocks are computed separately by sector, calculated as a number no larger than $(1/\delta_k)$ times the average investments for the first three years in the 1950's. The aggregate rental price PK_p is computed as total expenditures on private capital divided by the Divisia quantity index K_p . Further details on the construction of the aggregate K_p and PK_p are found in Hansson [1991c].

Aggregate public infrastructure capital K_I is computed as a Divisia quantity index of machinery and building stocks, with share weights reflecting ex ante rental prices as noted above; in particular, the government bond yield is employed as the measure of r . The core public infrastructure capital stock includes streets, roads and highways (central and local governments), mass transit, airports, sewers and water systems, railroads and electric facilities. Depreciation rates for individual asset types in the public sector were set to the same value as in the private sector, except that road maintenance was depreciated at 25% per annum. The 1960-88 time series of K_I is presented in Table A-1 in the appendix to this paper.

In 1960 (1988), the aggregate public infrastructure capital stock in Sweden consisted of the following sector-specific distribution: electricity generation and distribution, 40.8% (49.2%); water systems and sewers, 4.1% (7.5%); railway transport, 34.6% (20.6%); urban, suburban and interurban passenger transport, 3.3% (3.1%); air transport, 1.4% (3.4%); streets, roads and highways, 15.7% (16.1%). Since the electricity share is so large, and since private sector consumers purchase electricity services, we have constructed an alternative measure of the aggregate public infrastructure

capital stock that excludes the electricity generation and distribution sector. The 1960-88 time series of K_i excluding electricity is also given in Table A-1 in the appendix to this paper.

In terms of econometric implementation, our immediate task is to specify functional forms for the variable cost functions such as (11) and (12). The specifications we employ differ depending on the measure of output employed. In particular, when value-added is the measure of output (as it is in the case of the private business sector), the only variable input is labor, and in this case the variable cost function reduces to an input requirement function relating labor input to Q , K_p , K_i , and t . However, when gross output is used as the measure of output (it and value-added are alternative measures of output in the manufacturing sector), the variable cost function becomes more complex, incorporating not only Q , K_p , K_i and t , but also prices of the variable inputs.

We begin with the specification for value-added output. One convenient functional form for the labor input requirement function is the following, analogous to that considered in Hansson [1991a] (the corresponding variable cost function is simply obtained by multiplying both sides by P_L):

$$L = \beta_L + \beta_Q Q + \beta_{tQ} t \cdot Q + \beta_{QQ} Q^2 + \beta_p K_p + \beta_i K_i + \beta_{pQ} K_p \cdot Q + \beta_{iQ} K_i \cdot Q + \beta_{pi} K_p K_i / Q + .5 \cdot \beta_{pp} K_p^2 / Q + .5 \cdot \beta_{ii} K_i^2 / Q. \quad (19)$$

For estimation, to avoid potential problems with heteroskedasticity, it is useful to divide both sides of (19) by Q , thereby having L/Q as the dependent variable in the estimation equation. Note that with this functional form, no constraints are placed on long-run returns to scale. However, if one sets $\beta_L = \beta_{QQ} = \beta_{pQ} = \beta_{iQ} = 0$, then there are long-run constant returns to scale over

all private and public inputs (Meade's unpaid factors model), and if one instead sets $\beta_L = \beta_{QQ} = \beta_{pQ} = \beta_{pi} = 0$, long-run constant returns to scale occur for the private inputs (Meade's atmosphere model).

One convenient feature of the specification in (19) is that, using the marginal benefit equal marginal cost conditions in (16) and (18), one can solve for optimal amounts of K_p^* and K_i^* , provided that in the latter case one restricts benefits to those accruing to the private business sector (and excludes those infrastructure benefits enjoyed by final demand consumers). These optimal capital stock levels turn out to be

$$K_p^* = \frac{-Q}{\beta_{pp}J} \cdot \left[\frac{PK_p}{P_L} + \beta_p + \beta_{pQ}Q - \left(\frac{\beta_{pi}}{\beta_{ii}} \right) \cdot \left(\frac{PK_i}{P_L} + \beta_i + \beta_{iQ}Q \right) \right] \quad (20)$$

where

$$J = 1 - \left[\beta_{pi}^2 / (\beta_{pp} \cdot \beta_{ii}) \right]$$

and

$$K_i^* = \frac{-Q}{\beta_{ii}J} \cdot \left[\frac{PK_i}{P_L} + \beta_i + \beta_{iQ}Q - \left(\frac{\beta_{pi}}{\beta_{pp}} \right) \cdot \left(\frac{PK_p}{P_L} + \beta_p + \beta_{pQ}Q \right) \right]. \quad (21)$$

In the econometric implementation, an additive disturbance term is appended to the L/Q equation based on (19), and it is assumed to be independently and identically normally distributed. However, since Q could possibly be jointly determined with L/Q, a Hausman specification test will be undertaken to test for the correlation of the various transformations of Q with the equation disturbance term.¹²

For the manufacturing sector, when value-added is the measure of output we employ the same specification as for the private business sector, i.e., the

L/Q version of (19). However, when the gross output measure is employed in manufacturing, inputs other than L are variable. In this case, several specifications are available.

One possibility, in the tradition of Dale W. Jorgenson [1986], is to treat all the L, E, M and K_p inputs as variable, as in (11). Letting Q now be gross output rather than value-added, following Hansson [1991a] one can specify the total (private) cost function to have the following normalized general Leontief form, where $\pi = PK_p + P_L + P_E + P_M$ and $TC = PK_p K_p + P_L L + P_E E + P_M M$:

$$\begin{aligned}
 TC = Q \cdot [& \beta_{LL} P_L + \beta_{EE} P_E + \beta_{MM} P_M + \beta_{PP} PK_p + 2 \cdot (\beta_{LE} (P_L P_E))^{.5} \\
 & + \beta_{LP} (P_L PK_p)^{.5} + \beta_{EM} (P_E P_M)^{.5} + \beta_{EP} (P_E PK_p)^{.5} + \beta_{MP} (P_M PK_p)^{.5}] \\
 & + (\beta_L P_L + \beta_E P_E + \beta_M P_M + \beta_P PK_p) \cdot Q^{1.5} + (\beta_{iL} P_L + \beta_{iM} P_M + \beta_{iE} P_E + \beta_{iP} PK_p) \\
 & \cdot (K_i Q)^{.5} + (\beta_{Lt} P_L + \beta_{Et} P_E + \beta_{Mt} P_M + \beta_{Pt} PK_p) \cdot Q^{.5} \quad (22) \\
 & + \pi \cdot [\beta_i K_i + \beta_t t Q + \beta_{QQ} Q^2 + \beta_{iQ} Q \cdot K_i^{.5} + \beta_{tQ} t \cdot Q^{1.5} + \beta_{itQ} (K_i t Q)^{.5}]
 \end{aligned}$$

Using Shephard's Lemma as expressed in (18), we can derive cost-minimizing demands for the i^{th} input, simply by differentiating (22) with respect to P_i . This gives us four demand equations -- for L, E, M and K_p . As an example, for K_p the cost-minimizing demand equation consistent with the total cost function (22) is

$$\begin{aligned}
 K_p^* = Q \cdot [& \beta_{PP} + \beta_{LP} (P_L / PK_p)^{.5} + \beta_{MP} (P_M / PK_p)^{.5} + \beta_{EP} (P_E / PK_p)^{.5} + \\
 & + \beta_t t + \beta_{iQ} K_i^{.5}] + \beta_i K_i + Q^{.5} (\beta_{iP} K_i^{.5} + \beta_{itQ} K_i t^{.5} Q^{.5}) + \beta_{QQ} Q^2 \\
 & + Q^{1.5} \cdot (\beta_p + \beta_{tQ} t^{.5}). \quad (23)
 \end{aligned}$$

Demand equations for L, E and M can be derived analogously.

For econometric implementation, an additive disturbance term is appended to each of the five equations (the cost function (22), the demand equation for

private capital (23), and corresponding demand equations for L, E and M), and the resulting disturbance vector is assumed to be independently and identically multivariate normally distributed, with mean vector zero and constant covariance matrix Ω . Estimation can be carried out using the method of maximum likelihood, with appropriate cross-equation parameter restrictions imposed.

Note also that with this (private) cost total function (22), one can compute the shadow value using (13); in this case, however, the benefits of infrastructure capital consist of reduced costs over all the L, E, M and K_p inputs, not just over the L input as was the case in the value-added model considered earlier.

Moreover, since energy demands are explicitly incorporated, to avoid double-counting it is appropriate that the infrastructure capital stock K_i be re-defined in this gross output model as the previous core infrastructure capital minus the electricity generation and distribution capital.

V. Results: The Private Business Sector in Sweden

We begin by reporting results when the Cobb-Douglas functional forms of Aschauer and Munnell are employed, but with annual Swedish data for 1964-88.¹³ With no constraints placed on returns to scale, use of Aschauer's equation (2) and 1964-88 annual data for Sweden resulted in the following estimated model:

$$\ln Q - \ln K_p = -9.111 + 1.072 \cdot \ln L - 1.666 \cdot \ln K_p + 1.601 \cdot \ln K_i \quad (25)$$

$$\begin{array}{cccc} (2.92) & (4.11) & (5.58) & (5.20) \\ + 0.031 \cdot \ln CU + 0.021 \cdot t & & R^2 = 0.979, \text{ SER} = 0.0151 & \\ (1.64) & (3.60) & \text{DW} = 1.434 & \end{array}$$

where numbers in parentheses are absolute values of t-statistics. Note that although the 1.601 coefficient on $\ln K_i$ is positive and statistically significant, it implies an elasticity of output with respect to K_i greater

than unity -- hardly a credible result; the estimate of the labor elasticity is also greater than unity, although its 1.072 value is considerably smaller. Moreover, the -1.666 coefficient on $\ln K_p$ implies a negative marginal product for K_p capital, since the implicit estimated elasticity of output with respect to K_p is -0.666. Finally, the estimated overall returns to scale consistent with this Aschauer-type equation is 2.010 (1.072 - 1.666 + 1.601 + 1), which is not a plausible result. We conclude that estimating a Cobb-Douglas production function equation as Aschauer did but using Swedish data results in an equation that does not make much sense, even though the estimated coefficient on $\ln K_i$ is positive and statistically significant.^{14,15}

As we noted in Section II, the Cobb-Douglas functional form used by Alicia Munnell [1990a] is related to Aschauer's specification, but it excludes the time variable. Based on Swedish private business sector annual data from 1964 through 1988, we obtained the following OLS equation:¹⁶

$$\begin{aligned} \ln Q - \ln L = & -4.298 - 0.596 \cdot \ln L + 0.369 \cdot \ln K_p + 0.687 \cdot \ln K_i & (26) \\ & (1.21) \quad (2.58) \quad (3.71) \quad (3.12) \\ & + 0.075 \cdot \ln CU & R^2 = 0.995, \quad SER = 0.019 \\ & (4.21) & DW = 0.874 \end{aligned}$$

Here the implied elasticity of output with respect to infrastructure capital is smaller than above but still very large (0.687, and statistically significant), the elasticity with respect to K_p is more reasonable at 0.369, and that with respect to labor (-0.596 + 1 = 0.404) is somewhat small when compared to that for labor. The implied overall returns to scale estimate based on (26) is 1.460; this is not significantly different from unity, for the restriction of Meade's unpaid factors model is not rejected (χ^2 test statistic of 1.92, and a 0.05 critical value of 3.84), nor is the restriction rejected for Meade's atmosphere model (constant returns to scale for private inputs only), where the χ^2 test statistic is 1.46.¹⁷

We conclude, therefore, that although results obtained from Munnell's specification are a priori more plausible than those resulting from use of Aschauer's model, the Munnell model implies a very large elasticity of output with respect to infrastructure capital.¹⁸ Moreover, as we noted at the end of Section III, the Aschauer and Munnell Cobb-Douglas production function specifications have serious drawbacks, not only in terms of econometric specification (e.g., they ignore the endogeneity of labor demand), but also by not taking into account the optimizing behavior of firms. Recent developments in duality theory have helped overcome these drawbacks.

We now turn to results obtained when we estimated parameters of a dual restricted variable cost function, in particular, equation (19) with both sides divided by Q. Using annual Swedish data from 1960 to 1988, we obtained the following results:

$$\begin{aligned}
 L/Q = & -0.004 - 0.185E-3 \cdot t + 1300.4/Q + 0.539E-7 \cdot Q - 0.137 \cdot K_p/Q + 0.289 \cdot K_i/Q \\
 & (0.11) \quad (2.27) \quad (1.31) \quad (1.00) \quad (3.53) \quad (1.98) \\
 + & 0.175E-6 \cdot K_p - 0.431E-6 \cdot K_i + 0.267 \cdot K_p K_i / Q^2 - 0.091 \cdot K_p^2 / Q^2 - 0.676 \cdot K_i^2 / Q^2 \quad (27) \\
 & (4.79) \quad (4.15) \quad (4.18) \quad (3.87) \quad (2.76)
 \end{aligned}$$

with an R^2 of 0.9995, a SER of 0.00012, and a Durbin-Watson test statistic of 2.146. Since one might argue that this specification could suffer from a simultaneous equations bias due to Q being endogenous, we performed a Hausman specification test and checked whether the various right-hand variables involving Q were correlated with the equation disturbance term. The chi-square test statistic we obtained was 7.52, which is considerably less than the 0.10 (12.0) and 0.05 (14.1) critical values with seven degrees of freedom; hence we do not reject the null hypothesis that Q is exogenous.¹⁹

In terms of returns to scale specifications, the restrictions implied by long-run constant returns to scale over all inputs (Meade's unpaid factors model) are decisively rejected (the χ^2 test statistic is 93.60, while the 0.05

critical value with four restrictions is 9.49), as are the restrictions implied by long-run constant returns to scale over private inputs only (the χ^2 test statistic is 109.93, and a 0.05 critical value of 9.49).

As is seen in (27), the L/Q input-output coefficient is affected by K_p and K_i in a nonlinear fashion. We have computed the short-run elasticity of demand for private labor with respect to private capital, and with respect to public capital, that are implied by these parameter estimates. These short-run elasticity estimates vary considerably over the sample, even in sign. All that can be said in general is that during the 1960's and late 1980's, private labor and private capital were short-run substitutable inputs (the estimated elasticity of L with respect K_p was negative), while private labor and public capital were short-run complementary inputs (the estimated elasticity of L with respect to K_i was positive);²⁰ during the 1970's and up to the mid 1980's, the signs were reversed.

Of particular interest to us is the calculation of the optimal private and optimal public infrastructure capital stocks implied by equating the estimated shadow values (marginal benefits) of these stocks to their ex ante rental prices, as formulated in equations (16), (17), (20) and (21). We have computed these optimal capital stocks, and have then calculated the ratio of the optimal capital stock K^* to the actual capital stock K , by year for K_p and for K_i . Results of this calculation are presented in Table 2 below.

Before discussing these estimates, we believe it useful to remind readers that in the case of the public infrastructure capital K_i , use of (17) and (21) implies that the optimal amount of K_i , called K_i^* , is that amount that can be rationalized given that benefits (in terms of reduced labor costs) accrue only to the private business sector. To the extent that benefits computed in this way are understated (since any benefits to final consumers

are not incorporated), ceteris paribus, the ratio of K_i^* to K_i is also understated. Moreover, since the optimal private capital stock K_p^* rises with decreases in the one-period rental price of private capital PK_p , ceteris paribus, to the extent that PK_p is overstated owing to the fact that corporate taxes are not incorporated into the measure of PK_p (and on this see footnote 9), the ratio of K_p^* to K_p is understated. Hence, there is some reason to

Table 2

Ratios of Optimal to Actual Capital Stocks
Private Business Sector, Sweden, 1960-88

<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$	<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$
1960	1.030	1.044	1975	0.984	0.943
1961	1.057	1.041	1976	0.949	0.933
1962	1.055	1.033	1977	0.874	0.887
1963	1.072	1.048	1978	0.872	0.883
1964	1.089	1.064	1979	0.892	0.887
1965	1.067	1.047	1980	0.889	0.888
1966	1.033	1.021	1981	0.853	0.874
1967	1.030	1.017	1982	0.844	0.870
1968	1.021	0.987	1983	0.850	0.868
1969	1.037	0.987	1984	0.877	0.879
1970	1.067	1.000	1985	0.867	0.874
1971	1.033	0.975	1986	0.871	0.896
1972	1.022	0.965	1987	0.860	0.896
1973	1.032	0.963	1988	0.845	0.905
1974	1.016	0.957			

believe that both of these ratios are understated. However, if the bias can plausibly be argued to be relatively constant over time, the time trend in these ratios can still provide useful information.

We begin with the ratio of optimal to actual private sector capital stocks. As is seen in Table 2, this ratio is above unity and increases from

1960 to 1964, it stays above unity but falls and then increases until 1970, and then it begins falling more steadily, hitting levels below unity in 1975; at the end of the time period in 1988, the ratio had fallen to 0.845, implying that in 1988 the existing capital was underutilized, and that a capital stock about 15% smaller is all that could be rationalized by the marginal benefit equal marginal cost condition in the Swedish private business sector.

For the public infrastructure capital, the ratio of optimal to actual capital stocks is above unity from 1960 until 1967, it hits a peak of 1.064 in 1964, it falls from 1970 to about 1983, and then rises slightly at the end of the 1980's, reaching a level of 0.905 in 1988. Hence, if one incorporates as benefits of K_I only those reduced labor costs accruing to the private business sector in Sweden, in 1988 the level of K_I was about 9% too large. The extent of such apparent excess infrastructure capital was falling in the late 1980's, however, from 13% in 1983 to 9% in 1988, consistent with the widely held view that, for example, roads and highways were not as well maintained as had been the case in the 1970's and early 1980's.

Finally, to assess the effects on private sector productivity growth of changes in the public infrastructure capital stock, we have undertaken several historical and counterfactual simulations. Specifically, we first computed "actual" private business sector multifactor productivity (MFP) growth using historical data on output growth minus growth in aggregate input, where actual K_p growth is weighted by the ex ante rental price of capital PK_p ; we call this actual growth series MFP_a .

Second, to purge from this MFP_a series the effects of K_p not being in long-run equilibrium, we used the historical data series on PK_p , P_L , Q , t and K_I , as well as parameter estimates from (27), to compute optimal private capital K_p^* ; we then calculated the corresponding optimal L^* given K_p^* , Q , t

and K_1 . Finally, we constructed the corresponding aggregate input series over L^* and K_p^* using the Divisia index procedure, and then we obtained an MFP series as growth in output minus growth in this long-run equilibrium but counterfactual aggregate input. We call this private sector equilibrium productivity series MFP_e , reflecting the fact that it simulates private sector productivity growth had it been in long-run equilibrium. Note that any differences between MFP_a and MFP_e reflect the effects of the private sector capital stock being out of long-run equilibrium.

Third, there are several alternative ways by which one might investigate the effects on private sector MFP of varying growth paths of infrastructure capital K_1 . For example, one could fix for the entire 1960-88 sample the ratio of K_1 to Q from some chosen year (say, 1960, 1974 or 1988), generate a counterfactual K_1' series given historical growth in Q , calculate private sector long-run optimal K_p^* and L^* given this new K_1' series, and then compute the implied rate of MFP growth. While interesting, these results would vary with choice of the benchmark year (1960, 1974 or 1988), and thus interpretation would be problematic. This consideration led us to employ as an alternative K_1 series that amount of K_1 that could be rationalized by private business sector cost savings, i.e. we solved (20) and (21) to obtain K_p^* and K_1^* , inserted these values into (19) to obtain L^* , and then computed MFP growth as growth in output minus growth in this counterfactual but optimal aggregate private input; we call this optimal productivity growth series MFP_o .

The results of our calculations are presented in Table 3 below. In the first row of Table 3, it is seen that the slowdown in actual MFP growth from 1960-73 (an AAGR of 4.290%) to 1974-88 (1.188%) was 72.3% $((4.290 - 1.188) / 4.290)$. From the second row we see that had the private sector capital stock been in long-run equilibrium in each year, then the slowdown would have been

65.2% rather than 72.3% of 1960-73 actual MFP growth, or 9.8% smaller; thus 9.8% of the slowdown can be "explained" by private sector capital stock disequilibrium.

Table 3

MFP Average Annual Growth Rates Under Alternative Assumptions
Private Business Sector, Sweden, Parameters from Eq. 27

Scenario	Notation	(1)	(2)	(3)	Percent Slowdown	
		MFP 1960-73	MFP 1974-88	Percent Difference	"Explained" Marginal	Total
Actual	MFP _a	4.290	1.188	72.3%		
Private Sector K_p in Long-Run Equilibrium	MFP _e	4.080	1.419	65.2%	9.8%	9.8%
Private Sector K_p in Long-Run Equilibrium and Optimal K_i^*	MFP _o	3.920	1.538	60.8%	6.1%	15.9%

Note: Column (3) computed as [(Column 2 - Column 1)/Column 1].

In the bottom row of Table 3 we report MFP growth had the public infrastructure capital been optimal ($K_i = K_i^*$), as viewed through private business sector cost savings. There it is seen that had $K_i = K_i^*$, then private sector long-run optimal MFP growth would have been lower from 1960 to 1973 (3.920% vs. 4.290%), it would have been higher from 1974 to 1988 (1.538% vs. 1.188%), and thus the MFP growth slowdown would have been 60.8%, rather than the actual 72.3%. The marginal impact of optimal K_i^* , assuming private sector long-run equilibrium, is to reduce the slowdown by 6.1% ((0.652 - 0.608)/0.723), and the cumulative impact of private and public sector disequilibrium is to reduce the private sector MFP growth slowdown by 15.9% ((0.723 - 0.608)/0.723).

We conclude, therefore, that while reduced infrastructure capital investment in Sweden since 1974 has contributed to the productivity growth slowdown in the private business sector, this impact has been rather modest.²¹ Much of the productivity growth slowdown is apparently still "unexplained", although Hansson's [1991b] results provide intriguing evidence that reduced exploitation of scale economies may have played a very prominent role.

This completes our discussion of empirical results obtained for the private business sector. We now provide some preliminary, more detailed evidence using data from one sector within the aggregate private business sector, namely, the manufacturing sector.

VI. Results: The Manufacturing Sector in Sweden

Using annual 1960-1988 data for the Swedish manufacturing sector only, we have estimated by ordinary least squares parameters of the labor demand equation (19), where both sides are divided by value-added output Q. The results we obtained are as follows:

$$\begin{aligned}
 L/Q = & 0.0004 - 0.284E-3 \cdot t + 4809.0/Q + 0.289E-7 \cdot Q - 0.041 \cdot K_p/Q + 0.106 \cdot K_1/Q \\
 & (0.002) \quad (4.98) \quad (6.37) \quad (0.61) \quad (2.01) \quad (1.45) \\
 + & 0.448E-7 \cdot K_p - 0.166E-6 \cdot K_1 + 0.052 \cdot K_p K_1/Q^2 - 0.0004 \cdot K_p^2/Q^2 - 0.248 \cdot K_1^2/Q^2 \quad (28) \\
 & (1.85) \quad (2.39) \quad (1.78) \quad (0.03) \quad (1.73)
 \end{aligned}$$

with an R^2 of 0.9995, a SER of 0.00012, and a Durbin-Watson test statistic of 1.906.

In terms of returns to scale specifications, the restrictions implied by long-run constant returns to scale over all inputs (Meade's unpaid factors model) are also decisively rejected in the manufacturing sector (the χ^2 test statistic is 78.63, while the 0.05 critical value with four restrictions is 9.49), as are the restrictions implied by long-run constant returns to scale

over private inputs only (the χ^2 test statistic is 68.54, and a 0.05 critical value of 9.49).

Table 4

Ratios of Optimal to Actual Capital Stocks, Value Added Model
Manufacturing Sector Only, Sweden, 1960-88

<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$	<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$
1960	0.960	1.111	1975	0.851	0.774
1961	0.978	1.079	1976	0.828	0.779
1962	0.980	1.057	1977	0.765	0.762
1963	0.992	1.051	1978	0.766	0.766
1964	0.994	1.030	1979	0.773	0.762
1965	0.968	0.994	1980	0.764	0.759
1966	0.936	0.954	1981	0.731	0.758
1967	0.934	0.930	1982	0.718	0.763
1968	0.925	0.880	1983	0.719	0.768
1969	0.933	0.856	1984	0.733	0.771
1970	0.947	0.843	1985	0.721	0.769
1971	0.918	0.821	1986	0.726	0.789
1972	0.908	0.812	1987	0.708	0.770
1973	0.907	0.799	1988	0.690	0.760
1974	0.884	0.787			

We have also computed optimal private and public capital stocks, assuming that benefits in the form of reduced labor costs accrue only to the manufacturing sector. Our estimates are given in Table 4 above. A number of results are worth noting.

First, somewhat surprisingly, the ratio of optimal to actual private capital in manufacturing is less than one in all years, with its high value of 0.994 in 1964 and a lowest value of 0.690 in 1988; although there are a few wiggles in the late 1970's, this ratio falls rather steadily ever since 1970. These results imply that in the Swedish manufacturing sector, the amount of

underutilization of capital is considerable, and that this underutilization has increased in the last two decades.

With respect to public capital, a priori one would expect that if one computed benefits as reduced labor costs for only the manufacturing sector, the amount of public capital rationalized by this cost saving would be less than if benefits included the entire private business sector. Hence, one would expect the ratio of optimal to actual K_i viewed from the vantage of the manufacturing sector to be less than that when assessed from the viewpoint of the entire private business sector. For the most part, this is what we find. With the exception of the beginning years in the sample (1960-63), the ratio of K_i^* to K_i is smaller in Table 4 (for manufacturing only) than in Table 2 (for the entire private business sector). As seen in Table 4, in 1988, this ratio is but 0.760, while in Table 2 it is 0.905; hence the amount of excess infrastructure capital is about 25% when benefits are confined to the manufacturing sector, but only 10% when benefits include all components of the private business sector. While one might question the magnitudes of these estimated excess supplies of public infrastructure capital (and we certainly view these estimates with considerable caution), we are heartened that their relative sizes in the manufacturing and the entire private business sector are for the most part consistent with prior expectations.

To this point we have only considered value-added measures of output. As we noted in Section IV, when gross output becomes the measure of output, variable inputs include not only L , but also E , M and K_p . In this case the benefits of infrastructure capital are larger than simply labor savings, for they include the entire reduction in variable costs. Recall that in Section IV we discussed a gross output specification in which all private inputs (L ,

E, M and K_p) were considered variable -- a specification we called a total (private) cost function.

Table 5

Maximum Likelihood Estimates of Gross Output Total Cost Function
Swedish Manufacturing, 1960-88
(Absolute Value of Ratio of Parameter Estimate to Asymptotic
Standard Error in Parentheses)

<u>Parameter</u>	<u>Estimate</u>	<u>Parameter</u>	<u>Estimate</u>	<u>Parameter</u>	<u>Estimate</u>
β_L	- 0.191E-3 (2.71)	β_{LE}	- 0.277E-2 (6.47)	β_{Lt}	0.670E-3 (0.20)
β_E	0.779E-3 (1.21)	β_{LM}	0.630E-2 (2.23)	β_{Et}	- 0.013 (3.88)
β_M	- 0.458E-3 (4.38)	β_{LP}	- 0.317E-2 (0.94)	β_{Mt}	0.014 (1.79)
β_P	- 0.533E-4 (6.50)	β_{EM}	- 0.012 (8.29)	β_{Pt}	0.036 (1.89)
β_1	0.151 (4.54)	β_{EP}	0.084 (3.70)	β_{tQ}	- 0.215E-5 (0.69)
β_{11}	0.768E-4 (1.16)	β_{MP}	0.674E-2 (0.09)	β_{1t}	0.181E-2 (0.57)
β_{LL}	0.162 (4.05)	β_{1L}	- 0.265 (3.66)	β_{QQ}	0.101E-6 (3.20)
β_{EE}	- 0.056 (1.17)	β_{1E}	- 0.071 (0.88)	β_t	-0.101E-4 (1.25)
β_{MM}	0.837 (11.91)	β_{1M}	- 0.229 (2.26)		
β_{PP}	- 0.542 (1.65)	β_{1P}	1.074 (3.89)	$\ln L$	- - 1130.41

Using annual manufacturing data for Sweden from 1960 to 1988, we have estimated by maximum likelihood parameters of the total cost function (22), the K_p demand equation (23), and corresponding demand equations for L, E and M. Parameter estimates from this model are reported in Table 5 above.

Although it is difficult to interpret parameter estimates directly, all but six of the estimated 28 parameters are larger in absolute value than their estimated asymptotic standard errors. In terms of returns to scale, the restrictions corresponding with constant returns to scale over all inputs (Meade's unpaid factors model) are decisively rejected; the likelihood ratio test statistic is 85.5, while the 0.01 χ^2 critical value with seven degrees of freedom is 18.5; similarly, the null hypothesis of constant returns to scale over private inputs only is also rejected decisively, for the test statistic is 139.9, while the 0.01 χ^2 critical value with twelve degrees of freedom is 26.2.

The parameter estimates in Table 5 can be employed to compute various elasticities and shadow value relationships. In 1975, the approximate midpoint of the sample, the short-run elasticities of demand for variable inputs with respect to changes in the quantity of K_i capital are estimated to be -0.60 for L, 0.02 for M, 1.39 for E and 0.86 for K_p . Using (13), we have also computed the amount of K_i capital rationalized by the cost savings accruing to the manufacturing sector, called K_i^* , and divided it by the actual K_i value; the ratio of optimal to actual K_i capital is presented in Table 6 below, as are corresponding ratios for K_p capital, which in this case is assumed to be a variable input.

As in seen in Table 6, for the private capital input K_p , the ratio of optimal to actual K_p is on average about unity, and it has a U-shaped time trend, above unity at the beginning of the sample, a minimum value of 0.037 in 1978, and then it rises at the end of the sample. This U-shaped pattern implies of course an autocorrelated residual, which in turn might reflect a misspecification in treating K_p as a variable rather than a quasi-fixed input.

Table 6

Ratios of Optimal to Actual Capital Stocks, Gross Output Total Cost Model
Manufacturing Sector Only, Sweden, 1960-88

<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$	<u>Year</u>	$\frac{K_p^*}{K_p}$	$\frac{K_i^*}{K_i}$
1960	1.109	1.025	1975	0.994	0.852
1961	1.085	1.023	1976	0.999	0.824
1962	1.085	1.001	1977	0.950	0.760
1963	1.079	0.978	1978	0.937	0.746
1964	1.090	0.987	1979	0.975	0.783
1965	1.090	0.997	1980	0.966	0.777
1966	1.061	0.974	1981	0.941	0.743
1967	1.041	0.955	1982	0.950	0.736
1968	1.010	0.953	1983	0.989	0.766
1969	1.012	0.967	1984	1.031	0.798
1970	1.016	0.966	1985	1.045	0.799
1971	0.993	0.933	1986	1.079	0.787
1972	0.993	0.918	1987	1.091	0.777
1973	1.009	0.922	1988	1.095	0.749
1974	1.024	0.910			

For public infrastructure capital K_i , the time trend of optimal to actual K_i is generally decreasing over time until about 1982, having a high value of 1.025 in 1960, a minimal value of 0.736 in 1982, and then wiggling a bit, ending up at 0.749 in 1988. For the 1980's, the level of optimal to actual K_i from this total cost gross output model is surprisingly similar to that obtained using the value added specification (see Table 4); in both cases, the time trend indicates that viewed from the vantage of cost savings accruing only to the manufacturing sector, the amount of excess public infrastructure capital has decreased.

VII. Concluding Remarks

Our purpose in this paper has been to discuss alternative frameworks for evaluating and measuring the contribution of public infrastructure capital in Sweden on private sector output and productivity growth. We have reviewed the theoretical and empirical models developed by Aschauer and by Munnell, who have implemented them empirically using U.S. data. In our judgment, these Cobb-Douglas production function models have a number of serious drawbacks. When these models are estimated using Swedish data for the entire private business sector and for the manufacturing sector, we obtain coefficient estimates on public infrastructure capital that are statistically different from zero, but do not make much sense.

We then implemented a number of dual cost function models, and found that results were more plausible. In particular, although in each of the Cobb-Douglas production and dual cost function models the constraints of constant returns to scale over all inputs (Meade's unpaid factors model) are rejected, as are the restrictions implied by constant returns to scale over private inputs only (Meade's atmosphere model), we find that increases in public infrastructure capital, ceteris paribus, reduce private costs. We have computed that amount of public infrastructure capital that would rationalize the cost savings incurred by the private business and manufacturing sectors, and find that the amount that can be rationalized in this manner is less than what is in fact available in 1988, but that the extent of excess public infrastructure has been falling in the 1980's.

In interpreting these findings, we wish to offer several concluding remarks. First, the benefits we have estimated are those only realized by the private business sector (in some cases, the manufacturing sector), and do not

incorporate the cost and time savings of public infrastructure capital enjoyed by final consumers. Second, our estimates of the cost of capital need further work, not only to incorporate the effects of taxes²², but also in assessing the sensitivity of our findings to alternative choices of the discount rate for public projects.²³ Third, in some preliminary analyses we have not been able to obtain satisfactory results for a dynamic gross output model in the manufacturing sector when private capital is a quasi-fixed input; further research on this type of model could be very useful. Fourth, although our model is already a bit rich in parameters given the sample size, it would seem worthwhile investigating whether results could be sharpened when public infrastructure capital is disaggregated, say, into roads and highways, other transportation-related infrastructure capital, and all other public infrastructure capital. Finally, although our analysis has focused on implications for cost savings to the private sector of changes in public infrastructure capital stock, we have neglected entirely any discussion of the optimal pricing of such "public" or "near-public" goods; as Clifford Winston [1991] has recently emphasized, this too is an important and closely related issue.

FOOTNOTES

¹For other recent discussions, see Charles R. Hulten and Robert M. Schwab [1991], Catherine J. Morrison and Amy E. Schwartz [1991], John A. Tatom [1991], and Dale W. Jorgenson [1991].

²This issue has also been of considerable interest recently in the policy arena. See, for example, Svenska Vägforeningen [1990].

³For references, see the citations in Alicia Munnell [1990a,b], Keven T. Deno [1988], Jacob De Rooy [1978] and Koichi Mera [1973]. For a more general discussion, see W. Erwin Diewert [1980, 1986].

⁴Yet another notion of external economies involving spillovers among private sectors has been considered by Ricardo J. Caballero and Richard K. Lyons [1989].

⁵For important studies in this context, see Robert E. Hall [1988a,b], Paul Romer [1986] and Catherine J. Morrison [1989].

⁶Aschauer's estimated productivity equation (3) has the form

$$\ln A = -0.72 - 0.36 \cdot \ln L - 0.09 \cdot \ln K_p + 0.34 \cdot (\ln K_1 - \ln K_p)$$

(1.39) (3.82) (0.98) (9.20)

$$+ 0.45 \cdot \ln CU + 0.10 \cdot t \quad R^2 = 0.998, \quad SER = 0.0079$$

(11.15) (4.75) DW = 1.73

which indicates that increases in $\ln K_1$, *ceteris paribus*, have a strong and significant positive impact on multifactor productivity.

⁷Interestingly, although Aschauer considers the simultaneous equations bias issue, he focuses on the correlation of K_1 with the equation disturbance term, which could occur if current government spending "surprises" affected both Q and K_1 . Aschauer re-estimates his equations by two-stage least squares using lagged K_1 as an instrument, and finds his results are essentially the same as those obtained by OLS.

⁸For a review of recent developments in the econometric implementation of models of cost and production, see Berndt [1991], especially chapter 9, "Modeling the Interrelated Demands for Factors of Production: Estimation and Inference in Equation Systems".

⁹In private conversations with Jan Sodersten, we have learned that in many cases, assuming the marginal corporate tax rate is zero may well be a realistic assumption.

¹⁰For a discussion of measurement issues involved in constructing capital stocks, see, among others, Berndt [1991], especially chapter 6, section 1, "Investment and Capital Stock: Definitions and General Framework."

¹¹The private business sector is an aggregate of agriculture, mining, manufacturing, construction, wholesale and retail trade, restaurants and hospitals, parking and leasing, other passenger land transport, freight transport by road, water transport, supporting services to land transport, post office services, telecommunications, financial institutions, insurance and letting of other premises, business services and personal services.

¹²See Hausman [1978] for an elaboration on this test.

¹³The data begin in 1964 rather than 1960 since time series on CU in Sweden are not available before 1964.

¹⁴The returns to scale restriction in Meade's atmosphere (constant returns to scale in private inputs K_p and L) specification is decisively rejected, for the χ^2 test statistic with 1 degree of freedom is 24.1468, much larger than the critical value at any reasonable level of significance. Similarly, Meade's unpaid factor (constant returns to scale in all inputs) model is also rejected, for the χ^2 test statistic with 1 degree of freedom is 16.1924, which also is larger than the critical value at usual significance levels. Finally, since the Durbin-Watson test statistic was in the inconclusive region, we estimated this equation using the maximum likelihood procedure with an AR(1) stochastic disturbance specification. The unsatisfactory results remained. Specifically, the coefficients (absolute values of t-statistics) on $\ln L$, $\ln K_p$ and $\ln K_i$ were, respectively, 0.856 (3.05), -1.402 (4.23) and 1.278 (3.77).

¹⁵When $\ln K_i$ was excluded entirely as an input, the estimated returns to scale fell to 0.773.

¹⁶The results we obtained were much more reasonable when $\ln CU$ was employed rather than CU .

¹⁷With $\ln K_i$ is excluded entirely, the estimated returns to scale fall drastically to 0.484.

¹⁸Results deteriorate further when an AR(1) model is estimated.

¹⁹The instruments used in the first-stage regression of 2SLS include in addition to the constant term, t , K_p , and K_i , real gross domestic product in Europe, real gross domestic product in the US, the 5-year Swedish government bond yield, total hours worked in the local government sector, and total hours worked in the central government sector, as well as nonlinear transforms of these variables.

²⁰Note that these substitutability, complementarity relationships are similar to those reported by Munnell [1990b], based on the translog production function.

²¹One can also compute the elasticity of private sector multifactor productivity growth with respect to changes in the stock in public infrastructure capital; this elasticity varies by year, and in our sample it ranges from a low of 0.058 in 1960 to a high of 0.171 in 1985; in 1988, the last year of our sample, this elasticity was 0.149, very similar to the 0.15 elasticity reported by Munnell [1990b] in her pooled cross-section, time series estimation using US data by state.

²²On this, however, see footnote 9.

²³There is a very large literature on this issue. For a recent discussion, see Robert C. Lind [1982].

REFERENCES

- Aschauer, David A. [1989], "Is Public Expenditure Productive?", Journal of Monetary Economics, 23:2, 177-200.
- Berndt, Ernst R. [1990], The Practice of Econometrics: Classic and Contemporary, Reading, MA: Addison-Wesley Publishing Company.
- Caballero, Ricardo J. and Richard K. Lyons [1989], "The Role of External Economies in U.S. Manufacturing," Cambridge, MA: National Bureau of Economic Research, Working Paper No. 3033, July.
- Deno, Kevin T. [1988], "The Effect of Public Capital on U.S. Manufacturing Activity: 1970 to 1978," Southern Economic Journal, 55:2, 400-411.
- DeRooy, Jacob [1978], "Productivity of Social Overhead Capital: North-South Comparisons," Review of Business and Economic Research, 14:1, 44-60.
- Diewert, W. Erwin [1986], The Measurement of the Economic Benefits of Infrastructure Services, Lecture Notes in Economics and Mathematical Systems No. 278, Berlin: Springer-Verlag.
- Diewert, W. Erwin [1980], "Aggregation Problems in the Measurement of Capital," Chapter 8 in Dan Usher, ed., The Measurement of Capital, Chicago: University of Chicago Press for the National Bureau of Economic Research, 433-528.
- Diewert, W. Erwin [1974], "Applications of Duality Theory," in Michael D. Intriligator and David A. Kendrick, eds., Frontiers of Quantitative Economics, Vol. 2, Amsterdam: North-Holland, 106-171.
- Hall, Robert E. [1988a], "The Relation Between Price and Marginal Cost in U.S. Industry," Journal of Political Economy, 96:5, October, 921-947.
- Hall, Robert E. [1988b], "Increasing Returns: Theory and Measurement with Industry Data," unpublished paper, prepared for the National Bureau of Economic Research Program on Economic Fluctuations, October.
- Hansson, Bengt [1991a], "The Rate of Technical Change in Swedish Manufacturing," chapter 2 in draft Ph.D. dissertation, Uppsala University, Department of Economics, March.
- Hansson, Bengt [1991b], "Productivity Measurement Under Imperfect Competition and with Varying Degrees of Capacity Utilization," chapter 3 in draft Ph.D. dissertation, Uppsala University, Department of Economics, March.
- Hansson, Bengt [1991c], "Construction of Swedish Capital Stocks, 1963-1988: An Application of the Hulten-Wyckoff Studies," chapter 4 in draft Ph.D. dissertation, Uppsala University, Department of Economics, March.
- Hausman, Jerry A. [1978], "Specification Tests in Econometrics," Econometrica, 46:6, November, 1251-1272.

- Hulten, Charles R. and Robert M. Schwab [1991], "Public Capital Formation and the Growth of Regional Manufacturing Industries," College Park, MD: University of Maryland, unpublished working paper, March.
- Hulten, Charles R. and Frank C. Wykoff [1981], "The Estimation of Economic Depreciation Using Vintage Asset Prices: An Application of the Box-Cox Power Transformation," Journal of Econometrics, 15:3, August, 367-396.
- Hulten, Charles R. and Frank C. Wykoff [1980], "Economic Depreciation and the Taxation of Structures in U.S. Manufacturing Industries: An Empirical Analysis," ch. 2 in Dan Usher, ed., The Measurement of Capital, Chicago: University of Chicago Press for the National Bureau of Economic Research, 83-109.
- Jorgenson, Dale W. [1991], "Fragile Statistical Foundations: The Macroeconomics of Public Infrastructure Investment -- Comment on Hulten and Schwab," Harvard University, xerolith.
- Jorgenson, Dale W. [1986], "Econometric Methods for Modeling Producer Behavior," in Zvi Griliches and Michael D. Intriligator, eds., Handbook of Econometrics, Vol. 3, Amsterdam: North-Holland, 1841-1915.
- Lind, Robert C. [1982], "Introduction," in Robert C. Lind, ed., Discounting for Time and Risk in Energy Policy, Baltimore: Johns Hopkins University Press.
- Meade, James E. [1952], "External Economies and Diseconomies in a Competitive Situation," Economic Journal, 62, March, 54-67.
- Mera, Koichi [1973], "Regional Production Functions and Social Overhead Capital: An Analysis of the Japanese Case," Regional and Urban Economics, 3:2, 157-185.
- Morrison, Catherine J. and Amy E. Schwartz [1991], "State Infrastructure and Productive Performance," paper presented at the 1991 NBER Summer Institute, Cambridge, MA, July.
- Morrison, Catherine J. [1989], "Unraveling the Productivity Growth Slowdown in the U.S., Canada and Japan: The Effects of Subequilibrium, Scale Economies and Markups," Cambridge, MA: National Bureau of Economic Research, Working Paper No. 2993, June.
- Munnell, Alicia H. [1990a], "Why Has Productivity Growth Declined? Productivity and Public Investment," New England Economic Review, Federal Reserve Bank of Boston, January/February, 3-22.
- Munnell, Alicia H. [1990b], "How Does Public Infrastructure Affect Regional Economic Performance?", Boston: New England Economic Review, Federal Reserve Bank of Boston, September/October, 11-32.
- Romer, Paul [1986], "Increasing Returns and Long-Run Growth," Journal of Political Economy, 94:5, October, 1002-1037.

Samuelson, Paul A. [1953], "Prices of Factors and Goods in General Equilibrium," Review of Economic Studies, 21, October, 1-20.

Schultze, Charles E. [1990], "The Federal Budget and the Nation's Economic Health," in Henry J. Aaron, ed., Setting National Priorities: Policy for the Nineties, Washington, DC: The Brookings Institution.

Stiglitz, Joseph E. [1988], Economics of the Public Sector, Second Edition, New York: W. W. Norton & Co., Inc.

Tatom, John A. [1991], "Public Capital and Private Sector Performance," Federal Reserve Bank of St. Louis Review, 73:3, May/June, 3-15.

Winston, Clifford [1991], "Efficient Transportation Infrastructure Policy," Journal of Economic Perspectives, 5:1, Winter, 113-127.

Government Publications:

"Vägsystemet, produktivitet och inkomster," Stockholm: Svenska Vägförbundet, October 1990.

Table A-1

Capital Stock Estimates for Sweden, 1960-1988
Millions of Swedish Kroner in 1985 Prices

<u>Year</u>	<u>Private Business Sector - Total</u>	<u>Private - Mfg Sector Only</u>	<u>Public Core Infrastructure</u>	<u>Public Core but Excluding Elec.</u>
1960	284984	120615	173297	96632
1961	298348	127141	183550	103813
1962	314931	136376	191797	109045
1963	333219	145820	199500	114439
1964	352779	154460	208479	121150
1965	372624	160817	217793	127546
1966	392720	168487	226871	134122
1967	414027	177166	236142	141017
1968	431595	185052	249357	151431
1969	446605	192073	258402	158977
1970	464022	200231	266760	164917
1971	482777	208743	275250	170028
1972	498652	216306	282108	173318
1973	516394	224123	290808	177615
1974	538471	234473	297530	180515
1975	565474	247047	304837	183516
1976	590937	258217	310347	184527
1977	614495	268753	317334	186327
1978	628491	271700	323503	187371
1979	631312	269355	326937	187464
1980	641328	268415	328151	187085
1981	661112	272391	330711	186328
1982	672306	274157	332923	183989
1983	681728	271939	337471	182571
1984	695476	270904	342773	181689
1985	714878	273613	347606	181187
1986	748615	284016	350233	179494
1987	778376	293095	353995	180979
1988	816769	305794	355170	181407