How Does Public Infrastructure Affect Regional Economic Performance?

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Bridge collapses and water main explosions focus national attention on the crumbling condition of the nation's infrastructure. Catastrophic infrastructure failures are always a momentary spur to debate on the nation's capital investment policies. But increasingly these negative developments have been accompanied by economists' claims that public capital investment makes a significant contribution to national output, productivity, growth, and international competitiveness.

These conclusions, which emerge from the work of Aschauer and others, have generally been based on observed patterns of national and international spending on public capital and various measures of economic performance. Reaction to these claims has been cautious; critics have charged that the empirical work overstates the impact on productivity by ignoring other factors, that the direction of causation between public investment and output growth is unclear, and that even if the historical empirical relationships were estimated correctly, they provide no clear indications for current policy.

This paper is not designed to answer all the criticisms but rather to offer one more brush stroke to the emerging picture of the relationship between public capital investment and private economic activity. It does this by exploring the impact of public capital on output, employment growth, and private investment at the state and regional level. The

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paper consists of four parts. Since no comprehensive measures of public or private capital are available at the state level, the first section explains the construction of such data and describes the distribution of these wealth measures by state and region. The second section uses these data to estimate an aggregate production function, in order to see whether the positive relationship between output and public capital, which has been documented at the national level, holds up for individual states and regions. The third section moves from the steady state to the adjustment process and explores the relationship between public investment and private investment, attempting to determine the direction and magnitude of the effect. Finally, the fourth section introduces the public capital data into a firm location model in order to see whether variations in public capital by state have had any impact on state-by-state employment growth.

The conclusion is that those states that have invested more in infrastructure tend to have greater output, more private investment, and more employment growth. This evidence supports results found in earlier studies. The empirical work also seems to indicate that public investment comes before the pickup in economic activity and serves as a base, but much more work is required to spell out the specifics of the link between public capital and economic performance.

Public and Private Wealth by State and Region

The U.S. Bureau of Economic Analysis (BEA) publishes annual data from 1925 to the present on the stock of private and public tangible wealth; these data include equipment and structures, but exclude land inventories and rental residential real estate. Despite the availability of public capital data, until recently this kind of input had been virtually ignored in the analysis of national production and growth. The oversight is difficult to explain, since the stock of public capital is not small. As shown in Table 1, in 1988 public capital amounted to almost $2.5 trillion, compared to $4.4 trillion in the private sector. Even ignoring investments devoted to military purposes, the stock of public capital amounted to $2.0 trillion, or 46 percent of the value of the stock of private capital.

Most of the $2.0 trillion of nonmilitary public capital consists of assets owned by state and local governments. Highways and streets account for 39 percent of the total state and local wealth, and water and sewer systems for another 16 percent; buildings (primarily schools and hospitals), other structures, and equipment make up the rest (Table 2).

No data are available on the stock of private or public capital on a state-by-state basis. Hence, it was necessary to devise some way of

Table 1
Private and Public Nonresidential Net Capital Stock, 1988

Capital Stock[a]	Billions of Dollars	Percent of Total
Total	6846.4	100
Total Private	4364.8	64
Nonfarm business	4202.3	61
Farm	162.5	2
Total Public	2481.6	36
Military	490.9	7
Nonmilitary	1990.7	29
Federal	272.2	4
State and Local	1718.5	25

Note: Numbers may not add to totals because of rounding.
[a]Figures include equipment and structures only. Land, inventories, and rental residential capital are excluded.
Source: U.S. Bureau of Economic Analysis, unpublished data.

dividing up the national totals published by the BEA. In the case of public capital, the approach taken was to create a state capital series based on annual state public investment data and BEA depreciation and discard schedules, and use this distribution of capital to apportion the BEA public capital totals. In the case of private capital, state investment data (except for manufacturing) were not available, so the approach followed was to apportion the BEA total on the basis of various measures of each state's activity in agriculture, manufacturing, and nonmanufacturing (see Appendix A).

Table 2
State and Local Fixed Nonresidential Net Capital Stock by Type of Asset, 1988

Capital Stock	Billions of Dollars	Percent of Total
Highways and Streets	670.7	39.0
Water and Sewer Systems	265.7	15.5
Buildings and Other Structures		
Schools, Hospitals and Other Buildings	514.2	29.9
Conservation and Development Structures	29.3	1.7
Miscellaneous	126.7	7.4
Equipment	111.8	6.5
Total	1718.5	100.0

Note: Numbers may not add to totals because of rounding.
Source: U.S. Bureau of Economic Analysis, unpublished data.

Table 3
Stocks of Public and Private Capital by Region, 1988

Region	Public Capital		Private Capital		Ratio of Private to Public Capital
	Per Capita (Dollars)	Percent of Total	Per Capita (Dollars)	Percent of Total	
Northeast					
New England	5,953	4.9	13,748	4.4	2.3
Mid Atlantic	7,193	17.1	13,829	12.9	1.9
North Central					
East North Central	6,205	16.5	15,866	16.6	2.6
West North Central	7,501	8.4	18,455	8.1	2.5
South					
South Atlantic	5,788	15.3	14,520	15.1	2.5
East South Central	6,106	5.9	16,080	6.1	2.6
West South Central	6,330	10.7	25,165[a]	16.8	4.0
West					
Mountain	7,679	6.5	19,603	6.5	2.5
Pacific	6,573	14.8	15,256	13.5	2.3
Continental United States	6,509	100.0	16,551	100.0	2.5
Addendum					
Total Capital[b] (Billions of Dollars)	1,585.5		4,031.4		

[a]The high per capita private capital figure for the West South Central region is the result of a very large share of the nation's manufacturing and mining capital being allocated to Louisiana and Texas. The mining is understandable, since this sector consists largely of oil and gas production. Louisiana and Texas account for almost half of the nation's production of oil and gas, and oil and gas are extremely capital-intensive industries. The manufacturing capital is more difficult to explain, since the shares of manufacturing capital allocated to Louisiana and Texas are almost twice their shares of national value added by manufacturing industries. The main explanation appears to be the high ratio of capital to value added for the specific manufacturing industries located in these states. For example, both Louisiana and Texas are dominated by the petroleum and coal and the rubber and plastics industries; in 1985, these industries had a ratio of capital to value added of 1.37. This number was almost twice the ratio of capital to value added for the average of all the nation's manufacturing industries (.76). To ensure that these high private wealth figures were not distorting the results, separate equations were estimated for the remaining 46 states and the results were virtually unchanged.

[b]These totals differ from those shown in Table 1 for two reasons. First, they do not include Alaska, Hawaii, and District of Columbia. Second, the totals are beginning of year values, whereas the data in Table 1 represent end of year values.

Source: Author's calculations. See Appendix A.

The results of this estimation procedure are presented in Table 3, which shows the per capita stocks of public and private capital by region for 1988 and the ratio of private to public wealth. Table 4 presents information about the growth in public and private capital for the periods 1970–80 and 1980–88. The most striking aspect of the data is that while all regions invested in both private enterprises and public infrastructure during the 1970s, only the South and West continued to add to public capital in the 1980s.

Table 4
Average Annual Rates of Growth in Public and Private Capital by Region, 1970–80, 1980–88
Percent

	Public Capital								Private Capital	
	1970–80				1980–88					
Region	Highways	Water & Sewer	Other	Total	Highways	Water & Sewer	Other	Total	1970–80	1980–88
Northeast	1.0	4.8	2.7	2.4	0	1.0	−.2	.1	2.8	2.7
New England	.5	5.2	3.3	2.3	−.2	1.2	0	.1	3.0	4.1
Mid Atlantic	1.2	4.7	2.6	2.4	.1	1.0	−.3	0	2.8	2.2
North Central	1.2	2.3	2.5	1.9	.2	1.3	−.2	.2	3.3	.9
East North Central	1.0	2.1	2.1	1.6	0	1.2	−.5	0	3.3	.8
West North Central	1.6	2.9	3.7	2.5	.6	1.3	.3	.6	3.5	1.1
South	2.2	3.8	3.8	3.1	1.1	2.9	2.0	1.8	3.9	2.8
South Atlantic	2.8	4.4	4.4	3.7	1.0	3.0	2.4	1.9	4.6	3.8
East South Central	1.9	3.3	2.6	2.3	.6	1.1	−.3	.3	4.3	1.8
West South Central	1.6	3.2	3.7	2.6	1.7	3.6	2.9	2.5	3.2	2.3
West	1.2	2.9	1.9	1.8	.5	2.3	1.7	1.4	4.1	3.9
Mountain	1.9	3.1	4.7	3.1	1.9	4.7	4.1	3.2	4.3	2.7
Pacific	.9	2.9	1.3	1.4	−.2	1.5	.9	.7	4.1	4.5
Continental United States	1.5	3.4	2.8	2.3	.6	1.9	.9	.9	3.6	2.5

Source: Author's calculations. See Appendix A.

This process of constructing state-by-state capital measures has produced 19 years of data for each of the 48 states in the continental United States; the question is whether it has produced any real information or whether, in effect, it has simply reproduced the relationships between aggregate inputs and outputs many times over. This is a particularly important question given that the procedure for constructing both private and public wealth involved apportioning national totals. Here the nature of the methodology is crucial; if the totals had been distributed to states, say, based on the national ratio of capital to labor, no new information would have been added.

This was not the approach; the share of public capital allocated to each state was based on actual state public investment data and the share of private capital was based on each state's involvement in specific types of economic activity. As a result, the data show significant variation; for example, the ratio of private to public capital, which averaged 2.5 for the nation, ranged in the 1988 state data from a low of 1.5 for New York to a high of 5.1 for Louisiana. Moreover, the rate of growth of public capital varied enormously by state both in the 1970s and particularly in the 1980s. For example, California, the state that ranked twelfth in the ratio of public capital to labor in 1970, had dropped to thirty-fourth place by 1986, and West Virginia, which ranked thirty-fifth in 1970, had risen to seventh place at the end of the period. In short, the individual observations appear to contain real information.

The Role of Public Capital in the Production Process

Several studies have examined public capital as an input in the production process. Aschauer (1989) introduced the obvious, but heretofore neglected, notion that the stock of public infrastructure as well as the stock of private capital may be a key to explaining the level of national output in the private sector. His results showed a strong relationship between output per unit of private capital and the stock of public capital; he also found a statistically significant relationship between the level of multifactor productivity and the stock of public capital. Munnell (1990), examining the labor productivity slowdown in the 1970s, found a similarly strong, statistically significant, relationship between the nation's stock of public capital and the level of labor productivity.

Studies at the subnational level have generally been constrained by the lack of wealth data. Nevertheless, several researchers have attempted to relate proxies for public capital to output. For example, Garcia-Mila and McGuire (1987) analyzed the effect of the stock of highways and educational expenditures (representing publicly provided human capital) on statewide production functions, and found that both had a significant positive effect on output.

Eberts (1986) has done similar work on a metropolitan area level. He created annual values of the public capital stock for each of 38 metropolitan areas and introduced them into a translog production function, with value added as output, hours of production and nonproduction workers as labor input, and private manufacturing capital stock as private capital. Eberts found that the public capital stock made a positive and statistically significant contribution to manufacturing output, but that its output elasticity was quite small (0.03).

A few researchers have examined the relationship between the growth, as opposed to the level, of output and public infrastructure; the results have been mixed. For example, Hulten and Schwab (1984) explored whether the national productivity slowdown could be attributed to a decline in economic efficiency in the Snowbelt relative to the Sunbelt, due to aging infrastructure and a deteriorating capital stock.

They disaggregated the growth in manufacturing value added for the nine Census regions into its components, and found that regional variation in output growth was not due to differences in productivity growth but rather to variations in the rate of growth of capital and labor. This evidence appeared to leave no role for variations in public infrastructure in determining regional differences in output growth.[1]

On the other hand, Aschauer (1990) recently completed a paper examining the relationship between income growth and highway capacity using state data. He found that highway capacity and pavement quality had significant positive effects on income growth and that these effects were relatively stable across regions.

The following analysis builds on this earlier work and treats public capital as an input whose services enhance the productivity of both capital and labor. Hence, public capital becomes another input in the production function and the equation looks as follows:

$$Q = MFP * f(K,L,G), \tag{1}$$

where Q is output, MFP is the level of technology, K is the private capital stock, L is labor and G is the stock of public capital. Assuming a generalized Cobb-Douglas form of technology yields a more specific relationship between inputs and outputs:

$$Q = MFP * K^a L^b G^c. \tag{2}$$

Translating this equation into logarithms produces a linear function that can be estimated:[2]

$$\ln Q = \ln MFP + a\ln K + b\ln L + c\ln G. \tag{3}$$

[1] The problem with this interpretation is that no measure of infrastructure is included in the equation and total factor productivity is calculated as a residual. If public capital is a legitimate input, then omitting it from the equation produces a biased estimated of multifactor productivity. See Munnell (1990).

[2] The productivity component can also be specified in a fashion that yields a time trend when the equation is translated into logarithms. Specifically, if $Q = MFPe^{\lambda t}K^aL^bG^c$, then $\ln Q = \ln MFP + gt + a\ln K + b\ln L + c\ln G$. Since equations with the time trend differed little from the simpler version described in the text, the results were not generally reported. This is confirmed by comparing Equation 3 from Table 5 and the same equation including the time trend.

	lnMFP +	λt +	alnK +	blnL +	clnG +	dU%
Eq. 3	5.75		.31	.59	.15	−.007
	(39.7)		(30.1)	(43.2)	(9.0)	(4.7)
Eq. 3′	5.70	.002	.30	.59	.17	−.008
	(39.3)	(2.7)	(28.9)	(42.6)	(9.4)	(5.4)

The coefficients a, b, and c are the output elasticities of the factor inputs. In other words, the coefficients indicate the percentage change in output for a given percentage change in factor input. In production functions without public capital, making some further assumptions about factor markets and the nature of the production function allows the coefficients to be defined more precisely. Specifically, if factor markets are assumed to be perfectly competitive, so that factors are paid their marginal product, and if the production function exhibits constant returns to scale, so that a 10 percent increase in capital and labor leads to a 10 percent increase in output, then the coefficients equal the relative share of total income paid to capital and labor respectively. In the United States the relative shares of national income have been quite stable over many decades, with 35 percent of the total accruing to capital and 65 percent to labor.

While constant returns to scale over the private inputs has been the traditional assumption underlying most analysis of the Cobb-Douglas production function, the inclusion of public capital raises new questions about returns to scale. Given that increasing economies to scale play such an important role in determining the public provision of a good or service, one might be tempted to conclude that public capital in total may yield increasing returns to scale within the production function. Such a leap may be unwarranted, however. While a given highway may yield increasing returns to scale, the construction of an additional highway may not. Moreover, a doubling of the highway system would most certainly produce diminishing returns.

Given the uncertainty of the impact of public capital on returns to scale, several forms of the equation were estimated in addition to the original unconstrained equation. The first assumes that constant returns to scale holds only for the private inputs, but that the entire function shows increasing returns to scale. This assumption is captured by setting $a + b = 1$, so that the equation looks as follows:

$$\ln Q = \ln MFP + a(\ln K - \ln L) + \ln L + c\ln G. \tag{4}$$

The alternative is that constant returns to scale applies to the entire production function, so that $a + b + c = 1$. Imposing the second constraint produces the third equation:

$$\ln Q = \ln MFP + a(\ln K - \ln L) + \ln L + c(\ln G - \ln L). \tag{5}$$

The equations were estimated using pooled state output, capital and labor data for the period 1970 through 1986, the last year for which gross state product data were available. Labor is measured as total employment on nonagricultural payrolls from the Bureau of Labor

Table 5
Regression Results: Output as a Function of Private Capital (K), Labor (L), and Public Capital (G), 48 States, 1970–86

Equation for Output (lnQ)						$\bar{R}^2$	SE	DW
	Private Capital Only							
1) No Constraint:	lnMFP +	alnK	+ blnL +	dU%		.992	.092	2.0
	6.75	.36	.69	.006				
	(69.2)	(38.0)	(82.4)	(4.0)				
2) a + b = 1:	lnMFP	+a(lnK − lnL)+	lnL +	dU%		.990	.103	2.1
	7.32	.30	1.0*	−.002				
	(74.2)	(31.9)		(1.0)				
	Including Public Capital							
3) No Constraint:	lnMFP +	alnK	+ blnL +	clnG	+dU%	.993	.088	1.9
	5.75	.31	.59	.15	−.007			
	(39.7)	(30.1)	(43.2)	(9.0)	(4.7)			
4) a + b = 1:	lnMFP	+a(lnK − lnL)+	lnL +	clnG	+dU%	.992	.090	2.0
	6.33	.34	1.0*	.06	−.007			
	(59.6)	(39.6)		(15.9)	(4.6)			
5) a + b + c = 1:	lnMFP	+a(lnK − lnL)+	lnL	+c(lnG − lnL)	+dU%	.990	.102	2.0
	6.82	.27	1.0*	.08	−.002			
	(45.8)	(23.3)		(4.4)	(1.0)			

Note: Q = gross state product; MFP = the level of technology; K = private capital stock; L = employment on nonagricultural payrolls; G = stock of state and local public capital; and U% = state unemployment rate; t-statistics in parentheses.
*Constrained to equal 1.

Statistics. The public and private capital stocks are the data described in the first section. The unemployment rate is also included to reflect the cyclical nature of productivity. All dollar amounts used in the regressions are converted to 1982 dollars.

The regression results, which are summarized in Table 5, confirm, on the state level, that public capital has a significant positive impact on the level of output and does indeed belong in the production function. The first two equations show the estimated production functions without public capital; these equations look very sensible, with coefficients for capital and labor almost exactly in line with their shares of total income. When state and local public capital is added to the equation, it enters with a positive, statistically significant coefficient roughly half the size of that for private capital, and it reduces the standard error of the equation. The coefficient of 0.15 on public capital in equation 3 is noticeably smaller than the 0.35 estimated by Aschauer (1989) and Munnell (1990) in their analysis of national data. The number emerging from the state data implies that a 1 percent increase in public capital would raise output by 0.15 percent.

The equations also provide some information about returns to scale. The coefficients of the factor inputs sum to 1.05 in the unconstrained equation, implying slightly increasing returns to scale. Constraining the equation either to have constant returns over the private inputs $(a + b = 1)$ or over all inputs, both public and private, $(a + b + c = 1)$ slightly increases the standard error.

Since public capital is an unpaid factor of production, the question arises as to how the benefits accruing from its contribution to output are distributed. It appears that capital and labor each receive a share roughly proportional to their output elasticities. In other words, the unconstrained elasticities for capital and labor in equation 3 are 0.31 and 0.59, respectively; if the 0.15 contribution from output from public capital is divided up proportionately, the result is very close to the traditional 35/65 division of income between capital and labor.

The coefficient of public capital is also sensible in that it implies a reasonable marginal productivity for public capital and equality between the productivity of public and private capital. That is, the elasticity of private sector output with respect to public capital is roughly half that with respect to private capital, and the state and local public capital stock is approximately one-half the size of the private capital stock. With these proportions, the coefficients imply that a 1 unit increase in either public or private capital will increase output by 0.35 units.[3] This result is important since the high values implied for the marginal productivity of public capital in Aschauer's results have been the target of criticism (Schultze 1990, p. 63).

Further support for the reasonableness of the results can be gleaned by examining the impact of various components of public capital on output. Table 6 summarizes the regression results with public capital broken into highways and streets, water and sewer systems, and other structures and equipment. Disaggregating in this fashion has almost no impact on the private labor and capital coefficients, yet yields coefficients for the components of public capital in line with expectations. Specifi-

[3] In view of the importance of this number, it may be useful to report the calculation. The coefficient of each capital variable is the output elasticity, or the percentage change in output for a given percentage change in the input. In the case of public capital, this means that $0.15 = (\Delta Q/Q)/(\Delta G/G)$. Rewriting the equation in terms of marginal productivity produces $\Delta Q/\Delta G = 0.15(Q/G)$. In 1986, total gross state product (Q) was \$3,680 billion and total state and local capital (G) was \$1,595 billion. Substituting these values into the equation yields a marginal productivity of public capital of 0.35.

In the case of private capital, the relevant figures are 0.35 for the output elasticity and \$3,670 billion for private capital. Introducing these figures into the equation yields $\Delta Q/\Delta K = 0.35 \times 3{,}680/3{,}670 = 0.35$.

Table 6
Regression Results: Output as a Function of Private Capital (K), Labor (L), and Disaggregated Public Capital (H, WS, O), 48 States, 1970–86

Equation for Output (lnQ)							$\bar{R}^2$	SE	DW
			State-Local Capital						
lnMFP +	alnK +	blnL	+ clnH	+ dlnWS	+ elnO +	fU%			
5.72	.31	.55	.06	.12	.01	−.007	.993	.085	1.9
(42.0)	(28.1)	(35.4)	(3.8)	(9.6)	(.7)	(5.2)			

Note: Q = gross state product; MFP = the level of technology; K = private capital stock; L = employment on nonagricultural payrolls; H = stock of highways; WS = stock of water and sewer systems; O = other state and local public capital, primarily buildings; and U% = state unemployment rate; t-statistics in parentheses.

cally, the major impact on output from public capital comes from highways and water and sewer systems, while other public capital, which consists primarily of buildings such as schools and hospitals, has virtually no measurable impact on private production.

The lack of effect from schools and hospitals does not mean that government-provided educational and health services have no effect on productivity. One would expect a well-educated and healthy labor force to be more productive than one without such advantages. Rather, the results suggest that the stock of buildings devoted to, say, education may not be the best indicator of the quality of educational services; teachers' salaries, for example, might be a measure. Moreover, even if physical capital were a good measure of service quality, in a highly mobile society the state that provides the educational or health services may not be the one that reaps the benefits.

Finally, separate production functions were estimated for each of the four major regions of the country to see if the relationships were stable across the states (Table 7). The relationship between inputs and outputs appears to vary significantly from one region to another. The question is whether any story can be told that explains the regional variations in the coefficients on labor, private capital, and public capital.

One could argue that the large coefficient on labor for the Northeast, which indicates a high percentage change in output for a given percentage change in labor input, reflects the fact that the Northeast has a particularly well-educated, highly skilled labor force. At the same time, the relatively small coefficients on both the private and public capital in the Northeast may, in part, reflect the fact that this region has the lowest capital/labor ratio of any of the four; a relatively smaller amount of capital would imply a relatively smaller coefficient on capital in these equations, assuming the marginal productivity of capital is constant across the country. (These facts imply that the high wages earned by people in the Northeast are due to

Table 7
Regression Results: Output as a Function of Private Capital (K), Labor (L), and Public Capital (G), Four Regions, 1970–86

Equation for Output (lnQ)						$\bar{R}^2$	SE	DW
	Private Capital Only							
	lnMFP +	alnK +	blnL +	dU%				
Northeast	9.31	.11	.95	−.01		.997	.068	1.5
	(28.2)	(3.3)	(28.9)	(3.2)				
North Central	6.90	.34	.72	−.003		.998	.048	2.0
	(27.9)	(14.2)	(41.2)	(1.8)				
South	6.03	.42	.62	−.01		.983	.098	1.7
	(31.1)	(22.4)	(30.3)	(4.7)				
West	4.92	.54	.58	−.02		.997	.058	1.7
	(31.6)	(36.9)	(51.4)	(7.9)				
	Including Public Capital							
	lnMFP +	alnK +	blnL +	clnG +	dU%			
Northeast	8.83	.09	.90	.07	−.01	.997	.067	1.5
	(22.7)	(2.7)	(22.2)	(2.3)	(3.7)			
North Central	5.68	.34	.62	.12	−.004	.998	.046	2.0
	(15.8)	(15.1)	(22.3)	(4.5)	(2.6)			
South	3.15	.38	.36	.36	−.02	.988	.082	1.7
	(10.1)	(22.8)	(12.0)	(10.8)	(6.8)			
West	4.53	.51	.53	.08	−.02	.997	.056	2.0
	(23.4)	(28.0)	(28.7)	(3.2)	(8.4)			

Note: Q = gross state product; MFP = the level of technology; K = private capital stock; L = employment on nonagricultural payrolls; G = stock of state and local public capital; and U% = state unemployment rate; t-statistics in parentheses.

their intrinsic human capital rather than the amount of physical capital with which they have to work.)

The other surprising result pertains to the production functions for the South. This is the only region where the introduction of public capital significantly alters the coefficients on the private inputs. Once public capital is included in the equation, the coefficient on labor falls from 0.62 to 0.36; moreover, the coefficient on public capital itself is also very large (0.36). No obvious explanation leaps out; the only point that may be worth noting is that the South had the highest rate of public investment during the 1970s, and was virtually the only region that continued to increase its public capital stock in the 1980s.

In summary, estimates of production functions based on pooled cross-section state data for the period 1970–86 indicate that public capital contributes to private output. The coefficient on public capital implies that its marginal productivity is the same as that for private capital. The benefits of the contribution from public capital seem to be divided between private capital and labor in proportion to the elasticity of private sector output with respect to each input. Moreover, the components of public capital that one would expect to enhance private output—namely, highways and streets, and water and sewer systems—are the ones that have the statistically important relationship; public buildings, such as schools and hospitals, appear to have no direct measurable impact. Finally, the relationship between public capital and output holds up on a regional basis, although more work is needed to explain some of the variation in the coefficients.

Public Capital and Private Investment

Another aspect of the role of public capital in the production process is its impact on private investment. In other words, the discussion in this section shifts from documenting a steady-state relationship to exploring the adjustment process. In this process, two opposing forces may be at work. On the one hand, public capital appears to enhance the productivity of private capital, thereby raising the rate of return and encouraging more private sector investment. On the other hand, public capital may serve as a substitute for private capital; to the extent this occurs, more public capital will result in less private investment.

Eberts and Fogarty (1987), in an effort to determine the effectiveness of public infrastructure as a local investment policy, employed the Sims test of "Granger causality" for a sample of 40 metropolitan areas using investment data from 1904 to 1978. They found a statistically significant positive relationship between public outlays and private investment in all but seven of the 40 cases. In those cities where a relationship existed, public capital investment appeared to influence private investment the majority of the time, but in a substantial number of cases the opposite was true and private investment appeared to precede public investment.

This section explores what can be learned from the state-by-state public and private capital data to supplement the scant existing evidence on the relationship between private investment and public capital. The investigation consists of three parts: the first involves restating the production function estimated earlier to demonstrate the significant positive impact of public capital on the marginal product of private capital; the second involves the estimation of a translog production function where interaction terms can indicate the extent to which public and private capital are complements or substitutes; and the third consists of an effort to estimate an investment function that summarizes the key relationships.

The simple Cobb-Douglas production function used earlier can be

Table 8
Regression Results: Productivity of Private Capital as a Function of Private Capital (K), Labor (L), and Public Capital (G), 48 States, 1970–86

Equation for Private Capital Productivity (lnQ − lnK)					$\bar{R}^2$	SE	DW
lnMFP +	(a − 1) lnK +	blnL +	clnG +	dU%			
5.75	−.69	.59	.15	−.007	.91	.088	1.9
(39.7)	(67.2)	(43.2)	(9.0)	(4.7)			

Note: Q = gross state product; MFP = the level of technology; K = private capital stock; L = employment on nonagricultural payrolls; G = stock of state and local public capital; and U% = state unemployment rate; t-statistics in parentheses.

rewritten so that the productivity of private capital is the dependent variable. That is,

$$Q/K = MFP * K^{(a-1)}L^{b}G^{c}. \quad (6)$$

Again, translating this equation into logarithms produces a linear function that can be estimated.

$$\ln Q - \ln K = \ln MFP + (a - 1)\ln K + b\ln L + c\ln G. \quad (7)$$

The results of estimating this equation are shown in Table 8. Not surprisingly, given that it is simply a rearrangement of the general equation, the relationships are the same as those already described. For the current discussion, the usefulness of the equation in this form is that it highlights the positive, statistically significant relationship between the productivity of private capital and the stock of public capital. Through this mechanism, the stock of public capital would be expected to encourage private investment.

The next step is to determine the nature of the relationship between public and private capital. Are they substitutes or complements in the production process? One way of addressing this issue is to estimate a translog production function; this nonlinear relationship between output and factor inputs includes cross-product terms, which indicate the substitutability or complementarity of the inputs. Variables are entered in the translog function as deviations from their means.

The results of the estimation process are presented in Table 9. The first set of coefficients for private capital, labor, and public capital are similar to those estimated in the simple Cobb-Douglas production function; as before, public capital has a positive impact on private sector output. The coefficients of the quadratic terms provide an indication of economies of scale for each of the factor inputs. The coefficients indicate

Table 9
Regression Results: Translog Production Function, 48 States, 1970–86

Equations for Output (lnQ): Including Aggregate Public Capital	Coefficient (t-Statistic)	Disaggregating Public Capital	Coefficient (t-Statistic)
$\ln K-\ln\overline{K}$	.22	$\ln K-\ln\overline{K}$	.21
	(18.9)		(16.1)
$\ln L-\ln\overline{L}$	.69	$\ln L-\ln\overline{L}$	.67
	(37.5)		(35.7)
$\ln G-\ln\overline{G}$	.16	$\ln H-\ln\overline{H}$	.04
	(9.1)		(2.7)
		$\ln WS-\ln\overline{WS}$	.15
			(10.9)
		$\ln O-\ln\overline{O}$	−.02
			(1.1)
$(\ln K-\ln\overline{K})^2$	.27	$(\ln K-\ln\overline{K})^2$	.27
	(11.7)		(10.3)
$(\ln L-\ln\overline{L})^2$	.13	$(\ln L-\ln\overline{L})^2$	.17
	(3.2)		(3.1)
$(\ln G-\ln\overline{G})^2$	.03	$(\ln H-\ln\overline{H})^2$	.02
	(0.5)		(0.3)
		$(\ln WS-\ln\overline{WS})^2$	.01
			(0.4)
		$(\ln O-\ln\overline{O})^2$	.09
			(3.9)
$(\ln K-\ln\overline{K})(\ln L-\ln\overline{L})$	−.39	$(\ln K-\ln\overline{K})(\ln L-\ln\overline{L})$	−.35
	(9.8)		(7.9)
$(\ln K-\ln\overline{K})(\ln G-\ln\overline{G})$	−.14	$(\ln K-\ln\overline{K})(\ln H-\ln\overline{H})$	−.10
	(2.1)		(1.6)
$(\ln L-\ln\overline{L})(\ln G-\ln\overline{G})$	.12	$(\ln K-\ln\overline{K})(\ln WS-\ln WS)$	.08
	(1.4)		(2.1)
		$(\ln K-\ln\overline{K})(\ln O-\ln\overline{O})$	−.20
			(4.4)
		$(\ln L-\ln\overline{L})(\ln H-\ln\overline{H})$	.11
			(2.0)
		$(\ln L-\ln\overline{L})(\ln WS-\ln WS)$	−.05
			(0.6)
		$(\ln L-\ln\overline{L})(\ln O-\ln\overline{O})$	−.04
			(0.8)
U%	−.006	U%	−.006
	(4.7)		(5.2)
intercept	11.0	intercept	11.0
	(1190.3)		(1168.1)
$\overline{R}^2$	.995	$\overline{R}^2$	.996
DW	1.7	DW	1.7

Note: Q = gross state product; K = private capital stock; L = employment on nonagricultural payrolls; G = stock of state and local public capital; H = stock of highways; WS = stock of water and sewer systems; O = other state and local capital, primarily buildings; and U% = state unemployment rate; t-statistics in parentheses.

slight increasing returns to scale for the private inputs, but constant returns to scale for public capital.

Information on substitutability or complementarity is provided by the coefficients of the cross-product terms. These estimates show a strong substitutability between private capital and labor, as expected, and a somewhat weaker degree of substitution between private capital and public capital. Labor and public capital appear to be complements, although the relationship is not statistically significant.

In an effort to gain more information about the nature of the substitutability between private and public capital, another translog production function was estimated with public capital disaggregated into highways and streets, water and sewer facilities, and other public capital. As before, the results indicate that most of the impact of public capital on private production comes from water and sewer systems and, to a lesser extent, from highways; other public capital has no measurable impact. As in the equation with aggregate public capital, the quadratic terms indicate that none of the components of public capital exhibit increasing or decreasing returns to scale.

The coefficients of the cross-product terms of private capital and the components of public capital are completely in line with one's intuition. Highways and streets appear to be substitutes for private capital; this seems quite reasonable in that smooth, well-maintained roads will reduce the wear and tear on commercial vehicles. Moreover, private employers or developers may sometimes be required to build their own access roads. Water and sewer facilities are strong complements to private capital; these inputs are generally publicly provided and clearly augment private production. On the other hand, other public capital is a direct substitute. As noted before, this residual consists primarily of hospitals and schools, both of which have private sector counterparts; it also consists of power plants, which are definitely part of the private sector in some states.

Thus, public capital, as hypothesized, has the potential for either encouraging or discouraging private sector investment. One attempt was made to combine these two influences into the simplest possible model of investment. Specifically, the production function indicates that the desired stock of capital ($\overline{K}$) is positively related to the level of output (Q), the supply of labor (L) and the stock of public capital (G). At the same time, the desired stock is positively related to the marginal productivity of capital (MPK) relative to the cost of capital. Assuming the cost of capital is constant, the desired stock can be expressed as

$$\overline{K} = f(Q, L, G, MPK). \tag{8}$$

The simple Cobb-Douglas production function suggests that the marginal product of capital can be expressed as a function of the logarithms of private capital, labor, and public capital:

$$MPK = \ln MFP + (a - 1)\ln K + b\ln L + c\ln G. \tag{9}$$

This means that

$$\overline{K} = \ln MFP + (a - 1)\ln K + b\ln L + c\ln G + dQ + eL + fG. \tag{10}$$

A stock adjustment approach was taken, whereby investment in a given year partially closes the gap between the desired and the existing stock of capital; that is,

$$K_t - K_{t-1} = \alpha(\overline{K} - K_{t-1}). \tag{11}$$

Introducing the described specification of the desired capital stock into the stock adjustment model yields

$$K_t - K_{t-1} = \alpha(\ln MFP + (a - 1)\ln K + b\ln L + c\ln G + dQ + eL + fG - K_{t-1}). \tag{12}$$

The results of estimating this equation are shown in Table 10.[4] (In addition to the traditional coefficients and t-statistics, Table 10 includes beta coefficients; these coefficients, which standardize for the magnitude of the individual variables, provide a better indication of the relative importance of the various factors in explaining private investment.) The signs of the coefficients on public capital are as predicted. As one of the variables that determine the marginal productivity of private capital, public capital enters the equation with a positive coefficient. (Unfortunately, the signs on the other variables representing the marginal productivity of capital are reversed; the logarithm of private capital should be negative and the log of labor, positive.) Thus, public capital appears to stimulate private investment through its influence on the productivity of private capital. On the other hand, the stock of public capital has a negative, statistically significant effect on private investment. Given that private and public capital are substitutes, an increase

[4] In estimating the equation, it is necessary to use lagged values of the determinants of marginal productivity of capital, since these determinants include this period's capital stock—the dependent variable.

Table 10
Regression Results: Investment as a Function of the Marginal Productivity of Capital (MPK), Output (Q), Private Capital (K), Labor (L) and Public Capital (G), 48 States, 1975–86

Equation for $K_t - K_{t-1}$	Coefficient (t-Statistic)	Beta
Marginal Productivity of Capital		
lnK	199.7	.05
	(0.4)	
lnL	−853.1	−.23
	(1.2)	
lnG	959.9	.24
	(1.0)	
G	−.11	−.81
	(3.8)	
L	−861.6	−.44
	(1.1)	
$\sum_{i=0}^{4} Q$	.09	1.97
	(3.7)	
K_{t-1}	−.02	−.30
	(2.1)	
intercept	−10,641.0	
	(1.4)	
$\bar{R}^2$	.46	
DW	2.2	

Note: Q = gross state product; MFP = the level of technology; K = private capital stock; L = employment on nonagricultural payrolls; G = stock of state and local public capital; t-statistics in parentheses.

in the stock of public capital, all else equal, will reduce the required level of private capital and private investment.

It may be pushing these results too far, but it is hard to resist estimating the net effect of public capital on private investment. On the one hand, a 0.1 increase in the log of public capital implies a $96 billion increase in private investment. In dollar terms, 0.1 increase in the log is roughly equivalent to a 10 percent increase in the public capital stock, or $172 billion. From these numbers, $1 of additional public capital appears to increase private investment by 56 cents. On the other hand, the coefficient on last period's capital stock indicates that an additional $1 of public capital reduces private investment by 11 cents in that year (more in subsequent years). On balance, the equation suggests that each additional dollar of public capital appears to increase private investment by 45 cents.

The simple investment equation, however, can certainly be improved, so the results should be interpreted only as an invitation for future researchers to pursue this topic. The more robust results in the investment area are: 1) public capital positively affects the marginal productivity of private capital, and 2) public capital and private capital in the aggregate are substitutes. A careful estimation of the net effect of these two forces remains to be done.

Infrastructure and Firm Location

The third strand in the literature pertaining to infrastructure and economic activity focuses on the relationship between public capital and new business formation or employment growth. For, after all, to demonstrate a systematic relationship between public capital, output, and investment is only the first step; the challenge is to describe the mechanism through which public capital enters into the process.

Infrastructure could influence the location decisions of both firms and households. For example, high-quality roads, sewer systems, schools, and hospitals would be expected to encourage people to move to a given area; similarly, firms requiring large amounts of water in their production process, such as fabric dyeing, would be attracted, all else equal, to areas with water supply facilities that can meet their needs.

Although an enormous literature explores the factors entering the firm location decision, relatively little work has been done focusing on the role of infrastructure in that process.[5] A notable exception is a recent study by Eberts (1989), who examined the relationship between changes in metropolitan area capital stock and firm openings. He found statistically significant positive effects in the case of small businesses, with lesser impact on large firms. He also looked at changes in the public capital stock, but did not find a significant relationship between public investment and openings.

This section uses the state-by-state public capital data to see whether public infrastructure is important in explaining state variations in private economic development. At the state level, the best indicators of economic development and growth are employment trends; hence,

[5] Several studies have attempted to examine the impact of publicly provided services on firm location decision. Investigators commonly include a measure of spending on welfare, which may be perceived by firms as an "unwanted" public expenditure, as well as measures of spending on "wanted" public expenditures, such as education or police and fire protection. See Wasylenko and McGuire (1985), Plaut and Pluta (1983), Bartik (1989) and Helms (1985).

the empirical work examines the relationship between employment growth and public capital within the context of a firm location model.

The theoretical literature and empirical studies of firm location are heavily oriented toward the locational decisions of individual manufacturing firms. The theory assumes that firms want to maximize their after-tax profit, so the location decision is driven by the firm's profitability at alternative locations. Profits depend on the difference between sales and the costs of production. Sales, in turn, depend on the nature of the market. For a company making intermediate products, useful data include the number and size of potential purchasers of the intermediate product and the number and size of competitors. If the firm produces for the consumer market, then the number and income of potential customers at each location would be relevant. On the cost side, the most important factors are probably wages and the skill of the labor force, although land and energy costs are also relevant.

The equations estimated here include variables to capture both revenue and cost components of profitability. The specific form of the equation is based on the disequilibrium adjustment model, which is commonly used in cross-sectional studies of regional economic growth. In this model, the change in the dependent variable, in this case private nonagricultural employment, is related to levels of the explanatory variables at the beginning of the period. For example, the growth in employment between 1980 and 1988 will be related to revenue and cost measures in 1980.

Three explanatory variables are included in the equations to represent the labor market: the average hourly wage in manufacturing (WAGE), the state unemployment rate (U%), and the percent of the state's population with at least four years of college (COLL). Two additional variables are designed to measure energy costs: the cost per million BTUs of purchased fuels and electricity (ENERGY) and the normal daily maximum temperature in July (TEMP). Finally, population density (POP DENSITY) is included to capture the cost of land. On the sales side, the percent of the population residing in metropolitan areas (URBAN) was introduced to reflect the potential market. Since both firms and individuals are interested in after-tax income, a variable was included measuring total state and local taxes as a percent of state personal income (TAXES). Finally, the stock of public infrastructure (PUBLIC CAPITAL) was introduced to determine whether it had an independent direct effect, once these other economic determinants were taken into account. The regional values for most of these variables are summarized in Table 11, and the public capital data are shown in Table 3.

The regression results, which are shown in Table 12, are quite interesting and suggest that infrastructure does contribute towards a state's employment growth. Some general comments are required, however, before exploring the results in more detail. First, unlike the production function equations reported earlier, where the variables to be included are fairly well defined, the list of potential variables to explain state-by-state employment growth is limitless. For example, to estimate the effect of taxes on the growth in employment, one study employed five separate tax measures (Plaut and Pluta 1983). The goal of the exercise described below was to include only those independent variables whose presence would be viewed as essential by most observers.

Second, no matter how disciplined an investigator attempts to be, the temptation to try a number of different combinations or alternative measures is sometimes overwhelming. Since this part of the study involved some "fishing," the most useful way to proceed is to make all results available to the interested reader, report those that seem most persuasive, and then indicate what was learned from the process. One source of comfort is the fact that, while its statistical significance varies, the magnitude of the coefficient for public infrastructure remains virtually unchanged regardless of what modifications are made to the rest of the equation.

The first three equations in Table 12 are similar in approach; they vary only in the period spanned or the initial conditions. That is, the first equation explains employment growth over the 1970–88 period using 1970 values for wages, state unemployment rates, and so on; the second shortens the period of employment growth to 1970–80 but maintains the 1970 level for the independent variables; the third equation looks at employment growth over the 1980–88 period using 1980 levels of the independent variables. The fourth equation takes a somewhat different approach in that it attempts to explain employment growth for the 1980–88 period on the basis of what happened to the independent variables during the period 1970–80. For example, the independent variable becomes the change in the state's hourly wage level from 1970 to 1980 instead of the level of the wage in 1980.

The results are generally in line with what one would expect. The cost, availability, and quality of labor in a given state appear to play a central role in that state's employment growth; the lower the wage level, the greater the level of unemployment, and the more highly educated the work force in the base period, the greater the growth in employment during the subsequent period. Similarly, to the extent that population density serves as an indication of the cost of land, the results show that states with relatively plentiful, inexpensive land in the initial periods experienced the higher rates of growth in the subsequent periods.

The results for energy costs are somewhat less consistent. The original notion was that higher energy costs, all else equal, would

Table 11
Regional Data on Employment Growth (1970–80 and 1980–88) and Its Potential Determinants, 1970 and 1980

Region	Average Annual Rate of Private Employment Growth		Unemployment Rate		College Graduates		Urban Population		Tax Burden		Population Density[a]		Hourly Wage (Manufacturing)		Cost of Energy[b] (Per Million BTUs)	
	1970–80	1980–88	1970	1980	1970	1980	1970	1980	1970	1980	1970	1980	1970	1980	1970	1980
	Percent												1982 Dollars			
Northeast	.8	1.9	4.6	7.1	11.2	17.3	89.2	88.1	11.3	11.5	301	302	8.38	8.33	3.05	4.30
New England	1.9	2.6	4.9	5.9	12.2	19.3	82.9	81.2	10.5	10.4	189	196	7.92	7.61	3.81	4.52
Mid Atlantic	.5	1.7	4.5	7.5	10.9	16.6	91.2	90.5	11.6	11.8	372	369	8.53	8.60	2.91	4.26
North Central	1.7	1.3	4.7	8.2	9.6	14.8	71.5	70.5	10.3	9.6	75	78	9.20	9.66	2.96	3.91
East North Central	1.3	1.2	5.1	9.2	9.5	14.5	78.7	77.2	10.3	9.6	165	171	9.45	9.99	2.85	3.91
West North Central	2.7	1.5	3.8	5.7	9.9	15.4	53.8	54.0	10.5	9.7	32	34	8.51	8.85	3.35	3.93
South	3.7	2.6	4.5	6.4	9.7	15.0	66.8	67.8	9.3	8.7	71	86	7.26	7.65	1.86	4.20
South Atlantic	3.4	3.7	4.2	6.3	10.3	15.5	71.1	71.7	9.4	8.9	113	136	7.03	7.21	2.65	3.47
East South Central	2.9	2.1	4.8	7.9	7.7	12.1	53.5	53.4	9.4	8.7	72	82	7.08	7.48	2.08	3.76
West South Central	4.8	1.0	4.8	5.6	10.1	15.7	68.9	70.8	9.1	8.5	45	56	7.77	8.39	1.44	4.67
West	4.4	2.7	6.8	6.8	13.2	19.3	83.9	83.1	11.4	10.0	29	36	9.28	9.16	2.10	4.07
Mountain	5.9	2.6	5.1	6.2	12.9	18.9	60.7	62.4	10.8	10.1	10	13	8.42	8.60	2.22	3.32
Pacific	4.0	2.8	7.3	7.0	13.2	19.4	91.5	90.8	11.5	9.9	80	95	9.53	9.36	2.05	4.51

Note: See Appendix B for details on sources of data.
[a]Measured as number of persons per square mile of land area.
[b]Measured as the ratio of expenditures on fuel and purchased electricity to consumption of fuel and purchased electricity, for the industrial sector.

Table 12
Regression Results: The Role of Public Capital in Private Employment Growth, 1970–88, 1970–80, and 1980–88

	Employment Growth						1980–88 Growth (Based on 1970–80 Changes)	
	1970–88 (1970 Levels)		1970–80 (1970 Levels)		1980–88 (1980 Levels)			
Explanatory Variable	Coefficient (t-Statistic)	Beta	Coefficient (t-Statistic)	Beta	Coefficient (t-Statistic)	Beta	Coefficient (t-Statistic)	Beta
Cost of Labor								
WAGE	−1.4	−.52	−.8	−.20	−1.0	−.70	−.1	−.44
	(4.1)		(1.6)		(4.4)		(3.6)	
U%	.4	.39	.4	.28	.3	.36	.2	.20
	(3.3)		(2.3)		(2.2)		(1.4)	
COLL	.3	.46	.3	.33	.2	.39	.1	.09
	(3.8)		(2.7)		(2.5)		(.7)	
Cost of Land								
POP DENSITY	−.003	−.64	−.003	−.41	−.002	−.24	.06	.41
	(5.0)		(3.2)		(1.3)		(3.2)	
Cost of Energy								
ENERGY	2.8	.56	1.8	.24	−.1	−.05	−.003	−.10
	(4.2)		(1.7)		(.3)		(.7)	
TEMP	.08	.34	.1	.38	−.008	−.03		
	(3.0)		(3.4)		(.2)			
Potential Sales								
URBAN	.01	.31	−.006	−.09	.03	.50	−.01	−.01
	(2.0)		(.6)		(2.9)		(.1)	
TAXES	−.3	−.32	−.3	−.24	−.4	−.30	−.4	−.22
	(2.6)		(1.9)		(2.0)		(1.7)	
PUBLIC CAPITAL	.0001	.35	.0002	.45	.0002	.18	.03	.24
	(2.7)		(3.4)		(1.0)		(1.7)	
INTERCEPT	−5.0		−10.1		5.3		−.02	
	(1.7)		(2.2)		(1.1)		(.01)	
$\bar{R}^2$	.63		.62		.41		.45	
DW	1.9		2.1		1.9		1.8	

Note: For description of variables, see Appendix B.

reduce profitability and therefore discourage the establishment of new firms and inhibit employment growth. The data support this hypothesis in two respects. First, all else equal, states with warmer climates tend to have greater employment growth. Second, energy costs have a negative effect on employment growth in the 1980–88 period.

One might wonder how much weight to put on these results. As indicated above, several regressions were run, adding and deleting variables for unionization and personal income and substituting heating degree days for the maximum temperature variable. No matter which variables were included in the regression equation, the coefficient for public capital never fell below 0.0001 or rose above 0.0003 for any of the time periods. In terms of the statistical significance, the t-statistics never fell below 1.2 for the subperiods or rose above 4.1. The reader must come to her or his own conclusion, but the author is convinced that public infrastructure matters in firm locational decisions and thereby affects employment growth.

Before leaving this topic, one further equation was estimated. It may be a little unorthodox, but it is based on the notion that investment and employment decisions are less related to the initial levels of the relevant variables than to how these variables have been changing in the recent past. The results of testing this hunch empirically are summarized in the last equation of Table 12. As noted earlier, this equation relates the growth in employment for the period 1980–88 to the changes in the variables over the period 1970–80. The $\bar{R}^2$ indicates that this approach explains more of the variation in state employment growth than including the initial levels. Almost all the variables have the expected sign and magnitude (except for population density[6]), and the growth of public capital appears to be considerably more important in this equation than its initial level was in the earlier equations. This should be interpreted as nothing more than one additional bit of evidence that public capital affects state-by-state levels of economic activity.

Conclusion

This paper consisted of three exercises exploring the relationship between public capital and economic activity. The first looked at the role of public capital in the production process and found that public capital had a positive, statistically significant impact on private sector output.

[6] The change in population density appears to be playing the role of population growth rather than change in land cost in this equation. One would expect a close relationship between state population growth and the growth of nonmanufacturing employment, as local merchants expand to provide a wide array of services for the enlarged pool of consumers. Indeed, in an equation with manufacturing employment, rather than private nonagricultural employment, as the dependent variable, the change in population density is no longer statistically significant. This seems to confirm a strong positive relationship between the change in population density and the growth of nonmanufacturing employment.

These results were robust. The coefficient on public capital implied the same marginal productivity as for private capital. The benefits from public capital, an unpaid factor of production, seem to be divided between private capital and labor in proportion to the elasticity of private sector output with respect to each input. When public capital was disaggregated into highways and streets, water and sewer systems, and other structures and equipment, the coefficient of each component was in line with expectations. Finally, the relationship between public capital and output held up on a regional basis, although more work is needed to understand the variation in the coefficients.

The second exercise involved investigating the role of public capital in private sector investment. Here two opposing forces were at work. On the one hand, the evidence clearly indicated that public capital enhances the productivity of private capital; through this mechanism public capital would be expected to stimulate private sector investment. On the other hand, the results of a translog production function indicated the bulk of state and local public capital is a substitute for private capital; this substitutability indicates that, for any given level of output, the more public capital on hand the less private investment required. A simple investment equation suggested that both these effects were evident, but these results were not robust and much more work should be done.

The third exercise explored the relationship between public capital and employment growth in order to see whether the stock of a state's physical infrastructure influenced firm location and subsequent growth. Although the specific model into which public capital should be introduced is much less precise than that specified by a production function, the empirical work provided convincing evidence, at least to the author, that a state's investment in public capital had a significant positive impact on that state's private employment growth.

The evidence seems overwhelming that public capital has a positive impact on private sector output, investment, and employment. But public capital is not just another form of private capital. These physical resources were produced by the public sector because they contribute additional benefits that cannot be captured by a private sector investor; the presumption is that inadequate quantities would have been produced if left to private sector initiatives. The fact that public capital has these externalities and that the marginal productivities of public and private capital appear to be the same in the private production process suggest that the United States has underinvested in public capital. But one does not really need equations to arrive at that conclusion.

The conclusion that this country has underinvested in public capital and that public capital has a positive impact on economic activity does not mean that the United States should blindly double the amount of money it spends on public capital; nor does it mean that careful cost-benefit analyses are no longer needed for individual projects. Rather the results indicate that more spending on public investment, which is clearly needed to remedy serious safety hazards and to improve the quality of life, may also produce greater productivity and growth.

Appendix A—Creation of State Estimates of Capital Stocks

No state-by-state data are available on the stock of public or private capital. Hence, it was necessary to devise ways of dividing up the national totals published by the U.S. Bureau of Economic Analysis (BEA). The capital stock series selected were the constant-cost or "physical-volume" estimates, where assets are valued at a base-year price. In the case of public capital, the approach taken was to create for each year, 1969 to 1988, a state capital stock series based on annual state investment data and BEA discard and depreciation schedules, and use the state-by-state distribution of these series to apportion the BEA public capital totals for the nation. In the case of private capital, state investment data (other than for manufacturing) were not available, so the approach followed was to apportion the BEA national total for private capital on the basis of various measures of each state's activity in the agricultural sector, the manufacturing sector, and the nonfarm, nonmanufacturing sector. These calculations are described below.

Public Capital Stocks

An estimate of public capital stock was made for each state, and each state's share of the sum of these estimates was used to apportion the BEA national estimate of state and local public capital. The capital outlay data used as a basis for the state estimates of stock were taken from *Governmental Finances*, a U.S. Bureau of the Census publication, for the years 1958 to 1988. Capital outlay was defined as direct expenditure 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. Purchases of equipment, land, and existing structures were also classified as capital outlays. (Repair expenditures, classified under current operations expenditure, were not included here.)

Governmental Finances lists, state by state, the capital outlays for certain functions as well as total capital outlays. Some functions were not reported separately for the full time period, so it was not possible to estimate stock measures for all types of capital. Consistent series were available for highways, sewerage, and water supply facilities. (Data on capital outlays on water supply facilities were not available separately from 1958 to 1960, but as this is only a brief period and because water supply facilities are an important piece of "core" infrastructure, the stocks were estimated based on data from 1961 to 1988.)

The BEA procedure outlined in *Fixed Reproducible Tangible Wealth, 1929–1985* was followed in order to calculate public capital stock estimates for 1969 to 1988. The first step in this process was to deflate annual data on nominal dollar investment in each state into constant dollar investment, with the same deflators used by the BEA in its calculations of national public capital stocks. Obtaining an estimate for the gross capital stock required calculating the value of each year's investment that would have been discarded over the years. Assets are not always discarded at the end of the average service life, but rather some assets are discarded earlier and others remain in service longer. The retirement pattern used by the BEA to calculate gross stocks is a modified Winfrey S-3, with retirements starting at 45 percent of the average service life and ending at 155 percent of average life. The service lives used here were again taken from the BEA. Highways, sewer systems, and water supply facilities were assumed to last 60 years, thus this figure was used in the discard and depreciation calculations for these assets. The average service life for total public capital had to be estimated and was calculated as a weighted average of the service lives of its components, with the weights representing the component's percent of total constant dollar investment over the full period, according to the following formula:

$$\left(15 \text{ yrs.} * \frac{\sum \text{State \& local equipment investment}}{\sum \text{Total state \& local investment}}\right)$$

$$+\left(50 \text{ yrs.} * \frac{\sum \text{State \& local investment in buildings, ``other'' structures}}{\sum \text{Total state \& local investment}}\right)$$

$$+\left(60 \text{ yrs.} * \frac{\sum \text{State \& local investment in highways, water supply facilities, sewer systems, and conservation and development structures}}{\sum \text{Total state \& local investment}}\right) = 50.68 \text{ years.}$$

This calculation was based on BEA investment data. The value of discards was then subtracted from the annual real investments. Summing these investment figures over time gave the gross value of the capital stock. These estimates were then summed across states, with each state's share of this sum used to apportion the BEA national estimate of state and local gross public capital stock.

A similar procedure was used to derive net capital stock estimates. The value in the end year (that is, the year for which the stock is being estimated) of total depreciation on each year's original investment was calculated. The BEA assumption of straight-line depreciation over the average service life of the asset was used. (Service life estimates were the same as above.) Subtracting depreciation from the original annual investments left the net value in the end year of each year's investment. These values were summed to obtain the net value of the capital stock in that year. The stock estimates were then summed across states. Each state's share of this total stock was then used to apportion the BEA national total amount of state and local public capital stock for that year. Net capital stock estimates were used in estimating the production function; they better reflect the productive capacity of the stock because they are adjusted for wear and tear, accidental damage, and obsolescence.

The sum of estimates across states equaled approximately 75 percent of the BEA total state and local net stock measure in 1970. By 1980 the state stock estimates created here summed to 97 percent of the BEA total. The sum of state estimates in 1986 was 108 percent of the BEA total. This number exceeds the BEA total because of coverage and timing differences between Census expenditure data and the NIPA data on state and local expenditures used by the BEA.

Because public assets have long lives and investment data begin only in 1958, the stock estimates in the earlier years have the potential to underestimate stocks in the older parts of the country, where much investment may have occurred prior to 1958. Similarly, it may overestimate capital stocks in the newer areas of the country. Looking at the results of the procedure, the bias does not seem too pronounced, since older industrial states like New York, Illinois, Pennsylvania, Ohio and Michigan are all ranked in the top ten in terms of total public capital stock in 1969. While these estimates could undoubtedly be improved by collecting data over a longer time period, given the complete dearth of information on public capital stocks at the state level, and the limitations of consistent, currently available data, they represent a reasonable first attempt.

Private Capital Stocks

Private capital stocks were calculated by apportioning BEA national stock estimates of various sectors among the states, using a procedure similar to the one outlined in Costa, Ellson, and Martin (1987). This approach was adopted because investment data by state are available only for the manufacturing sector, while the production function is to be estimated for the state economy as a whole. Thus data limitations prevented using the perpetual inventory method to calculate private capital stocks. The private capital stock in a state is given by the following formula:

$$K_i = (AGK_i / \sum AGK_i)AGK + (MFGK_i / \sum MFGK_i)MFGK$$
$$+ (NFNMFGK_i / \sum NFNMFGK_i)NFNMFGK$$

where:
AGK = BEA constant-cost value of capital stock in the agricultural sector
MFGK = BEA constant-cost value of capital stock in the manufacturing sector
NFNMFGK = BEA constant-cost value of capital stock in the nonfarm, nonmanufacturing sector
AGK_i = proxy for capital stock in agriculture in state i
$MFGK_i$ = proxy for capital stock in manufacturing in state i
$NFNMFGK_i$ = proxy for capital stock in the nonfarm, nonmanufacturing sector in state i.

Much of the data used as proxies was taken from the economic censuses, which occur every fifth year: agriculture, manufacturing, and several nonfarm, nonmanufacturing sectors: construction, mining, services, and retail and wholesale trade. Several nonfarm, nonmanufacturing sectors were apportioned using data from sources other than the economic censuses: rail, air and water transportation, trucking, electric and gas services, telephone, and banking. A state's share of the proxy in the census year was used to distribute BEA assets for that year, preceding years and following years. Thus, data from the 1972 Census were used to apportion among the states the BEA national stock estimates for 1969 to 1974; 1977 shares were used for the 1975 to 1979 stock estimates; 1982 shares were the basis for the estimates from 1980 to 1984; and 1987 data were used to apportion national asset totals for 1985 and 1986. (In cases where data were not available for the census year, data for the closest year were used or another estimating procedure was employed. These exceptions are described below.)

The BEA estimate of capital in agriculture was distributed among states based on the value of land, buildings, and equipment in agriculture. The value of land, buildings, and equipment taken from the *1987 Census of Agriculture* was used as a proxy to calculate the stock for 1985 and 1986. Data from the 1982 *Census* were used to calculate shares for 1980 to 1984. Stocks for 1976 to 1979 were based on data from the 1978 *Census*. Data from the 1974 *Census* were used in estimating stocks for 1972 to 1975, while stocks for 1969 to 1971 were estimated using 1969 *Census* data.

The BEA estimate of capital in manufacturing was distributed among states based on their shares of the gross book value of depreciable assets in manufacturing. Asset data were taken from the 1977 and 1982 *Census of Manufactures*. State asset data were not yet available from the 1987 *Census* so the 1985 *Annual Survey of Manufactures* was used to estimate 1985 and 1986 stocks. The 1972 *Census* did not report asset data by state so the 1971 *Survey* was used as a proxy for stocks for 1970 to 1974, while the 1969 *Survey* was used to apportion the 1969 stock.

The BEA estimate of capital in the nonfarm, nonmanufacturing sector was divided among the states according to the sum of estimates for many subsectors: construction, mining, retail and wholesale trade, banking, railroad transportation, trucking and warehousing, water transportation, air transportation, electric services, gas services, telephone and telegraph, and services. The sum of asset estimates for all states, for all subsectors, represented nearly three-quarters of the BEA national total of nonfarm, nonmanufacturing assets. The following equation describes this estimating procedure:

$$NFNMFGK_i = (shCONSTR_i * CONSTRK) + (shMI_i * MIK) + (shR_i * RK)$$
$$+ (shW_i * WK) + (shBK_i * BK) + (shRAIL_i * RAILK) + (shTRUCK_i * TRUCKK)$$
$$+ (shBOAT_i * BOATK) + (shAIR_i * AIRK) + (shELEC_i * ELECK)$$
$$+ (shGAS_i * GASK) + (shTEL_i * TELK) + (shSVCS_i * SVCSK)$$

where sh = share.

The BEA estimate of assets in construction (CONSTRK) was distributed among states based on their share of the gross book value of depreciable assets taken from the *Census of Construction* for 1972, 1977 and 1982. No state data were yet available from the 1987 Census so 1982 shares were used to estimate stocks from 1980 to 1986.

Assets in mineral industries (MIK) were apportioned in two parts: assets in oil and gas extraction, and assets in all other mineral industries. The BEA figure for assets in oil and gas extraction was apportioned among the states based on their shares of oil production in 1972, 1977, 1982 and 1986. Production values for 1972 and 1977 were taken from the *Minerals Yearbook* while values for 1982 and 1986 were taken from the Energy Information Administration's *Petroleum Supply Annual*. (Since 1982, when the Department of Energy was created, it has been responsible for publishing data on fuel production. Prior to that time these data were tracked in the Bureau of Mines' *Minerals Yearbook*.) Assets in all other mineral industries were distributed according to the following methodology. The *Census of Mineral Industries* for 1977 and for 1982 listed end of year gross book value of depreciable assets, by state. These same data were not calculated in 1972, and the 1987 data were not available yet. The proxy for 1986 shares (used to distribute total asset values for 1985 and 1986) was calculated by increasing each state's 1982 asset value by the ratio of each state's value of nonfuel mineral production in 1986 to the value of its nonfuel mineral production in 1982:

$$\text{assets}_{i86} = \text{assets}_{i82} * \frac{\text{Value of non-fuel mineral production}_{i86}}{\text{Value of non-fuel mineral production}_{i82}}.$$

The 1972 proxy was calculated in a similar manner, with the 1977 asset value multiplied by the ratio of the value of 1972 production to the value of 1977 production. State asset values were summed, and then each state's share of this total value was calculated and used to apportion the BEA's total national value of assets in mineral industries (excluding oil and gas extraction).

The values of retail and wholesale trade assets (RK and WK) were apportioned according to each state's share of sales, taken from the *Census of Wholesale Trade* (1972, 1977, 1982, and 1987) and the *Census of Retail Trade* (1972, 1977, 1982, and 1987). According to Costa, Ellson and Martin (1987), the differing structure of retail and wholesale trade across states does not significantly affect the asset/sales ratio.

Assets in banking (BK) were distributed in a manner similar to wholesale and retail trade, using each state's share of deposits in 1972, 1977, 1982, and 1986. The source for deposit information was the *Statistical Abstract of the United States*, and the data reflect deposits of insured commercial banks.

The national estimate of assets in rail transportation (RAILK) was divided among states based on their proportion of track mileage in 1972, 1977, 1982, and 1986. Data on miles of track by state were taken from *Railroad Facts*.

Trucking and warehousing assets (TRUCKK) were distributed to states using the number of trucks in each state. Data on number of trucks by state were available from the *Census of Transportation* for 1972, 1977 and 1982, and from the *1987 Census of Transportation* for a limited number of states. The average growth rate in the number of trucks for states that had both 1982 and 1987 data points was used to extrapolate the number of trucks in 1987 for states without 1987 data.

The BEA national estimate of assets in water transportation (BOATK) was apportioned among states based on data from *Waterborne Commerce of the United States* (1972, 1977, 1982, and 1986) on the value of commerce in ports.

Each state's share of total civil aircraft was used to distribute the national value of assets in air transportation (AIRK). The Federal Aviation Administration's *Census of U.S. Civil Aircraft* (1972, 1977, 1982 and 1986) provided the data on the number of aircraft.

The proxy used to distribute assets in electric services (ELECK) was the generating capacity installed in each state, taken from the *Statistical Abstract* for 1972 and 1977, and the *Inventory of Power Plants in the United States* for 1982 and 1986.

The national estimate of gas services assets (GASK) was divided among states based on their share of miles of pipeline and main. *Gas Facts,* a publication of the American Gas Association, was the source for these data.

Assets in telephone and telegraph (TELK) were divided among states using their share of miles of wire in cable. These data came from the Federal Communication Commission's *Statistics of Communications Common Carriers* for 1972, 1977, 1982, and 1986.

The final categories of assets to be distributed among states are those in the services sector (SVCSK). BEA national asset estimates in six service categories were apportioned using each state's share of sales in that category. These six estimates were summed for each state to approximate assets in services. The six categories were hotels, personal services, business services, auto repair services, amusement services, and legal services. Sales data were taken from the *Census of Service Industries* for 1972, 1977, 1982 and 1987.

The next step was to sum the asset estimates of all these nonfarm, nonmanufacturing subsectors for each state to arrive at a proxy for nonfarm, nonmanufacturing assets. These values were then summed across all states and each state's share of this sum was used to apportion the BEA national estimate of capital stock in the nonfarm, nonmanufacturing sector.

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Appendix B
Variables Used in the Firm Location Model of Employment Growth

Variable Name	Definition	Source
Dependent:		
CHPE	Average annual percent change in private nonagricultural employment	U.S. Bureau of Labor Statistics, *Handbook of Labor Statistics*, 1989
Independent:		
Cost of Labor		
WAGE	Hourly wage in manufacturing	U.S. Bureau of Labor Statistics, *Handbook of Labor Statistics*, 1989 and 1976
U%	Unemployment rate	U. S. Bureau of Labor Statistics, *Employment and Wages, Annual Averages 1980* and U.S. Department of Labor, *Employment and Training Report of the President, 1976*
COLL	Percent of the population aged 25 years or older that has completed at least four years of college	U.S. Bureau of the Census, *Census of Population, General Social and Economic Characteristics*, 1970 and 1980
Cost of Land		
POP DENSITY	Population density calculated as the ratio of total population to land area	U.S. Bureau of the Census, *Statistical Abstract of the United States*, 1979 and 1989
Cost of Energy		
ENERGY	Cost per million BTUs of purchased fuels and electricity in the industrial sector	U.S. Bureau of the Census, *Statistical Abstract of the United States*, 1983 and 1984 and U.S. Department of Energy, Energy Information Administration, *State Energy Price and Expenditure Report, 1987, State Energy Data Book, 1960–1979*
TEMP	Normal daily maximum temperature in July	U.S. Bureau of the Census, *Statistical Abstract of the United States*, 1979 and 1989
Potential Sales		
URBAN	Percent of the population living in metropolitan areas	U.S. Bureau of the Census, *Statistical Abstract of the United States*, 1984
TAXES	Total state and local taxes as a percent of personal income	U.S. Bureau of the Census, *Governmental Finances*, 1969–70 and 1979–80, and U.S. Bureau of Economic Analysis, *Survey of Current Business*, August 1987
PUBLIC CAPITAL	Per capita public capital stock	See Appendix A for a discussion of the creation of public capital stocks. Population data from U.S. Bureau of the Census, *Statistical Abstract of the United States*, 1979 and 1989

Note: All dollar values for equations employing 1970 levels were expressed in 1970 dollars, while dollar values for equations using 1980 levels were expressed in 1980 dollars. The variables in the equation employing changes in independent variables from 1970 to 1980 were calculated as the percent change in constant (1982) dollars for variables measured in dollars or the absolute change for those variables measured as percentages.

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Discussion

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It was almost ten years ago that the Boston Fed held a conference on the causes of the post-1973 productivity slowdown. That conference came just after the second oil-price shock of 1979, and much of the discussion focused on the role of energy. It was hard to resist the intuitive idea that the OPEC oil price shocks had precipitated the slowdown, and this intuition was buttressed by econometric studies that seemed to show that energy explained almost all the decline in labor productivity.

Now, ten years later, few growth analysts would argue that the energy crisis was the sole explanation of the productivity slowdown. However, a new candidate for "Cause of the Slowdown" has appeared: Aschauer and others have noted a strong relationship between public infrastructure and economic growth and have argued that the slowdown could be largely attributed to a decline in public investment spending. (Aschauer also implies that international differences in productivity growth rates can be largely explained by differences in public investment spending.) This explanation was missed by previous studies, it is said, because they did not take into account the trend in the stock of public capital.

As with the earlier energy explanation, the basic issue is to sort out the relative importance of the many factors that influence economic growth, including public capital and energy. The study by Alicia Munnell provides a valuable step in this direction by using estimates of gross state product and of private inputs of capital to develop estimates

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of public capital stocks for forty-eight states over the period 1970 to 1986. These data are then used to estimate Cobb-Douglas and translog production functions. The analysis is then supplemented with a discussion of the factors influencing regional employment growth in the private sector. Munnell concludes that "The evidence seems overwhelming that public capital has a positive impact on private output, investment, and employment."

The production function approach has generally provided support for the hypothesis that infrastructure matters a lot, so this conclusion comes as no great surprise. What is surprising is the relatively small magnitude of the effect: the output elasticities associated with public capital are much smaller than the output elasticity associated with private capital (6 percent to 15 percent versus 27 percent to 34 percent). This result is consistent with the results reported in studies by Eberts and by Garcia-Mila and McGuire, which also analyzed state-level data, but differs sharply from some of the results obtained in studies based on times series. The latter typically find much larger output elasticities with respect to public capital (often exceeding the corresponding private capital elasticity).

The smaller estimates are much more plausible. Infrastructure capital typically is in the form of networks of interacting investments, and the completion of a network, where none had previously existed, can have a major impact on economic growth. For example, the growth of the United States was greatly stimulated by the building of the intercontinental railroads, and the establishment of electricity, road, and irrigation networks in developing economies can have a huge payoff. However, *adding* to an existing network will rarely have the same return: at some point, the increasing returns to scale aspects of infrastructure are exhausted and, other things equal, marginal additions bring increasingly smaller benefits. Since the primary U.S. infrastructure networks were well established by 1970, a regression analysis based on post-1970 data should not be expected to show a large infrastructure effect, and even the smaller estimates of this paper may overstate the benefits of *additional* investment in public capital.

It is also important to recognize that the positive association between infrastructure and output growth does not necessarily mean that too little public capital existed during the time period studied. An efficient allocation of resources requires that the ratio of marginal social product to input cost be the same for all inputs. The paper does not address this second issue directly, but a comment is informative: "The coefficient of public capital is also sensible in that it implies a reasonable marginal productivity for public capital and equality between the productivity of public and private capital." If the corresponding resource costs of both types of capital are roughly the same—that is, opportunity cost plus depreciation and maintenance—the results of this paper would imply an *efficient* allocation of capital, and not an underinvestment in public capital. Since resource costs are not presented, it is not appropriate to conclude that the allocation of capital is efficient, but neither is it appropriate to draw the opposite conclusion.

The results of this paper should also be interpreted in light of several potential biases. First, the measure of public capital that enters the state production function is the own-public capital stock of each state. This implies that an additional road in Ohio affects output in Ohio alone, and ignores the productivity benefits of Ohio's roads that accrue to other states. A 1 percent increase in roads in every state may thus have productivity effects greater than the sum of the direct state benefits, if the spillovers are important. Although this does not necessarily lead to a problem (for example, if spillovers are perfectly symmetric and public capital increases at a uniform rate everywhere), the estimates will, in general, exhibit a bias that depends on the extent and nature of the spillovers.

Second, no adjustment is made for congestion or intensity of use. The capital services obtained from a highly congested road could be less, per unit of capital stock, than the services associated with an uncongested road. The direction of any bias is unclear, however, since congestion can be high both in new, rapidly growing areas where investment has not kept up with growing demand and in older, declining areas where a declining fiscal situation has led to underinvestment. My own research suggests that a crude correction for utilization in an aggregate time series analysis considerably weakens the correlation between private output and public capital. This is, in my view, a crucial area for further research.

Third, it is reasonable to expect a lagged response in private sector output to a change in the quantity of schools, roads, and the like. A new subway system may, for example, have a sizable impact on private output, but only after businesses have had a chance to adjust to the new patterns of demand and supply. The finding of a high contemporaneous correlation between public capital and private output is thus somewhat implausible.

Finally, and most important, it should be recognized that the production function is but one structural equation in a system of simultaneous equations, and that the correlation between public capital and private output might come from other parts of the economic system. Specifically, rising incomes in rapidly growing areas may cause voters to demand more infrastructure. If this is the case, then the direction of causality is ambiguous: more public capital may help produce more output, but more output leads to an increase in the amount of public capital. To associate this joint relation with the first effect alone is to generally overstate the impact that an exogenous increase in public capital would have on output growth.

These problems are hardly unique to Munnell's paper, and pose interesting and difficult challenges that must be confronted by future research. This paper is, indeed, to be applauded for the progress it makes on a tough problem, particularly in the area of data development. Considerable effort went into the development of public capital stocks by states, and such an effort is not always appreciated by nonspecialists. This data set will be a valuable input to future infrastructure research.

Discussion

*Ann F. Friedlaender**

In her interesting and exhaustive paper, Alicia Munnell argues convincingly that public infrastructure investment has a positive impact upon regional output and growth. I, for one, do not have to be convinced of this; on a purely intuitive and anecdotal level in both developed and less developed countries, one senses that regions with an extensive base of public infrastructure have stronger economic performance than those with a weak or decaying base. It would have been surprising if Munnell had failed to find positive relationships between infrastructure and output and growth.

While Munnell's empirical findings are convincing, I am somewhat uncomfortable with the analytical structure that she utilized. In what follows, I would like to sketch out an alternative approach, one that I believe is not only on a somewhat firmer analytical footing, but also subject to empirical estimation. In doing so, I hope to stimulate work on this important and as yet relatively unresearched topic.

Cost versus Production Functions: An Alternative Approach

While a long tradition is associated with using production functions to estimate technology and technical change, economists have also recognized that the econometric estimation of production functions

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suffers from an important problem of misspecification. In particular, since input prices affect factor utilization and thus where firms are positioned on their transformation function, omitting them in an econometric analysis of technology could lead to substantial biases in the estimated technological coefficients. Of course, if relative input prices are constant over the sample, this is not a problem. A substantial variation in input prices over the sample probably would be a legitimate cause for concern, however.

While I am not an expert in this area, casual empiricism suggests that the omission of input prices could create bias in Munnell's analysis. Not only did real interest rates rise significantly while real wages fell somewhat during the sample period, but it is also likely that one would observe significant regional differences in relative input prices in view of regional differences in the composition of output, the work force, and capital. Indeed, the rather striking differences in the estimated production functions by region may well reflect these differences, rather than differences in technology per se.

This suggests that it might make sense to estimate a cost function rather than a production function. Not only would this incorporate input price effects into the analysis, but it would also enable one to determine the extent to which public infrastructure is under- (or over-) capitalized, providing some boundaries for those who believe a major shortfall in public infrastructure exists.

To see the basic framework, assume that labor and private capital are adjustable over a year and thus are in equilibrium, but that public capital is not. (Note that we could assume that private capital is also in disequilibrium and adjust the analysis accordingly.) We would consequently estimate a short-run variable cost function of the following form:

$$C^v = C^v\ (Q,\ w,\ r,\ G,\ t) \qquad (1)$$

where Q = output, w = the wage rate, r = the cost of private capital, G = the amount of public infrastructure, and t represents a time trend to capture technical change. If we assume a Cobb-Douglas production function, omit the time trend, and substitute a technological factor instead, this equation can be thought of as the dual of Munnell's production function. It is inherently more general, however, since it permits technical change (the time trend (t) can be introduced to represent neutral and non-neutral technical change) as well as the explicit role of input prices in the equilibrating process.

Although this approach presents significant data problems, they are probably not insurmountable. Munnell's analysis shows that it is possible to construct reasonable data on regional output (Q), labor (L), private capital (K), and public infrastructure (G). Since short-run variable costs are simply the sum of the costs of the variable inputs,

$$C = wL + rK. \tag{2}$$

To estimate a regional cost function, we therefore need additional data on regional wage rates (w) and the cost of private capital (r).

Data on regional wage rates should be relatively straightforward to obtain from the U.S. Bureau of Labor Statistics or similar sources. Estimating regional data on the cost of capital is considerably more difficult, however. As a first approximation, one could assume that regional capital markets are spatially perfect, but that the cost of capital differs by broad industry groups (to reflect differences in inherent risk as well as debt structures). By utilizing data on the regional composition of output, one could then construct Divisia indices of the private cost of capital by states. While admittedly difficult, it does not appear to be impossible to obtain the requisite information to estimate this regional cost function.

Using this short-run cost function, it is possible to estimate elasticities of substitution among the various inputs, the nature of technical change (neutral, labor-augmenting, and so forth), and returns to scale, as well as the relative marginal products of the various inputs.

In addition, by utilizing Shephard's lemma (admittedly one may have to make a leap of faith about cost minimization and perfect input markets), one could use the input demand functions to estimate the direct investment and employment effects associated with public infrastructure. Equally important, it should also be possible to determine whether the amount of public capital is in equilibrium, by considering the relationship between short-run and long-run costs. In particular, total costs are given by

$$C = C^{v}(Q, w, r, G) + \gamma G \tag{3}$$

where γ represents the opportunity cost of public infrastructure and $C^{v}(\cdot)$ represents the variable cost function.

The shadow value of public infrastructure represents the savings that would accrue to variable costs if the stock of public capital were raised by one unit. Thus we define:

$$\rho = \frac{\partial C^{v}(\cdot)}{\partial G}.$$

It is straightforward to show that the equilibrium amount of public infrastructure obtains when the opportunity cost of public capital equals its shadow value. Thus in equilibrium

$$-\frac{\partial C^{v}(\cdot)}{\partial G^{*}} = \gamma \tag{4}$$

where the asterisk indicates the cost-minimizing level of G. If the shadow value of capital is greater than its opportunity cost, this indicates insufficient public infrastructure (and the reverse is true if the shadow value of capital is less than the opportunity cost). More importantly, by solving this equation for the equilibrium level of infrastructure (G^*), one can determine the amount of under- (or over-) capitalization that exists with respect to public capital.

Of course, the validity of this analysis depends on our ability to estimate the opportunity cost of public capital, admittedly not an easy task. Nevertheless, to the extent that state bonds are issued for infrastructure investments rather than for operating costs, state bond yields could be used to construct regional series on the cost of public capital. Thus by utilizing this framework it should be possible to estimate the extent to which particular states and/or regions are underinvested or overinvested in public capital.

While it may be pushing things a bit, it should also be possible to incorporate demand effects into this framework and extend the analysis in a fashion that is somewhat analogous to that followed by Munnell in her analysis of the relationship between employment and public infrastructure. Instead of utilizing a reduced-form analysis, however, this approach explicitly models the demand effects of infrastructure.

Assume that a regional or state authority is interested in maximizing the net benefits of public infrastructure. The cost function is given in equation (3), above, while the benefit function depends on regional activity or output (Q), prices (P), and infrastructure (G). Gross benefits can be expressed as

$$B = B\,(Q, P, G), \tag{5}$$

while net benefits can be expressed as

$$NB = B\,(Q, P, G) - C^{v}\,(Q, w, r, G) - \gamma G. \tag{6}$$

If the regional authority seeks the welfare-maximizing level of infrastructure, it is straightforward to show that this is given when

$$\frac{\partial B(\cdot)}{\partial G^*} - \frac{\partial C(\cdot)}{\partial G^*} = \gamma. \tag{7}$$

This indicates, of course, that to the extent that public infrastructure enters regional demand as well as regional production functions, the equilibrium level of infrastructure rises. Thus, if one were to observe undercapitalization with respect to the amount of public infrastructure based on an analysis of costs alone, it is likely that the true extent of undercapitalization is even greater than indicated. Conversely, if one observed overcapitalization on the basis of a cost analysis alone, to the extent that infrastructure affected regional demand, one would have to discount the extent of overcapitalization.

I have to admit that I have not fully formulated a gross benefit function suitable for estimation. Presumably, the benefit function represents the consumer surplus accruing to the population, that is, the area under the appropriate demand function. This suggests that it might be possible to estimate a marginal benefit function that depends on prices and infrastructure. Alternatively, following the literature on the benefits associated with air pollution, it might be possible to estimate a marginal benefit function for infrastructure directly. This, however, is obviously a difficult activity, because of problems posed by spatial aggregation, omitted variables, and the like. Nevertheless, intuition tells me that such an analysis is probably feasible and that it also could yield interesting results.

Conclusion

Let me close by stressing again the valuable insights and contributions provided by Munnell's paper. She has, I believe, convincingly shown that public infrastructure has a positive effect upon regional output, investment, and employment. Equally important, she has created a significant data set that could be utilized to explore interesting questions for future research.

While not directly addressing the details of Munnell's paper, these comments have attempted to sketch out an alternative framework that could yield not only the insights contained in Munnell's analysis but also further insights into efficiency aspects of the provision of public capital. This is clearly one area that could produce important dividends for future research. We owe Munnell our thanks for a stimulating and provocative paper.