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SCALE ECONOMIES, RETURNS TO VARIETY, AND THE PRODUCTIVITY OF PUBLIC INFRASTRUCTURE

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ABSTRACT

We examine the productivity of public infrastructure in a general equilibrium context. In our model, infrastructure lowers costs in a manufacturing sector characterized by both firm-level returns to scale and industry-level external returns to variety. Infrastructure alters factor prices, intermediate prices and the allocation of factors across sectors. The effect on manufacturing or aggregate output, however, is indeterminate. In particular, our theory suggests that the degree of monopoly power influences public capital's productivity effect.

We test the model using state-level panel data. We confirm the absence of direct effects on output, but find suggestive evidence of a positive impact of public capital on manufacturing variety as measured by the number of manufacturing establishments. These results indicate the need for future research on potentially important indirect channels by which public capital affects manufacturing productivity.

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1. INTRODUCTION

The impact of publicly-provided infrastructure capital on private sector productivity has attracted considerable attention in recent years. Beginning with Aschauer [1989], a number of researchers estimated social returns to infrastructure far in excess of those for other investments (e.g., private capital).[1] In response to these claims, a series of increasingly sophisticated econometric studies have focused on the estimated return to public capital and at this juncture there appears to be little support for a special role for infrastructure in boosting aggregate productivity.[2]

A somewhat surprising feature of this literature is the noticeable absence of formal economic models of the productivity effects of infrastructure.[3] Instead, the empirical literature has centered on estimates of the technical constraints facing firms—in the form of production or cost functions—at the aggregate, regional, or state level.[4] While useful for their "bottom-line" estimates of productivity effects, these studies shed little light on the mechanism by which infrastructure affects firms, markets, and equilibrium production in each sector of the economy.

Our purpose in this paper is to construct such a model, building into it several features that previous research suggests are important. First, a number of studies have focused on the manufacturing sector, while others have directed attention toward total (private) output. We embed infrastructure within a two-sector model that permits us to account directly for a differential effect between manufactures and non-manufactures. Specifically, we model infrastructure as having direct, cost-saving effects in the manufacturing sector of the economy.[5] As a result, we can answer questions such as: "Is it possible for infrastructure to have cost-saving effects in manufacturing, yet not raise aggregate output?" Second, recognizing that additional infrastructure may reallocate resources among sectors and, as a consequence, alter factor prices, we use a general equilibrium framework. The model incorporates these private-sector responses as well as the direct effect of infrastructure on the stock of productive inputs.

The model has several additional features that highlight the mechanism by which infrastructure affects output. The first is the characterization of scale economies. There are two forms of scale economies in the model: internal scale economies in the production of intermediates, and returns to variety that act as external scale economies in the production of finished manufactures. These scale economies provide an explicit rationale (other than public-goods concerns) for considering public infrastructure provision. A second feature is the treatment of market structure, which plays a crucial role in determining the productivity effect of infrastructure. The empirical research on infrastructure has not acknowledged the role of market structure, but our results indicate that the nature of competition among firms influences both the magnitude and the sign of infrastructure productivity.

The remainder of the paper is organized as follows. In the next section, we develop our model of the role of infrastructure in the economy. Despite the relatively simple structure of the model, the productivity effects of providing more infrastructure are ambiguous. Hence, we turn in Section 3 to an empirical investigation designed to shed light on the key determinants of the effects of additional infrastructure on manufacturing and non-manufacturing output. The final section is a summary with suggestions for further work in this area.

To anticipate the key results, we confirm the absence of significant direct effects on output from infrastructure. However, we find suggestive evidence that public capital may alter productivity through its effect on the number and variety of manufacturing establishments in the local manufacturing base.

2. A MODEL OF PUBLIC INFRASTRUCTURE AND EQUILIBRIUM OUTPUT

We employ a model of a small, open economy producing two goods, "wheat" and finished "manufactures," drawn from Ethier [1979,1982]. Fixed supplies of capital and labor are intersectorally mobile and are allocated in competitive factor markets in each sector.[6]

Wheat is supplied by perfect competitors using capital and labor in a constant-returns-to-scale technology. Alternatively, capital and labor may be used in another constant-returns-to-scale technology to form "factor bundles." Factor bundles are inputs into the production of "components," intermediate goods that are necessary for the production of the finished manufactured good.

The limited endowments of capital and labor, and the technology for producing wheat *(W)* and factor bundles *(m)* define a transformation function for the economy

$$W = T(m) \ , \tag{1}$$

which may be represented by a familiar convex-to-the-origin production possibilities frontier, with $T'(m) < 0$ and $T''(m) \leq 0$. Because wheat and factor bundles are sold under competitive conditions, the relative price of factor bundles in terms of wheat—which serves as our numeraire—is given by the opportunity cost

$$P_m = -T'(m). \tag{2}$$

Changes in the relative price of factor bundles, P_m, play an important role in what follows. It is useful to summarize the elasticity of P_m with respect to quantity of bundles used in the non-wheat sector, m, as

$$\xi = \frac{dP_m}{dm}\frac{m}{P_m} = \frac{T''(m)m}{T'(m)} \geq 0 \ . \tag{3}$$

Finished manufactures are costlessly assembled from intermediate manufactured components according to the production function

$$M = n^{\alpha}\left[\sum_{i=1}^{n} \frac{x_i^{\beta}}{n}\right]^{\frac{1}{\beta}} \tag{4}$$

where x_i is the input of component i into the production of manufactures, M. In the production function (4), α is a measure of scale economies with respect to the range of intermediates, with $\alpha > 1$ indicating increasing returns to variety. Also, components are assumed to be imperfect substitutes; the parameter β ($1 > \beta > 0$) provides a measure of the degree of "differentiation" between any pair of x_i as the elasticity of substitution between any pair is $1/(1-\beta)$. Higher values of β indicate greater ease of substitution of components in the assembly process, hence less differentiation among the components. It is useful to note here that the terms "components" and "assembly" need not be interpreted literally.[7] Instead, the structure is intended to embody the reliance of final-goods manufacturing on a wide variety of specialized business services and goods as inputs.

In equilibrium, n varieties of components will be produced, and we may use n as an index of the range of economic activity. Thus, one might think of increases in n, *ceteris paribus*, as indicating a more robust economic environment characterized by a greater variety of active firms.

Because a greater variety of intermediate-producing firms enhances the productivity of factors used in finished-manufactures assembly, an important question for policy is the degree to which additional infrastructure increases n.

As in Ethier [1982] and Markusen [1989], we assume that all varieties of components have identical production technologies. Since each variety enters symmetrically into the production of finished manufactures, in equilibrium an identical quantity, x_o, will be supplied of each variety. Thus (4) collapses to

$$M = n^{\alpha} x_o. \tag{4'}$$

We see from (4′) that finished manufactures are linearly homogeneous in x_o but homogeneous to degree α in n. These economies are external to the finished manufactures industry as components are assembled into finished manufactures by many competitive firms, each of which takes n as given. This raises the possibility that even if infrastructure policy does not alter x_o, it may raise n and, thus, enhance productivity.

2.1 Equilibrium and Public Infrastructure

We assume that wheat and finished manufactures are tradeable; unlimited quantities of either final good may be purchased or sold at the relative price given by P_M. However, we assume that intermediate components are not traded, thereby capturing the notion that there are services unique to the local economy that contribute to manufacturing.[8] Finished manufactures, therefore, are assembled from intermediate goods and services produced exclusively in the home jurisdiction.

The imperfect substitutability of components accords some market power to each producer of components. However, we allow free entry into the industry and assume that n is sufficiently large that component producers behave as monopolistic competitors, taking the behavior of other component producers as given.

The number of factor bundles required to produce x units of any variety is $ax + b$ $(a, b > 0)$, indicating returns to scale at the firm level. Infrastructure is tantamount to providing "factor bundles" (roads, bridges, etc.) to the manufacturing sector, hence reducing the private resources needed for production. Of course, government capital may serve to lower either variable costs or fixed costs, or both. If we let s denote the subsidy to variable costs, and let G measure the reduction in fixed costs, the production of x units of any variety in the presence of infrastructure requires $(a\text{-}s)x + b\text{-}G$ factor bundles at a private cost of $P_m((a\text{-}s)x + b\text{-}G)$.

Each component producer sets marginal cost equal to marginal revenue, resulting in a price for each component of [9]

$$P_c = \frac{P_m(a - s)}{\beta}. \tag{5}$$

Notice that as β rises, the market power of each component producer declines, and the mark-up of price over marginal cost diminishes as well. The profit, $P_c x_0 - P_m((a - s)x_0 + b - G)$, of each individual component firm is driven to zero in equilibrium by free entry and exit. Thus, using (5) and solving for x_0, the equilibrium output of each firm is

$$x_0 = \frac{\beta(b - G)}{(1 - \beta)(a - s)}. \tag{6}$$

It is useful to note that x_0 is increasing in β; each firm produces more when its variety is more easily substituted for other varieties.

The aggregate demand for factor bundles stems from two sources: component producers and infrastructure provision by the government. With regard to the latter, one possibility is that an expenditure of \$*n* by the government is needed to provide \$1 of additional infrastructure to each of the *n* components producers. If so, the government has no special ability to provide infrastructure any "cheaper" than the private sector. Alternatively, infrastructure may be a pure public good; a \$1 expenditure by the government would be sufficient to provide \$1 of additional infrastructure to each of the *n* intermediate producers. And, of course, the appropriate treatment of infrastructure may lie between these extremes. We capture the range of these possibilities by summarizing total demand for factor bundles as

$$m = n((a-s)x_0 + b - G) + n^{\gamma}(sx_0 + G) . \tag{7}$$

If γ=0, G and s are pure public goods, while the case of γ=1 corresponds to treating them as pure private goods. Note that (7) summarizes the total resource demand. Regardless of the total purchases by the government, each firm receives a subsidy combination that reduces its variable costs by s and its fixed costs by G.

The domestic supply price of finished manufactures must equal the external price P_M. There are zero profits in the assembly of components into manufactures, implying $P_M M = P_c x_o n$. Using the relationship $M = n^{\alpha}x_o$, the equilibrium domestic supply price of manufactures is linked to the price of components via

$$P_M = n^{1-\alpha}P_c . \tag{8}$$

An increase in n raises productivity and, therefore, lowers the supply price. An increase in P_c, in contrast, raises P_M.

2.2 The Effect of Increased Public Infrastructure

We begin our examination of infrastructure policy by asking whether increasing public infrastructure expands the output of finished manufactures and then turn to the non-manufacturing sector.[10] To clarify the effects, we abstract from issues of distortionary-tax financing and assume that government spending is funded by lump-sum taxation of households.

Effect on Manufacturing Sector. The provision of infrastructure alters the cost structure of each producer of components, altering their preferred levels of output. This may be seen by totally differentiating (6) and using "^" to denote proportionate changes

$$\hat{x}_0 = \frac{-G}{b - G}\hat{G} + \frac{s}{a - s}\hat{s} \equiv -\delta_G \hat{G} + \delta_s \hat{s}. \tag{9}$$

Increases in G reduce x_o, with the proportionate change dependent upon the ratio of public to privately-provided fixed costs. Note that, in contrast, infrastructure provision that has the effect of lowering variable costs will raise output for each component.

Infrastructure provision induces changes in the price of components, the variety of components, and the share of resources devoted to manufacturing. Total differentiation of the remaining equations of the system (5), (7), and (8) yields

$$\hat{P}_c = \xi \hat{m} - \delta_s \hat{s}; \tag{10}$$

$$\hat{m} = \phi_n \hat{n} + \phi_x \hat{x} - \phi_s \hat{s} - \phi_G \hat{G}; \tag{11}$$

where

$$\phi_n = \frac{n\left((a-s)x_0 + b - G\right) + \gamma n^{\gamma}(sx_0 + G)}{m}, \tag{12a}$$

$$\phi_x = \frac{n\left((a-s)\,x_0 + n^{\gamma}\, sx_0\right)}{m}, \tag{12b}$$

$$\phi_s = \frac{(n - n^{\gamma})\, s x_0}{m}, \tag{12c}$$

$$\phi_G = \frac{(n^{\gamma} - n)\, G}{m}; \tag{12d}$$

and

$$\hat{P}_M = 0 = (1 - \alpha)\,\hat{n} + \hat{P}_c . \tag{13}$$

The price of components is affected directly by the subsidy to variable costs and also by changes in m that influence the relative price of factor bundles (see (10)). If resources are pulled away from wheat production $(\hat{m} > 0)$, the price of factor bundles will rise, with the extent of this rise dependent upon the curvature of the production possibility frontier (ξ). One may trace the change in demand for factor bundles $(\hat{m})$ to three sources: changes in the number of components producers, changes in the level of their production, and changes in direct government purchases of factor bundles (see (11)). Equation (13) embodies the external-price constraint on the supply price of finished-manufactures. An increase in the number of components has a negative effect on the supply price (if $\alpha > 1$), which must be offset by the positive effect of an increase in the price of components.

How does infrastructure affect output and productivity in equilibrium? To begin, focus on changes in G; i.e., infrastructure provision that reduces fixed costs. Solving (9) through (13) yields the proportionate changes in the price of components, factor bundle demand, and the number of component varieties. The resulting changes are

$$\frac{\hat{P}_c}{\hat{G}} = \frac{(\alpha - 1)\xi\,(\phi_x \delta_G + \phi_G)}{D} > 0 , \tag{14}$$

$$\frac{\hat{m}}{\hat{G}} = \frac{(\alpha - 1)(\phi_x \delta_G + \phi_G)}{D} > 0 \ , \tag{15}$$

and

$$\frac{\hat{n}}{\hat{G}} = \frac{\xi(\phi_x \delta_G + \phi_G)}{D} > 0 \ , \tag{16}$$

where $D \equiv \xi\phi_n - (\alpha\text{-}1) > 0$.[11]

Equation (14) is the key to understanding why an increase in G causes n to rise. The external market for finished manufactures disciplines this small economy. Infrastructure provision pulls primary factors into component production, raising the marginal cost of factor bundles in terms of wheat. *Ceteris paribus*, component producers pass along the cost increase, but with a mark-up determined by the extent of their market power (β). An increase in component prices must be accompanied by an expansion in varieties if the economy is to remain a competitor in finished manufactures. Because of the mark-up, however, profits in the components industry are positive at the initial n, inducing entry. Thus, an increase in public infrastructure increases the number of component producers and enhances any external economies of the finished manufactures industry.

Unfortunately, an increase in the number of components producers is not sufficient to guarantee an expansion of the manufacturing sector. Using (4′), the proportionate change in finished manufactures is

$$\hat{M} = \alpha\hat{n} + \hat{x}_o. \tag{17}$$

As seen in (9), an increase in public infrastructure that reduces the firm's fixed costs lowers the profit-maximizing level of output. Using the solutions for $\hat{n}$ and $\hat{x}_o$,

$$\frac{\hat{M}}{\hat{G}} = \frac{\xi\delta_G(\alpha\phi_x - \phi_n) + \alpha\xi\phi_G + (\alpha - 1)\delta_G}{D} \quad . \tag{18}$$

A sufficient condition for $\hat{M} > 0$ is that $\alpha\phi_x - \phi_n > 0$ as the other terms in the numerator of (18) are positive. To see the forces at work, consider the effect of initial infrastructure provision by evaluating this expression in the vicinity of $s = 0$, $G = 0$. In this case, $\hat{M} > 0$ if

$$(\alpha - 1)\left[\frac{ax_0}{b}\right] > 1 \ . \tag{19}$$

Essentially, the less important are fixed costs, the less the decline in fixed costs affects x_0, and the more likely M is to rise. Alternatively, one may rewrite (19) as

$$(\alpha - 1) > \frac{(1 - \beta)}{\beta} \quad . \tag{20}$$

The left side of (20) is the rate at which the economy realizes returns to variety (see Ethier [1982]) while the right side is a measure of firms' market power: the percentage markup over marginal cost. If the return to variety dominates the ability of firms to capture the returns to restricting output, M will rise. Alternatively, if firms have sufficient market power to enforce greater markups, the contraction of x_0 will dominate and M will fall. Equation (20) drives home the lesson that the productivity effects of infrastructure depend upon market structure as well as technological factors.

As noted earlier, it may be inappropriate to characterize infrastructure as reducing fixed costs exclusively, suggesting a parallel investigation of the effects of changes in s on the structure and level of output in the manufacturing sector and the economy as a whole. To begin, recall that a subsidy to marginal costs raises the scale of production (x_0) for each producer of components (see (10)). However, unlike G, changes in s also affect directly the pricing decisions of components producers (see (11)). Hence, the predicted impacts differ substantially. Specifically, the effects on the price of components, factor bundles used in manufacturing, and the variety of components are given by

$$\frac{\hat{P}_c}{\hat{s}} = \frac{-(\alpha - 1)[\xi(\phi_x \delta_s - \phi_s) - \delta_s]}{D} \gtrless 0, \tag{21}$$

$$\frac{\hat{m}}{\hat{s}} = \frac{\phi_n \delta_s - (\phi_x \delta_s - \phi_s)(\alpha - 1)}{D} \gtrless 0, \tag{22}$$

and

$$\frac{\hat{n}}{\hat{s}} = \frac{-[\xi(\phi_x \delta_s - \phi_s) - \delta_s]}{D} \gtrless 0. \tag{23}$$

Clearly, to the extent that infrastructure has its effect on marginal costs in the manufacturing sector it will be difficult to predict its impact. Consider first the pricing of components. The subsidy directly reduces the marginal cost of factor bundles and, *ceteris paribus*, lowers P_c. However, if the new equilibrium results in a net increase in m, the increase in the gross price of factor bundles may outweigh this subsidy.

However, as shown in (22) the direction of impact on total factor usage is unclear, a direct result of the ambiguous effect on variety (23). Intuitively, an increase in s raises output per producer of components. Other things equal, this increases m, P_m, P_c, and, hence, the number of varieties required in equilibrium to meet the external competitive pressures imposed by P_M. However, at the same time, the subsidy directly reduces the price of components (see (5)), and, hence, reduces the number of varieties required to meet trade pressures. The net effect is ambiguous.

Given the ambiguities, it is hardly surprising that manufacturing output may either rise or fall in response to the reduction in variable costs. Formally,

$$\frac{\hat{M}}{\hat{s}} = \frac{\alpha \epsilon \phi_s + \delta_s - \epsilon \delta_s (\alpha \phi_x - \phi_n)}{D} \gtrless 0. \tag{24}$$

A sufficient condition for $\hat{M}>0$ is that $\alpha \phi_x - \phi_n < 0$, exactly the opposite of the sufficient condition for G examined above. In this case, if firms have little mark-up power, the subsidy will lead to a relatively small reduction in P_c and have accordingly smaller effects on n. In these circumstances, the increases in x_0 will dominate and manufacturing output will rise.

To summarize, our investigation suggests that the effects of infrastructure provision are far from direct and clear-cut. Reductions in fixed costs will have far different effects than reduction in variable costs, and the effects of the latter are quite complex.

Effect on Non-Manufacturing. With fixed supplies of capital and labor, wheat production rises (falls) as factor bundles are released (acquired) by the manufacturing sector; m and W move in opposite directions. Inspection of (15) and (22) reveals that W will fall as G rises, but increases in s will have an ambiguous effect on non-manufacturing production.

3. INFRASTRUCTURE AND PRODUCTIVITY: EMPIRICAL ANALYSES

In this section, we use the general equilibrium model presented above to guide our empirical analysis of the relationship between infrastructure provision and productivity in the manufacturing and the non-manufacturing sectors. We begin with a discussion of data sources and econometric considerations and then turn to the empirical results.

3.1 Data

The first step is to choose empirical counterparts to the variables in our highly stylized model. We measure M as output of the manufacturing sector, using the Bureau of Economic Analysis' (BEA) state-by-state series on Gross State Product originating in the private sector. Similarly, W is measured as the output of the non-manufacturing sector from the same source. While it may be tempting to consider each major group within the manufacturing sector separately, data limitations (especially private capital) preclude such an approach. Moreover, we have no theoretical guidance for untangling the differential responses of each subgroup to expanded infrastructure provision. Still, such disaggregation may be a fruitful area for future research.

A distinguishing feature of our approach is the important role played by variety in the intermediates sector. In the theory, the number of firms, n, corresponds exactly to variety since no two firms produce exactly the same variety of input. Obviously, our data do not identify "intermediate varieties"; indeed, they do not contain direct estimates of activity at each stage of production. The manufacturing sector is, however, extensively interlinked, with the products of each sector (e.g., steel) serving as inputs to the production of other sectors (e.g., autos). And, at least to some extent, each production facility has its own set of activities. Hence, we use data on the number of manufacturing establishments as a proxy for the range of varieties contributing to manufacturing productivity. These data are obtained from the quintennial Census of Manufactures for each of the 48 contiguous states for the years 1972, 1977, 1982, and 1987.

Several issues arise in our use of these data. First, as with our output measures, it would be desirable to distinguish between producers of final goods and producers of intermediates, but such a distinction is simply not possible. Second, we would like to guard against the possibility that an increase in the number of establishments does not represent a rise in the variety of activities. For example, consider two states, one with 100 establishments concentrated in a single activity and the other with 80 establishments distributed evenly across the range of manufacturing sectors. It seems inappropriate to identify the former state as having greater variety than the latter.

With this in mind, we develop a measure of the dispersion of manufacturing establishments across activities. For each state, we compute the coefficient of variation (c.v.) of the number of manufacturing establishments across 2-digit Standard Industrial Classification codes (SIC). Note that if there are the same number of establishments in each SIC code, and hence a great variety of manufacturing activity, the coefficient of variation will be equal to zero. In contrast, if establishments are concentrated in a few, or even a single, area, the c.v. will be quite large.[12]

We turn now to our measures of public and private inputs. Public capital stocks are estimates of the stock of state and local government capital in each state as constructed by Holtz-Eakin [1993]. (The exclusion of federal government capital is unimportant in practice as it is largely devoted to military capital.) These data include the total real capital in each state for each year, but also individual estimates for capital devoted to specific government functions such as schools, streets and highways, etc. In large part, we focus on total public capital in our analysis. However, because this measure includes capital such as public school buildings, which may not be included in common definitions of infrastructure, we test the sensitivity of our results to using a narrower measure of public capital which we call "core infrastructure." Core infrastructure is measured as the sum of capital in streets and highways, sanitation and sewerage systems, and utilities.

For private inputs, estimates of private sector capital in each state and sector are taken from Munnell [1990]. Labor inputs are measured using BEA data on full-time and part-time wage and salary employees in each state and sector.

3.2 Econometric Considerations.

In what follows, we will be interested in equations having the generic form

$$y_{it} = x_{it}\beta + \gamma_t + \mu_{it} , \tag{25}$$

where i indexes states, t indexes years, y is the logarithm of, for example, manufacturing output, x is a vector of (logarithms of) explanatory variables including public sector capital, γ_t is a year-specific intercept, and μ_{it} is a regression disturbance term.

In analyzing the effects of infrastructure, Holtz-Eakin [1994] demonstrates the importance of controlling for unobserved heterogeneity among the states. In short, because more productive states have a greater ability to undertake public works, *ceteris paribus*, cross-sectional heterogeneity in productivity will generate variation in public capital. In the presence of this reverse causality, ordinary least squares will yield inconsistent estimates of the parameters. To confront this difficulty, we augment our basic estimating equations with f_i, a state-specific intercept. Importantly, the state-specific effects are time-invariant, capturing the effects of location, climate, mineral endowments, and so forth. Thus, the equations become

$$y_{it} = x_{it}\beta + \gamma_t + f_i + \mu_{it} . \tag{26}$$

To control for the state effects, we employ standard fixed-effect techniques that estimate the parameters using the variation "within" each state over time. Specifically, we transform the data into deviations from state-specific means, yielding

$$\tilde{y}_{it} = \tilde{x}_{it}\beta + \gamma_t + \mu_{it}, \tag{27}$$

where $\bar{y}_i$ is the mean value of y_{it} for state i, $\bar{x}_i$ is defined analogously, $\tilde{y}_{it} \equiv y_{it} - \bar{y}_i$, and $\tilde{x}_{it} \equiv x_{it} - \bar{x}_i$. As indicated by the absence of the f_i from equation (27), the use of deviations eliminates the state-specific effects.[13]

3.3 Results

It is by now widely recognized that there is a positive correlation between infrastructure and output. In the context of our data, this finding is confirmed; a regression of the logarithm of manufacturing output on the logarithm of public capital yields a coefficient (standard error) of 0.637 (0.127), while a similar regression for non-manufacturing private output yields a coefficient of 0.360 (0.0877).[14,15]

Our theoretical model assumes that public capital does not directly affect non-manufacturing. Its only influence is through its effect on private sector inputs ("factor bundles") to the sector. Thus, as a first check, we examine the effect of public capital, K_g, on W, controlling for private sector labor, L_W, and capital, K_W, in non-manufacturing. Looking at the data yields

$$\tilde{W} = \underset{(0.0623)}{0.326}\,\tilde{K}_W + \underset{(0.0661)}{0.744}\,\tilde{L}_W - \underset{(0.0343)}{0.00776}\,\tilde{K}_g. \tag{28}$$

These results support the notion that public capital's direct productivity effect, if one exists, arises in the manufacturing sector.

Our model suggests that infrastructure affects manufacturing through a variety of channels. The first of these is by altering the preferred scale of production for each firm in the manufacturing sector. Recall from above that to the extent that infrastructure subsidizes fixed costs, x_0 will fall, while to the extent that it reduces variable costs we anticipate greater output. We do not have a direct measurement of intermediate output per firm, but we can examine the impact of infrastructure on output per establishment in the manufacturing sector, *M/n*. Examination of equation (4′) indicates that this does not directly yield an estimate of x_0. Instead

$$\frac{M}{n} \equiv x'_0 = n^{\alpha-1}x_0, \tag{29}$$

suggesting that if one first controls for variation in n, the effect of infrastructure on x'_0 and x_0 will coincide. Implementing this strategy, we regress output per manufacturing establishment on the logarithms of the number of establishments and public capital (K_g). The result is

$$\tilde{x}' = \underset{(0.113)}{0.0332}\,\tilde{n} + \underset{(0.116)}{0.0608}\,\tilde{K}_g, \tag{30}$$

indicating a small, imprecisely estimated impact of additional infrastructure on output per firm.[16] In the context of the theoretical model, the result suggests that the reduction in fixed costs embodied in infrastructure nearly offset the concomitant reduction in variable costs.[17]

As noted earlier, we wish to check the robustness of our results using our c.v. measure of the dispersion of establishments across SIC codes. To do so, we interact n with our c.v. measure, σ. Recall that a larger value of σ is associated with lower variety, hence, we expect this interaction term to have a negative sign. Our augmented regression is[18]

$$\tilde{x}' = \underset{(0.121)}{0.163}\,\tilde{n} - \underset{(0.00934)}{0.0379}\,\widetilde{\sigma n} + \underset{(0.107)}{0.0147}\,\tilde{K}_g. \tag{31}$$

The interaction variable is statistically significant and indicates a positive relationship between the richness of the local environment and output per establishment. With regard to public capital, however, expanding our control for variety has little impact on the small, positive, imprecisely-estimated effect on output per establishment.[19]

The second major channel by which infrastructure may operate is through the equilibrium number of firms. A simple regression of the logarithm of the number of manufacturing establishments on (log) public capital yields a coefficient of 0.557 (0.0882); the data reveal a positive and significant correlation between public capital and the number of establishments.[20] One objection to this procedure is that it fails to control for the resources available to the manufacturing sector. Augmenting the regression with private capital (K_P) and labor (L_P) in the state yields

$$\tilde{n} = \underset{(0.0683)}{-0.202}\tilde{K}_P + \underset{(0.0815)}{0.828}\tilde{L}_P + \underset{(0.0500)}{0.169}\tilde{K}_g \,. \tag{32}$$

Our theory does not provide an interpretation of each coefficient in this reduced form, but the regression continues to indicate that public capital does more than transfer private resources to the manufacturing sector. Infrastructure appears to contribute significantly to the growth of the number of manufacturing establishments.[21]

Thus far, the picture that emerges is one in which public capital has little effect on the level of production per establishment, but an upward effect on the number of firms in manufacturing. As a check on the model, however, note that infrastructure provision should influence total manufacturing output only through its effect on output per firm and the number of varieties. The first of these effects appears to be roughly zero. Thus, if one controls for the private inputs (factor bundles) used to produce x_0 and the number of firms, public capital should have little residual explanatory power. We use manufacturing capital per firm and labor per firm to proxy for the factor content of x_o and implement this strategy, yielding the regression

$$\tilde{M} = \underset{(0.0426)}{0.300}\tilde{k}_M + \underset{(0.0877)}{0.892}\tilde{l}_M + \underset{(0.0678)}{0.995}\tilde{n} - \underset{(0.0675)}{0.132}\tilde{K}_g, \tag{33}$$

where lower case letter denote per-firm values; e.g. $k_M \equiv K_M/n$. In equation (33) the per-firm levels of capital and labor (our controls for "factor bundles" per firm) have a strong (and not surprising) influence on the level of manufacturing output. Similarly, the number of manufacturing establishments translates into greater output.[22] Notice, however, that after controlling for these features, additional public capital does not lead to greater manufacturing output; indeed, the point estimate is negative.[23]

Consistent with our earlier discussion, we augment equation (33) with our c.v. measure to improve the control for returns to variety. As above, the interaction with the c.v. measure enters significantly

$$\tilde{M} = \underset{(0.0423)}{0.287}\tilde{k}_M + \underset{(0.0865)}{0.881}\tilde{l}_M + \underset{(0.0675)}{1.04}\tilde{n} - \underset{(0.00633)}{0.134}\widetilde{\sigma n} - \underset{(0.0639)}{0.144}\tilde{K}_g. \tag{34}$$

In (34), the controls for firm-level resources ($\tilde{k}_M$ and $\tilde{l}_M$) continue to display an important role.[24] However, the alternative specification does *not* alter our calculations regarding public capital.

Equations (33) and (34) are modified versions of the standard "production function" approach to analyzing the productivity effects of public infrastructure, and the absence of direct effects from K_g are consistent with the findings of that literature. However, viewing the data through the lens of our equilibrium model suggests that the existing analyses do not capture an important feature of the data. While additional public infrastructure may have little direct effect on manufacturing output, the results presented above are suggestive of an important effect on the number of manufacturing firms. More generally, the character of these results suggests that the focus should shift from the effect of infrastructure on the *level* of manufacturing activity to its effects on the *composition* of activity. To the extent that increases in the range of manufacturing yield returns to variety, public infrastructure may raise the productivity of manufacturing-sector inputs.

4. SUMMARY

In this paper we have sought to analyze the productivity effects of public infrastructure in the context of a general equilibrium model. Our model was constructed in accordance with several features of the empirical literature on infrastructure productivity: potentially different effects on the manufacturing and non-manufacturing sectors, potential cost reductions in manufacturing, and returns to scale in manufacturing. By its nature our equilibrium model accounts for factor price changes induced by the provision of infrastructure.

The analytics of our model suggest that infrastructure has few unambiguous effects. Instead, the results hinge upon the degree to which publicly-provided capital reduces fixed costs of production or provides a subsidy to variable costs. Further, the magnitudes of key effects are sensitive to the market structure in which producers operate.

Framing our empirical investigation of public capital in the context of the model indicates little in the way of direct output effects from infrastructure, supporting previous production function studies. Our results, however, are suggestive of a more subtle role for public capital, working through increases in the number of manufacturing establishments. Taken at face value, the results show no productivity effects outside the manufacturing sector, and no influence on output per establishment. However, infrastructure increases the number of individual establishments, thus raising manufacturing output. Moreover, to the extent that the increase in establishments carries external returns, manufacturing productivity rises as well. Hence, our results are consistent with cost-saving and productivity effects in manufacturing.

Our study represents a first step in the use of equilibrium models to analyze infrastructure, and our results await further corroboration. However, they also point to several promising areas for future research: the role of infrastructure in the dynamics of firm creation and destruction, the measurement of external effects and returns to variety, and the differential effects of infrastructure in more disaggregate analyses.

Notes

1. See, especially, Munnell [1990a,b].

2. See Evans and Karras [1994], Garcia-Mila, McGuire and Porter [1993], Holtz-Eakin [1994], Hulten and Schwab [1991], and Tatom [1993].

3. An exception, albeit quite simple, is Holtz-Eakin and Schwartz [1995], who embed infrastructure within a neoclassical model of state-level economic growth.

4. Aschauer [1989], Munnell [1990], Garcia-Mila and McGuire [1992], and Holtz-Eakin [1994] directly estimate the production function. Nadiri and Mamuneas [1994] and Morrison and Schwartz [1992] estimate cost functions for the manufacturing sector. Hulten and Schwab [1991] indirectly examine the effects of infrastructure using growth-accounting techniques for regional manufacturing.

5. This is consistent with the findings of Morrison and Schwartz [1992] using empirical estimates of flexible cost functions for state-level manufacturing. Despite the cost-saving effect, however, our theoretical results will also be consistent with those of Hulten and Schwab [1991], who argue that a growth-accounting framework indicates little role for infrastructure in determining output.

6. Alternatively, the model can be framed using three factors: mobile capital and two immobile factors, land and labor. In this framework, all three factors are used in production of both wheat and factor bundles, with constant-returns-to-scale technology and no factor-intensity reversals. It is straightforward to show that the price-output response is normal if land and labor are substitutes so that demand for one rises when the price of the other rises. If this condition is met, the opportunity cost of factor bundles in terms of wheat rises as wheat output expands. Consequently, the results derived here for immobile factors carry over to the case of mobile capital.

7. Components have been interpreted in several ways. Ethier [1982] emphasizes specialized intermediate inputs. He intends to capture, via the endogenous determination of the number of component varieties, the possibility of returns to scale arising from the division of labor. He notes that, alternatively, one could interpret the intermediate goods as successive manufacturing stages. Markusen [1989] interprets the intermediate goods as producer services that are knowledge-intensive, requiring a high initial investment in learning.

8. Ethier [1979,1982] assumes components are traded. In contrast, Markusen [1991] assumes that intermediates are nontradeable, identifying them as knowledge-based, specialized business services. Markusen argues that such services are costly to trade internationally or face high tariff barriers. Our emphasis on geographical concentration is similar in spirit to recent analyses of spillover and agglomeration; see, for example, Dekle and Eaton [1994] or Henderson [1994].

9. Marginal private cost is $P_m(a\text{-}s)$, while marginal revenue is βP_c. The latter may be derived by recognizing that cost-minimizing producers of manufactures will have relative demands $x_o = x_1 (P_{c1}/P_{c0})^{\frac{1}{1-\beta}}$ for any two components x_0 and x_1, leading to a revenue function $P_0 x_0 = P_1 (x_1)^{1-\beta} x_0^{\beta}$.

10. Our focus is on the positive effects of infrastructure. Normative questions are analyzed in Holtz-Eakin and Lovely [forthcoming].

11. The condition $D > 0$ is necessary for the manufacturing sector to display a positive price-output relationship. We assume $D > 0$ throughout; effectively limiting our analysis to the concave portion of the production frontier for W and M. See Markusen [1989] for a discussion of the features of this frontier.

12. One issue that arises is the treatment of zeros. One might wish to concentrate on variety *given* that there is some activity at all (i.e., exclude zeros). Also, for confidentiality reasons some establishments are not identified in the *Census of Manufactures*. In practice, the exclusion of zeros has little impact on the character of the results. However, with the latter issue in mind, we concentrate on the c.v. computed excluding zeros.

13. See Hsiao [1986] for a discussion of fixed-effect estimations.

14. Each regression reported herein controls for state-effects, and contains an intercept and dummy variables for the years 1977, 1982, and 1987. Heteroskedasticity-consistent (Huber) standard errors are reported in parentheses.

15. Using our narrower measure of core infrastructure capital does not alter the character of the relationship. The respective estimates are 0.489 (0.113) and 0.362 (0.0750).

16. Our theoretical model suggests as well that n is determined simultaneously with x. Recall that endogeneity in the cross-section will likely manifest itself as fixed effects, and our equations control for this feature of the data. Variations in n and x over time remain, however, suggesting that it might be desirable to apply an instrumental variables technique to (30). (Similar considerations apply in other circumstances below.) Unfortunately, it is difficult to construct a variable affecting the number of establishments that is unrelated to output per establishment, especially given the paucity of data at our disposal. Hence, we do not pursue this route.

17. Also, the point estimate of α implied by equation (30) is 1.033, but this coefficient is imprecisely estimated. Using core infrastructure yields similar results. One might be concerned that the specification in (30) treats public capital as a pure public good. Notice, however, that entering public capital in per-firm units would not affect its coefficient. Instead, only the coefficient on the growth of firms (and our estimate of α) would be affected (rising toward 1.1).

18. One could include the level of σ as well as its interaction with n. This reduces the precision of the individual estimates, but does not alter their qualitative character.

19. One may derive an estimate of α from (31) by differentiating with respect to n and evaluating the result at the mean value of σ (1.173). The result implies an α of 1.12.

20. Again, using core infrastructure public capital does not alter the basic conclusion. The estimates are 0.399 (0.0821).

21. Again, focusing on infrastructure capital alone give qualitatively similar results.

22. The implied value of α here is 0.995, somewhat smaller than that estimated by equations (30) or (31).

23. As above, entering the public capital in per-firm units does not alter this conclusion. See note (17). Also, while the magnitudes differ, the point estimates derived using core infrastructure capital are quite similar in character.

24. As before, including the dispersion of establishments as a control raises the implied estimate of α, here raising it from 0.995 to 1.02. We obtain similar results if we use core infrastructure or if we enter the level of σ directly into (34).

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