Public Infrastructure and Economic Productivity

A Transportation-Focused Review

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Economists' interest in the question of public infrastructure productivity has grown steadily since the 1980s. This paper reviews the literature on this topic with a particular focus on transportation's economic impact. Cumulative evidence reveals that, first, estimates of the elasticity of output with respect to public capital have declined over time and are currently indistinguishable from zero. Second, highways have local negative spillover effects that arise from economic activities being drawn to infrastructure-rich locations at the expense of adjacent areas. Third, transportation infrastructure is subject to congestion, which reduces the productivity of such infrastructure even when stocks remain constant. Finally, highways consistently enhance the productivity of manufacturing firms even when they do not do so for firms in other sectors.

Is transportation economically productive? The answer to this question is no small matter. Over the past half century, the United States has built the world's most extensive transportation system, the bulk of which involved laying in over 160,000 miles of Interstate and other National Highway System roads (*1*).

Justifications for creating this expanse of public infrastructure have evolved over the years. A common thread, however, is the notion that transportation infrastructure makes the economy more productive. Over the past 20 years, a growing number of researchers have studied the validity of this justification through a much broader question: is total government capital, usually defined as transportation infrastructure, water facilities, and sewer systems, economically productive?

Although this broader question may cloud the waters somewhat, lessons learned from this body of research have highly focused implications for the transportation professions for a number of reasons. First, transportation comprises the single largest component of most public capital stock estimates used in studies. The Bureau of Economic Analysis (*2*) estimated that in 2003, transportation infrastructure accounted for 35% of the estimated $5.5 trillion in total state and federal (nonmilitary) fixed assets. Other large categories of public capital included education structures (19%); water, power, and sewer facilities (15%); and commercial, office, and residential structures (12%). Fraumeni (*3*) reviews these and other estimates, revealing the many ways that public capital can be measured and categorized.

Second, there is a strong theoretical and intuitive connection between transportation and productivity. An enormous literature on agglomeration economics suggests that distance adds cost to most economic transactions because time and energy must be spent to cover distance. Thus, improving transportation should make the economy more efficient by reducing the amount of time and energy necessary to cover distances between firms, consumers, and employees. By this reasoning, transportation infrastructure is frequently perceived to influence productivity more than other types of public capital. Mikelbank and Jackson (*4*) provide a thorough summary of the link between transportation, economic development, and productivity.

Finally, transportation investment decisions are strongly influenced by the federal government via the federal transportation bill. Because of this, and because transportation is the single largest component of total public infrastructure, policymakers frequently equate "public capital" with "highways." Thus, research analyzing public infrastructure can affect transportation investment policy more strongly than the other types of government capital listed above.

The present challenge is thus to review and discuss the findings of this growing literature with a focus on implications for transportation professions, including planning and policy. This paper begins with a review of evidence on transportation and total public capital productivity. This section highlights the three most common methodologies, generally following the evolution of the literature. The paper then addresses the question of spillover effects; that is, whether economic impacts of infrastructure are contained within a specified region. This section addresses the question, "if a highway has positive local effects, do they come at the expense of other jurisdictions in the larger region?" Finally, the cumulative evidence is summarized, and a broad interpretation is offered of some of the major results and trends.

STUDIES AND RESULTS

Aggregate Production Function Studies

The aggregate production function (APF) has been the most common tool used to study the economic productivity of public infrastructure. The most basic model postulates that national output Y is a function of a few variables:

$$Y = A[f(K, L, G)] \tag{1}$$

where f is an unspecified function of private capital K, labor L, and exogenously supplied public infrastructure G. The constant A describes total factor productivity. To estimate the model, most researchers assume a Cobb–Douglas functional form:

$$Y = AK^{\alpha}L^{\beta}G^{\gamma} \tag{2}$$

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Taking natural logs and adding an error term forms the estimable equation

$$\ln Y = \ln A + \alpha \ln K + \beta \ln L + \gamma \ln G + \epsilon \qquad (3)$$

where γ is the elasticity of output with respect to public capital. The elasticity, mathematically defined as $\partial Y/\partial G * G/Y$, is interpreted as the percent change in output resulting from a 1% increase in public capital. Marginal productivity, then, is calculated as $MP = \gamma * Y/G$, revealing the return to each dollar invested in public infrastructure.

Differences among research results arise primarily from differences in data classification and model specification. Data vary in levels of geographical aggregation (United States, regions, states, metropolitan areas, counties), and public capital can be disaggregated to varying degrees, thereby testing the effect of different types of public infrastructure. More important is model specification. There are many variations of the Cobb–Douglas model, and a few researchers have used alternative functional forms. Within the Cobb–Douglas framework, different assumptions are possible regarding returns to scale, and for any specification, the error term may be expanded to control for various types of estimation bias. Each of these possible variations affects the qualitative nature of research results. These topics are addressed as they arose in the evolution of the literature.

The idea of adding public capital to an APF has been around at least since Arrow and Kurz (5), although Ratner (6) was the first to explicitly develop such a model. Using the Cobb–Douglas functional form, Ratner found public capital to significantly improve firms' productivity with an output elasticity of 0.058. His model, which included a variable to control for time trends, was estimated using aggregate public capital for the entire United States.

Ratner's results stimulated interest in the question of public capital productivity, and by the end of the 1980s a wave of research reached journals. Among these were Eberts (7) and da Silva Costa et al. (8). These two studies broke new ground by assuming a translog functional form for firm production. The translog specification is shown below with Y, K, L, and G as natural logs.

$$Y = a + bK + cL + dG + eK^2 + fL^2 + gG^2 + hKL$$
$$+ iKG + jLG + \epsilon \qquad (4)$$

The primary benefit of this model is its reduced parametric form. By including quadratic terms, returns to scale can be tested within the model rather than imposed on it, as is frequently done with the Cobb–Douglas form. Further, interaction terms provide information about whether any two inputs are complements or substitutes. Eberts (7) used a cross-section of manufacturing data for 38 metropolitan areas to calculate a just-significant output elasticity of 0.04. Using a variant of Equation 4 with value added as the dependent variable, da Silva Costa et al. (8) found public capital to have a positive and highly significant effect, rejecting the possibility of a Cobb–Douglas specification.

Interest in the question of infrastructure productivity reached a fevered pitch following research by David Aschauer and Alicia Munnell, who used updated capital stock estimates to estimate very high output elasticities. Using national data, Aschauer (9) determined nonmilitary public capital over the span 1949 to 1985 to have had an output elasticity of 0.39, and that the corresponding value for "core infrastructure," including highways, mass transit, airports, and water and sewer facilities, was 0.24. Munnell (10, 11) published two studies in 1990. The first used revised national public capital stock estimates to recalculate Aschauers's model. Results confirmed high output

elasticities ranging from 31% to 39%. Concerned that national-level studies captured spillover effects nonexistent at smaller geographies, Munnell (11) estimated state stocks of public capital. Used in a similar model, these less aggregated data suggested a lower but still qualitatively impressive elasticity of 0.15, with highways alone contributing 0.06. Together, these results were extraordinary because they implied that government capital offered a better rate of return than other types of investment at the time and was more beneficial to output than private capital. For example, Munnell's state data suggested that $1.00 spent on government infrastructure increased national output by $0.60, a rate twice as high as private capital for the period studied.

The elasticities found by Aschauer (9) and Munnell (10, 11) were corroborated by other researchers. For example, Holtz-Eakin (12), Ram and Ramsey (13), and Ford and Poret (14) each used national data in Cobb–Douglas specified APF models to calculate elasticities of 0.39, 0.24 and 0.39–0.54, respectively. The upper range of Ford and Poret's results suggested a rate of return near 100%. Eisner (15) used state-level data in a model similar to Munnell (11) to calculate an output elasticity of 0.17. Finally, Garcia-Milà and McGuire (16) found highways to be productive at the state level with an elasticity of 0.05.

As evidence accumulated that government spending on infrastructure had positive effects on productivity at the national and state levels, some researchers and politicians reasoned that the falloff in infrastructure spending beginning around 1973 may have partially contributed to the period of sluggish productivity in the following decade (12, 17). Several conferences were held in the early 1990s to address the so-called infrastructure crisis.

At the same time, however, a second wave of research surfaced to challenge the astonishing productivity results implied by the bulk of the previous research. Initially, it was argued by Aaron (18), Jorgenson (19), and Hulten and Schwab (20) that the high values and wide range of output elasticity estimates rendered the overall conclusions circumspect. This broad question of robustness led to more specific methodological criticisms. The first was that time-series data are not stationary and must be detrended to eliminate spurious correlation. Related to this, models estimated using state or metropolitan area cross-sectional data were criticized for not controlling for region-specific effects. In other words, in a state model, public capital investment and productivity increases could each be a byproduct of variation in state economic vitality. Finally, researchers considered the possibility of reverse causality, the idea that rather than public capital increasing productivity, rising productivity increased governments' ability to finance public capital or stimulated demand for such infrastructure (or both). These criticisms are well summarized in reviews by Munnell (17) and Gramlich (21).

Two early attempts to address some of the above criticisms were made by Eberts and Fogarty (22) and Tatom (23). The first set of authors examined the question of causality by testing whether public investment led private investment for 40 metropolitan areas from 1904 to 1978. Their results were ambiguous, however, due to their finding that the direction of causality depended on whether the metropolitan area grew rapidly before or after 1950. Tatom (23) tested for stationarity, determining that merely using log levels introduces bias into the results. He addressed this problem by translating variables to first-differences and adding a time trend in the error term. First differencing uses changes over constant time intervals; for example, $(Y_{1973}–Y_{1953}; Y_{1974}–Y_{1954})$. Using a first-differenced Cobb–Douglas model including energy as an input, Tatom (23) found no evidence that public infrastructure significantly affects national productivity.

Further research refined the APF approach. Evans and Karras (24) tested a variety of error specifications in both Cobb–Douglas and

translog models. Their "best" model used a first-differenced Cobb–Douglas model detrended for state and time effects. Using disaggregated public capital estimates, the authors found strong evidence that educational capital is productive but that all other types of government capital, including highways, are unproductive, and frequently negative. These conclusions were substantiated by similar studies by Sturm and de Haan (25) and Holtz-Eakin (26), who raised the question of using fixed versus random state effects. He further offered the possibility of using long-differences, or differences over all possible time periods, for example (Y_{1973}–Y_{1953}; Y_{1973}–Y_{1954}). Estimating a variety of models, Holtz-Eakin (26) concluded that "findings of a statistically and economically significant, positive elasticity for public sector capital are an artifact of restrictions placed on the error structure. When using more appropriate techniques, the most plausible estimate of this elasticity is zero."

In similar work, Garcia-Milà et al. (27) rigorously and systematically evaluated various Cobb–Douglas specifications to arrive at a model using first-differences (versus levels) and fixed state effects (versus no state effects or random effects). Their model, estimated with disaggregated public capital stock estimates, suggests that highways have a negative output elasticity of -0.058. Krol (28) achieved the same qualitative result using both Cobb–Douglas and translog specifications.

Recent research using the APF explores subtler questions of public infrastructure productivity than does earlier work. For example, Kelejian and Robinson (29) tested for spatial autocorrelation in the residual term of a variety of Cobb–Douglas specifications. This approach, which will be discussed further in the section on spillover effects, suggested that total public capital and highways contribute negatively to output. Other research by Holtz-Eakin and Schwartz (30) that focused on spillover effects confirmed a slightly negative output elasticity of highways.

Boarnet (31) and Hulten (32) independently made a conceptual breakthrough by noting that if infrastructure is productive, it is so because of the service it provides (mobility, in the case of highways). Moreover, they recognized that streets and highways are subject to congestion that can reduce the flow of services, even when capital remains constant. Boarnet (31) examined the differential impact of increasing the size of highway stock (i.e., expanding capacity) versus using the existing highway network more efficiently. Using California county data in a Cobb–Douglas production function that controlled for congestion, Boarnet (31) determined that "transportation policies should focus at least as much on reducing congestion as on building more street and highway capital."

Finally, Fernald (33) confronted the question of causality by hypothesizing that if highways are productive, industries highly dependent on transportation should benefit disproportionately from expanding highway infrastructure. A refutation of this hypothesis would indicate that causality runs from productivity gains to infrastructure investment. Fernald (33) developed a Cobb–Douglas model that included variables for both the amount of transportation infrastructure and the flow of service it provides. Using national data disaggregated by industry type, he found that over the period 1953 to 1989, vehicle-intensive industries benefited disproportionately from road building, which suggests causality from roads to productivity. However, he also found returns to be much higher before 1973 than after, and concluded that

> the industry data do not support the view that roads offer an abnormal return at the margin, or that returning road growth to pre-1973 levels would raise productivity growth to pre-1973 levels. In essence, the

evidence suggests that the massive road-building of the 1950's and 1960's . . . offered a one-time increase in the level of productivity, rather than a continuing path to prosperity.

Aggregate Cost Function Models

Although not as frequently used as the production function, the aggregate cost function (ACF) offers a more theoretical approach to understanding not only if but how public capital is productive. The basic model builds an ACF for firms in a specific geographic area or industry:

$$C = f(Y, \boldsymbol{X}, \boldsymbol{P_X}, t) + P_K K + P_G G \qquad (5)$$

In this equation, f is an unspecified variable cost function dependent on output Y, a vector of variable inputs $\boldsymbol{X}$, a vector describing the prices of variable inputs $\boldsymbol{P_X}$, and a time variable t measuring disembodied technical change. Variable public inputs such as services extracted from highway and water infrastructure are included in $\boldsymbol{X}$. The remaining two cost function terms are fixed private inputs K and public inputs G with corresponding prices. If firms are thought to bear no cost of public capital investment, the last term is dropped, and the entire effect of public capital comes through variable costs.

This framework captures potential cost savings from infrastructure investment through "shadow values." If government builds a highway that is useful to firms, cost savings are realized through their ability to reduce the levels of other variable cost inputs. From this shadow value, it is possible to calculate the cost elasticity of public capital, defined as the percent change in costs resulting from a 1% change in public capital. Infrastructure is productive if this elasticity is negative. Morrison and Schwartz (34) noted that under the assumptions of constant returns to scale and instantaneous adjustment, cost elasticity has the same magnitude and opposite sign of output elasticity determined with the APF method using equivalent data.

The ACF has several interrelated advantages over the production function method. Qualitatively, the cost function more realistically models economic decisions made by firms by acknowledging the influence of factor prices on firms' decisions. Because prices (and technology) are the only exogenous variables in the cost function model, output and inputs are set endogenously (as a function of prices) and it is possible to trace indirect effects of changes in public capital. These indirect effects reveal whether public capital either complements or substitutes other production inputs. APF models, in contrast, do not consider prices or costs, taking only inputs as exogenous. Cost function studies are limited, however, because historical price data is typically available only for manufacturing firms, whereas input estimates are much more widely available.

In the earliest application of the cost function to study the productivity of public capital, Keeler and Ying (35) considered how the U.S. Federal-Aid Highway System affected the cost structure of the trucking industry from 1950 to 1973. Using a translog cost function with data aggregated by U.S regions, the authors found, perhaps unsurprisingly, that the U.S. Highway System significantly reduced the costs of trucking firms, with a cost elasticity of −0.073. Deno (36) took a slightly different approach by estimating a profit function for manufacturing industries in 36 standard metropolitan statistical areas (SMSAs) over the period 1970 to 1978. This approach differs only slightly from the cost function by adding a revenue term and by assuming that firms maximize profit rather than minimize costs. Using data disaggregated into water, sewer, and highway public capital, Deno (36) found that total public capital increased the output with an elasticity of 0.688. The equivalent figure for highways was 0.313. Deno's

(*36*) research also made an early attempt to capture the flow of services from public capital by "apportioning." However, his method, which multiplied a city's public capital stock by the percent of the population employed in manufacturing, did not capture congestion, and this likely inflated his results. Lynde and Richmond (*37*) employed a translog model similar to Keeler and Ying's (*35*) to study the effects of public capital on the U.S. nonfinancial corporate sector from 1958 to 1989. They tested models for a variety of econometric restrictions, ultimately preferring constant returns to scale. The authors disaggregated public capital into federal and state and local components but did not distinguish between different types of infrastructure. They found that public capital provided by all government levels significantly reduced costs.

These three early ACF studies cumulatively suggested that public capital increased output by magnitudes on par with the research of Aschauer (*9*) and Munnell (*10, 11*). Following the "infrastructure crisis" debate in the early 1990s, Nadiri and Mamuneas (*38, 39*) published two cost function studies with more moderate results. The first tested U.S. manufacturing firms' response to publicly financed infrastructure and research and development (R&D) capital from 1955 to 1986. They specified a translog cost function with constant returns to scale in private inputs and used a more sophisticated apportioning method than did Deno (*36*). The model, estimated using national data disaggregated only by industry code, suggested that both types of government capital significantly reduce costs, although the cost elasticity for infrastructure was much lower than previously calculated values. Across 12 manufacturing sectors, elasticities ranged from 0 to −0.21 with an average of −0.13.

The second study published by Nadiri and Mamuneas (*39*) focused on transportation's exclusive role in reducing production costs, specifying a symmetric generalized McFadden cost function. The authors estimated the model using several alternative econometric procedures, arriving at a final model using first differenced data and controlling for spurious correlation and reverse causality. They also attempted to extract service flow from transportation capital by using apportioning techniques similar to those used in their previous research. However, their "capacity utilization" method did not capture network congestion. Using an extensive data set that included 35 sectors of the U.S. economy over roughly four decades (1950 to 1989), Nadiri and Mamuneas (*39*) calculated an overall output elasticity of 0.05 and concluded that since the end of the 1980s, "there appears to be no evidence of under or over-investment in highway capital."

Finally, Morrison and Schwartz (*34*) employed a variable cost model to study the effects of infrastructure (highways, water, and sewer capital) on manufacturing firms' cost functions in U.S. regions from 1971 to 1987. They used a generalized Leontief specification with price defined as marginal cost to determine significant cost savings. However, recognizing that government money spent on infrastructure has alternate uses, they used the "social cost" of investment levels to qualify their results and ultimately compute cost–benefit ratios. In their words,

> when a social price of public infrastructure capital is recognized, the net valuation in terms of cost savings is lower, although still positive over most years and regions . . . , but the cost-benefits of additional infrastructure for manufacturing firms alone may be smaller, on average, than the price of this investment.

General Equilibrium Models

Throughout the development of the APF and ACF literature, researchers have struggled with the limitations of these methods. Fun-damentally, production and cost function studies deliver productivity estimates without providing much insight into full market reactions to an increase in public infrastructure. While production functions assume perfectly inelastic factor inputs, and cost functions assume fixed prices, there is evidence that neither assumption is valid, particularly at state and metropolitan scales. Haughwout (*40*) noted that "if households and firms are mobile across regions, then wages and land values will vary in response to infrastructure provision, and the ACF and APF approaches can not adequately estimate the marginal productivity of public capital, let alone its social value." Thus, the closely related concepts of price variability and factor mobility cannot be addressed by traditional models. This shortcoming will be further addressed in the discussion of spillover effects. Haughwout's statement also raises the point that cost and production function studies have no way of determining the utility of public capital to households. This is no small oversight, however, because households "consume" infrastructure at least as much as firms, frequently vote it into existence, and usually pay for it. Further criticisms of the production and cost approaches arise from data issues. Because these approaches require either price or input data, models are restricted mainly to manufacturing sectors because disaggregated data for other sectors are rarely available.

The general equilibrium approach to the problem of public infrastructure productivity offers attractive solutions to these and other issues. To illustrate a basic example and clarify the above discussion, Haughwout's (*41*) model is followed. Firms produce output as with Equation 1, but minimize costs, defined as

$$C = WL + P_Z Z \tag{6}$$

where W is the wage rate for labor L, and Z is a local land input with rent P_Z. Households maximize utility obtained from consuming output Y, land Z, and public infrastructure G, represented by

$$U = U(Y, Z, G) \tag{7}$$

but are constrained by a fixed income earned by inelastically supplying one unit of labor in the production process. Thus,

$$W = P_Y Y + P_Z Z \tag{8}$$

Firms and households compete for scarce land until they reach spatial equilibrium such that households everywhere have constant utility and firms everywhere have constant costs. Equilibrium condition is defined by a particular rent structure and wage structure across the region, with corresponding equilibrium inputs and prices.

This model has several characteristics relevant to the previous discussion. First, households are included in the model, thus capturing the "social" utility of infrastructure. Second, both inputs and prices are determined endogenously, thus allowing mobile factor inputs to move in response to changes in public capital. In the model, public infrastructure is productive if $\partial Y^*/\partial G$ is positive, where Y^* is the equilibrium output level. Haughwout (*41*) demonstrated using comparative statics that it is impossible to predict the sign of this expression without specifying functional forms for technology and preferences. Thus, in the face of increased pubic infrastructure, a reduction in firms' costs does not necessarily imply that output increases, or vice versa. This result arises because household utility complicates the interaction between input costs and output.

Drawing on these lessons, Haughwout (*40*) expanded this model framework to include multiple regions and estimated it using data for select U.S. metropolitan areas. Each metropolitan area offered a fixed

land market with mobility allowed among cities. Firms could enter and leave the market but were constrained by zero profits. Furthermore, Haughwout (40) calculated the flow of services from public capital by dividing capital stocks by total population, roughly capturing congestion. His model suggests that public capital was significantly productive for the period 1972 to 1992. This productivity, however, accrued primarily to households, while marginal productivity to firms was quite low.

Haughwout was not the first researcher to employ the general equilibrium approach to this problem, however. The first such effort was made by Holtz-Eakin and Lovely (42). Their model considered the productivity of public capital in a two-sector economy with manufacturing and nonmanufacturing firms (and no households). This model allowed the authors to examine how an exogenous increase in public capital redistributed scarce resources between sectors as well as the number of firms. Using state data for the period 1972 to 1987, Holtz-Eakin and Lovely found few unambiguous results. However, they found that public infrastructure provides cost savings to manufacturing firms, thus increasing the overall number of manufacturing firms, but the net two-sector effect was likely to be negligible.

Next, Dalenberg and Partridge (43) employed a firm–household spatial equilibrium model similar to Haughwout's (40), with the important difference that Dalenberg and Partridge focused on the impacts of highways as opposed to total infrastructure. Using state-level data from 1972 to 1991, the authors estimated the model twice: once for the total private sector, and once for manufacturing firms only. As with Haughwout (41) their results suggest that highways act more as a household amenity than as an unpaid input to firms. The results also support previous research suggesting that highways benefit the manufacturing sector more than others.

More recently, Rudd (44) and Mamuneas and Nadiri (45) expanded the theoretical envelope of general equilibrium models by endogenizing government behavior. In these models, households and firms demand infrastructure investment. The government responds to the demand, financing infrastructure through taxation. Thus, public capital investment decisions are made within the model and are dependent on the behavior of firms and households. Rudd (44) estimated such a model for a single cross section (1980) of 40 SMSAs using public capital disaggregated into various components. He found that total SMSA capital stock was productive with a modest output elasticity of 0.08. Highways alone contributed significantly to output with an elasticity of 0.07. Rudd's results, however, are limiting because his model relied on only one year's observation. Addressing this limitation, Mamuneas and Nadiri (45) estimated a similar model using a half-century of data (1949–2000). In their model, which focuses exclusively on transportation infrastructure, government adjusts capital investment and taxation to minimize "deadweight loss" in the economy. Results indicate that the rate of return to highway investment was highest (and roughly constant) from 1949 to 1959 but has steadily declined since then. From 1990 to 2000, rates of return were very close to long-term interest rates, implying, according to the authors, "that the highway capital is optimally provided." Finally, the estimated marginal benefit to consumers steadily rose over the study period, while the marginal benefit to firms peaked in the 1980s and has since declined.

SPILLOVER EFFECTS

A key question studied by an increasing number of researchers using a variety of modeling methods is whether highways and other public infrastructure have spillover effects. Spillover effects arise when a particular economic activity has uncaptured (and frequently unintended) consequences beyond the scope of the activity. For public infrastructure, there exist two contrasting theories. The first posits that infrastructure has positive spillover effects; that is, the "network effect" of highways yields aggregate productivity gains beyond the sum of local gains. The network effects theory suggests that if one state builds a highway network, that network will be more productive if it is connected to a larger network of, say, surrounding states. This theory arose when early APF studies revealed greater productivity at greater levels of aggregation. According to Munnell (17) "the most obvious explanation is that, because of leakages, one cannot capture all of the payoff to an infrastructure investment by looking at a small geographic area."

More recently, researchers have theorized that transportation and other public capital could have negative spillovers at local geographies. Following this theory, productivity gains realized by infrastructure investment are to some extent offset by productivity losses in neighboring jurisdictions. Losses arise because current and future economic activity may be drawn to the locale with the infrastructure investment and away from otherwise equivalent areas.

The challenge, then, is to determine whether spillover effects are positive or negative, and at what scale they occur. Evidence has come from a variety of empirical studies. At the largest levels of aggregation, evidence has been largely anecdotal, following Munnell's logic. However, a number of researchers have focused on spillovers at the state, metropolitan, and county level.

Holtz-Eakin and Schwartz (30), Kelejian and Robinson (29), Haughwout (46), and Boisso et al. (47) each considered spillover effects at the state level. Holtz-Eakin and Schwartz (30) added a "neighboring states" term to a standard APF model and found no statistically significant evidence that the amount of highway capital in adjacent states affected a state's economies. Kelejian and Robinson (29) confirmed this result using a similar approach. Boisso et al. (47) offered contradicting evidence by employing Malmquist indexes to measure productivity growth. They found that "neighboring states' highway capital contributes to productivity growth," clarifying that this growth resulted from improved technology. Haughwout (46) took an alternative approach, considering the impact of infrastructure on house prices. His model offered detailed evidence for both state- and metropolitan-level spillover effects. He found that the level of state infrastructure had negative impacts on central cities and suburban house values, but that central city infrastructure had a positive effect on suburban house values. This second result confirmed previous metropolitan-level research by Haughwout (48).

More recent research on spillover effects utilizes smaller geographies. Studies by Rephann and Isserman (49), Boarnet (50), and Chandra and Thompson (51) all estimate productivity to firms at the county level. The first set of authors used quasiexperimental matching methods to examine regional effects of interstate highways. They categorized all U.S. counties receiving highway investments from 1965 to 1984 as urban, suburban, or rural, and they also defined counties adjacent to those receiving the highways. They found that in response to highway construction, suburban counties benefited the most, urban counties benefited a small amount, and rural counties received no measurable benefit. Adjacent counties were found to encounter many negative effects, the most significant of which was loss of retail activity.

Boarnet (50) used California county data from 1969 to 1988 to reach similar conclusions. His research first developed a theoretical model of two competing cities showing that if one city gets a productive (exogenous) increase in highway investment, then mobile factors

such as capital and labor will migrate toward that city in response to wage and price changes. The net theoretical result is that output increases in the city receiving the highway come at the expense of the other city. Drawing on the lessons from this model, Boarnet estimated an APF model similar to that of Holtz-Eakin and Schwartz (*30*), with the difference that more than one "neighbor" parameter was developed. Boarnet (*50*) concluded that "street-and-highway capital is associated with higher output within the same county and with lower output in counties with similar population density, income, or employment shares in the FIRE sector."

Most recently, Chandra and Thompson (*51*) focused on the impacts of highways on rural U.S. counties. Using a model based on Hotelling's (*52*) model of spatial competition that accounts for the age of the highway investment, the authors found negative spillover effects. Counties receiving highway investment showed statistically significant gains in total earnings roughly a decade after construction, with specific gains in Foundation for Intermodal Research and Education (FIRE), retail, and transportation and communication sectors. Adjacent counties were shown to receive a small boost in manufacturing earnings but a steady, consistent decline in retail and farming industries. The authors interpreted the evidence to indicate that "highways raise the level of economic activity in the counties that they pass directly through, but draw activity away from adjacent counties, thereby leaving the net level of economic activity unchanged in non-metropolitan areas."

SUMMARY AND INTERPRETATION

The research presented above draws together an enormous amount of theory and data. Cumulatively, the results are highly variable and frequently contradict one another. Nonetheless, there are common themes in the research, and even seemingly contradictory results can bring to light relevant trends. The following discussion highlights several of these trends.

First, research methods have continually improved over the history of public capital productivity research, increasing the robustness of recent work relative to earlier work. Methodologically, research progressed from simple production and cost function studies to highly theoretical general equilibrium models. The general equilibrium model is an attractive framework for studying the productivity question because such models can capture direct and indirect consequences of economic disturbances, model benefits to households as well as firms, and measure spillover effects by allowing economic activity to migrate to where it is most productive. According to Haughwout (*40*), general equilibrium models "emphasize the importance of infrastructure investments in affecting the relative attractiveness of places, potentially redirecting growth from infrastructure-poor areas to those which have invested more heavily." This is not to say that the simpler models, such as the APF, are without merit. Although early models may have suffered from misspecification, the literature has shown an increasing awareness of the importance of empirical specification, and recent APF research has proven fruitful in studying specific aspects of the link between infrastructure and productivity, as demonstrated by Boarnet (*50*).

Second, the question of whether highways have positive or negative externalities depends on the level of geographic aggregation and time period studied. For example, it is entirely possible for a specific transportation investment to simultaneously have positive and negative externalities at different geographic levels, a point emphasized by Mikelbank and Jackson (*4*). For example, network effects could

strengthen a multistate region while infrastructure-poor counties within that region lose economic activity to infrastructure-rich counties. It should be noted, however, that the evidence for negative spillover effects is stronger than that for positive network effects. Further, if positive network effects were ever present, authors such as Fernald (*33*) suggest that they are subject to diminishing returns. In other words, one highway network might be productive, but a second one probably is not. This perspective could help explain the consistent empirical result that estimated returns to highway and other public capital investments have declined over time.

Third, in a point highly related to the previous discussion, the productivity of transportation infrastructure cannot be adequately measured or discussed without addressing congestion. As noted by Boarnet (*50*) and many others, mobility is what is truly productive about transportation infrastructure, and congestion compromises mobility. This fact may also help reconcile early studies suggesting large output elasticities with more recent research indicating low (possibly zero) elasticities. Intuitively, returns to highway investment were high when travel speeds were unconstrained, but as congestion increased, investments in highway capital were less productive on the margin.

Fourth, the research cumulatively suggests that highways are and continue to be productive to manufacturing firms, even when they are not to other sectors. This is an interesting result, possibly explained by the fact that shipping is more important to manufacturing firms than other sectors. Moreover, manufacturing firms rely on Interstate transportation more than intraurban transportation; thus, congestion, which is mostly an urban phenomenon, may not affect manufacturing as severely as it does service sectors.

Finally, there are notable omissions in the body of research summarized above, and many questions remain. Primary among these is how differing types of transportation investment might affect the economy. For example, resurfacing and widening are two types of highway investment. Although Boarnet (*31*) touched on this issue, his APF results are far from definitive, particularly in the light of improved general equilibrium models. Moreover, public transit and highways are two different types of transportation infrastructure. No effort has been made, however, to study the differential impacts of these two types on urban areas. Given the fact that congestion continues to increase on urban networks, this is no small oversight.

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