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Spiros Bougheas,
Panicos O. Demetriades and
Theofanis P. Mamuneas

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P.O. Box 20537, 1678 Nicosia, CYPRUS Tel.: ++357-2-892101, Fax: ++357-2-750310
Web site: http://www.econ.ucy.ac.cy

INFRASTRUCTURE, SPECIALIZATION AND ECONOMIC GROWTH

By

Spiros Bougheas
Nottingham University

Panicos O. Demetriades*
South Bank University, London

Theofanis P. Mamuneas
University of Cyprus

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Abstract

We introduce infrastructure as a cost-reducing technology in Romer's (1987) model of endogenous growth. We show that infrastructure can promote specialization and long-run growth, even though its effect on the latter is non-monotonic, reflecting its resource costs. We provide evidence using data from the US Census of Manufactures which suggests that the degree of specialization is positively correlated with core infrastructure, as predicted by the model. We also provide evidence from cross-country regressions, using physical measures of infrastructure provision, which shows a robust non-monotonic relationship between infrastructure and growth.

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*Corresponding author: Professor Panicos Demetriades, Business School, South Bank University, Borough Road, London SE1 OAA, UK. Tel: +44 171 8157012. Fax: +44 171 8157076. Email: demetrpo@sbu.ac.uk.

1. Introduction

There is little doubt that the services provided by the infrastructure capital stock - for instance power, transport, telecommunications, provision of water and sanitation - are fundamental to economic activity.[1] Until the late 1980s, however, economists paid little attention to the role of infrastructure in either theoretical or empirical studies (Gramlich, 1994). Since then, interest in this issue has begun to increase largely as a result of a series of papers by Aschauer (1989a, 1989b, 1989c) which ascribed the slowdown in US productivity growth to declines in investment in infrastructure. The very high rates of return which Ashauer's work implied (in the range of 60-100 per cent per annum) sparked off a debate in the empirical literature focusing on technical issues such as the form of the production function used, and estimation techniques (for a survey see Gramlich, 1994). In particular, the work of Evans and Karras (1994) and Holtz-Eakin (1994) demonstrated quite convincingly that the high estimates found by Ashauer capture the degree to which increased income causes a higher level of government activity rather than the contribution of the latter to private productivity. Nevertheless, the same authors acknowledge that their findings do not necessarily support the argument that infrastructure is unproductive. Rather, they suggest that the inability of the literature to identify the benefits of infrastructure stems from the use of aggregate data. Characteristically, Holtz-Eakin (1994) comments: "Because there likely are narrow circumstances in which the productivity effects are positive, future research in this area should be devoted to making more precise the microeconomic linkage between the provision of infrastructure and the nature of the production process." (p. 20).

More recently, there have also been made some attempts to investigate the contribution of public capital in the context of models of economic growth (e.g. Day and Zou, 1994; Easterly, 1993; Ferreira and Issler, 1995; Holtz-Eakin and Schwartz, 1994) but the resulting models have also fallen short of explaining the precise role of public capital. Rather, it has been customarily assumed that public capital is another factor of production, which can be entered in an aggregate production function alongside private physical capital.

In this paper, we put forward a plausible explanation of the way in which the stock of public capital can contribute to the process of economic growth. We extend Romer's (1987) endogenous growth framework, which relies on specialization in production, by introducing infrastructure as a technology which reduces the fixed costs of producing intermediate inputs. Because final output is increasing in the number of intermediate inputs, infrastructure fosters economic growth by promoting specialization.[2] We model the accumulation of public capital explicitly by assuming that infrastructure formation requires resources to be taken away from the production of the final good.[3] Thus, even though infrastructure accumulation may enhance economic growth through increased specialization it has a retarding influence on growth as a result of its resource costs. These two opposing forces are shown to lead to a non-monotonic relationship between the proportion of output devoted to infrastructure formation (the "tax rate") and the steady-state rate of economic growth.

The empirical section of the paper presents two kinds of evidence that is consistent with our theoretical propositions. Firstly, we present evidence from the US Economic Census which shows that the degree of specialization in manufacturing, measured by the number of 4-digit manufacturing establishments, is positively correlated with core infrastructure. Secondly, we present evidence from cross-country growth regressions, conditioning on variables that other studies have found important in explaining growth, which confirms the existence of a non-monotonic relationship between infrastructure and long-run growth. Our infrastructure indicators comprise physical measures of infrastructure that have recently been published by the World Bank (1994). Our empirical analysis addresses possible endogeneity problems and checks the robustness of our results using extreme bound analysis (Leamer, 1983; Levine and Renelt, 1992).

The rest of the paper is organized as follows. Section 2 presents the theoretical analysis while section 3 provides the empirical findings. Section 4 summarizes and concludes with some cautionary remarks.

2. Theoretical Framework

Romer (1987) models specialization using a production technology in which the output of a final consumption good is a function of intermediate inputs, defined continuously on $\Re^+$. Specifically, the production function for final output *Y* is specified as:

$$Y(x) = \int_{R^+} x(i)^{\alpha} di \,, \qquad (1)$$

where $x(i)$ denotes the amount of input i and $0 < \alpha < 1$.[4] In order to provide an upper bound to the number of intermediate inputs, which captures the degree of specialization, Romer introduces fixed costs in their production, which uses as input a primary resource, Z. One of the cost functions considered by Romer is the following:

$$h(x(i)) = \frac{1 + x(i)^2}{2}, \qquad \forall i \qquad (2)$$

where $h(x(i))$ measures the amount of the primary input that is needed for the production of $x(i)$ units of the intermediate input i. This cost function "…capture[s] the idea that fixed costs limit the degree of specialization" (Romer, 1987, p. 57) and leads to a U-shaped average cost curve. Consequently, at the optimum $x(i)$ is strictly positive and, because of symmetry across cost functions, takes a constant value $\bar{x}$. Equation (1) then implies that final output is directly proportional to the measure of intermediate inputs, M. In Romer's words: "This loosely captures the idea that a *ceteris paribus* increase in the degree of specialization increases output." (ibid).

Infrastructure and Specialization

Endogenizing the fixed costs in the above cost function provides a natural way of introducing infrastructure into the model, as it is plausible to expect that they are largely determined by the availability and quality of transport and telecommunications infrastructure. We, therefore, assume that the fixed costs of producing intermediate inputs vary inversely with the stock of public capital *relative to the size of the economy*. Because of congestion, a given level of infrastructure is likely to be less productive the greater the amount of economic activity that it supports. This intuition leads to the following re-specification of the cost function for intermediate inputs:[5]

$$h(x(i), G/Y) = \frac{C(G/Y) + x(i)^2}{2}, \qquad \forall i \qquad (2')$$

where G measures the stock of public capital and Y measures, as before, final output. We further assume that $C' < 0$ and $C'' > 0$.

The primary resource constraint of the economy is:

$$\int_{R^+} h(x(i), G/Y)di = M \cdot h(\bar{x}, G/Y) \leq Z \qquad (3)$$

We close the model by assuming that infrastructure is provided by the government, which runs a balanced budget and finances infrastructure by a proportional tax rate, τ, on final output:[6]

$$g \equiv \dot{G} = \tau Y \qquad (4)$$

It is instructive to start with the single period version of the model, in which the initial stock of public capital is assumed to be equal to zero and the primary resource Z is constant. In this case, $g = G$ and $G/Y = \tau$.[7] In the decentralized equilibrium of this economy, which consists of a competitive final output sector and a continuum of monopolistically competitive intermediate input producers, agents treat τ and G as parameters. Final output producers maximize the following profit function:

$$\int_{R^+} (1-\tau)x(i)^{\alpha} di - \int_{R^+} p(i)x(i)di \qquad (5)$$

where $p(i)$ denotes the relative price of intermediate input i. The f.o.c. for each i yields a corresponding inverse demand function:

$$p(i) = (1-\tau)\alpha \cdot x(i)^{\alpha-1} \qquad (6)$$

Intermediate input producers use these derived demand curves to maximize:

$$(1-\tau)\alpha \cdot x(i)^{\alpha} - R\frac{C(\tau) + x(i)^2}{2} \qquad (7)$$

where R is the unit price, measured in units of final output, of the primary resource. In equilibrium all intermediate input producers earn zero profits. Solving the system of equations consisting of the f.o.c. of the above problem, the zero-profit condition and the resource constraint (3), we obtain the following solutions for $\bar{x}$, *M*, and *R* as functions of the policy parameter τ:

$$\bar{x} = \left(\frac{\alpha C(\tau)}{2-\alpha} \right)^{1/2} \tag{8}$$

$$M = \frac{Z(2-\alpha)}{C(\tau)} \tag{9}$$

$$R = (1-\tau)\alpha^2 \left(\frac{\alpha C(\tau)}{2-\alpha} \right)^{(\alpha-2)/2} \tag{10}$$

Equations (8) - (10) demonstrate the costs and benefits of infrastructure. The costs are straightforward and measured by the loss of income due to taxation. The equilibrium conditions (8) and (9) reveal that $\bar{x}$ and *M* are, respectively, negatively and positively related to infrastructure investment, τ. Because infrastructure reduces the fixed costs in the production of intermediate inputs, it promotes competition in that sector, i.e. a higher *M*, and consequently encourages further specialization, which in turn implies higher final output.

Infrastructure and Economic Growth

In the dynamic version of the model the primary resource, *Z*, is allowed to accumulate, as in Romer, at the following rate:

$$\dot{Z}_t = (1-\tau)Y_t(x) - c_t \tag{11}$$

where for simplicity depreciation is set equal to zero and c_t denotes per capita consumption. Equations (11) and (4) describe the dynamics of the production side of the model. However, notice that now we have to distinguish between the rate of accumulation of public capital, $g_t \equiv \dot{G}_t$, and the stock of public capital, G_t. This requires that we substitute G_t / Y_t for τ in the fixed cost function. The above implies that the rate of return of the economy, R_t, is time-dependent.

On the consumption side of the model, intertemporal preferences are, conventionally, specified as:

$$\int_0^\infty U(c_t)e^{-\rho t}dt \qquad (12)$$

where $U(c_t)$ is given by:

$$U(c_t) = \frac{c_t^{1-\sigma} - 1}{1-\sigma} \qquad (13)$$

where $0 < \sigma < \infty$. The above specification of preferences implies that the growth rate of consumption equals:

$$\frac{\dot{c}_t}{c_t} = \frac{1}{\sigma}\left(R_t - \rho\right) \qquad (14)$$

because in this economy the only asset that consumers own is the primary resource. Its rate of return is equal to R_t because the depreciation rate is equal to zero.

Along a balanced growth path, the variables *c*, *Y*, *Z*, and *G* will grow at the same rate. In such a long-run equilibrium, the ratio *G/Y* will remain constant which, in turn implies that the fixed cost function, *C(·)*, and, consequently, the rate of return, *R*, will take constant values. Equating the growth rates of *G* and *c* using (4) and (14) and substituting (10) for *R*, we get:

$$\frac{\dot{G}}{G} = \frac{\tau Y}{G} = \frac{1}{\sigma}\left\{(1-\tau)\alpha^2\left[\frac{\alpha C(G/Y)}{2-\alpha}\right]^{(\alpha-2)/2} - \rho\right\} \qquad (15)$$

In what follows, we show that there is a positive monotonic relationship between the policy parameter τ and the *G/Y* ratio. As a consequence, the government's choice of tax rate also determines the long-run growth rate of the economy. Suppose *C(·)* has the form:

$$C(G/Y) \equiv \theta/(G/Y) \qquad (16)$$

where θ is a positive constant. This specification implies that (a) in the absence of infrastructure, fixed costs approach infinity, i.e. specialization becomes impossible, and (b) fixed costs never vanish, i.e. there is a limit to the degree of specialization.

Substituting (16) into (15) and rearranging terms we get:

$$\left(\frac{G}{Y}\right)^{2-(\alpha/2)} = \frac{\rho}{(1-\tau)\lambda}\left(\frac{G}{Y}\right) + \frac{\tau\sigma}{(1-\tau)\lambda} \qquad (17)$$

where:

$$\lambda \equiv \alpha^2 \left(\frac{\alpha\theta}{2-\alpha}\right)^{(\alpha-2)/2} > 0 \qquad (18)$$

For $0 < \tau < 1$, (17) has exactly one positive root,[8] i.e. the tax rate uniquely determines the long-run equilibrium ratio of *G/Y*. Furthermore, using the implicit function rule, we find that, for positive growth rates, the relationship between τ and *G/Y* is positive monotonic. In particular, let

$$\frac{G}{Y} = f(\tau), \qquad f'(\tau) > 0 \qquad (19)$$

describe that relationship. Then, the balanced growth rate of the economy is given by:

$$\gamma \equiv \left[(1-\tau)\lambda f(\tau)^{1-(\alpha/2)} - \rho\right]\frac{1}{\sigma} \qquad (20)$$

The above describes a non-monotonic relationship between the tax rate and the long-run growth rate of the decentralized economy. There is, therefore, a unique growth maximizing tax rate that balances the allocation of savings between private and infrastructure capital.

3. Empirical Evidence

Our theoretical analysis predicts a number of relationships which, in principle, could be tested. These are as follows:

(i) a positive association between the measure of intermediate inputs (specialization) and infrastructure (equation 9);

(ii) an inverse relationship between the average output of intermediates and infrastructure (equation 8);

(iii) a non-monotonic (inverted-U) relationship between the long-run growth rate and the stock of infrastructure scaled by the level of national output (equation 20).

The first two predictions, while unique to our model, are notoriously difficult to test because of serious measurement problems and lack of firm-level data on the production of intermediates.[9] Furthermore, even if such measures were available, the volume of infrastructure does not vary across industries, which does not allow estimation of the relationship between intermediates and infrastructure within the same economy. We, nevertheless, circumvent these obstacles using alternative proxies for specialization and constructing utilization rates of core infrastructure across industries in order to create the required variation in the infrastructure data.

The third prediction is less problematic to test, given that cross-country growth regressions could be employed. Having said this, many of the results obtained by this method have in the past been shown to be sensitive to reverse causality or endogeneity problems (Arestis and Demetriades, 1997) and model specification (see Levine and Renelt, 1993). We, therefore, use Instrumental Variable estimation (IV) to control for the possible cross-sectional endogeneity of infrastructure and set-up the sample in such a way as to avoid time-series induced endogeneity. Finally, we test the robustness of our results using extreme bounds analysis (Leamer, 1983).

Infrastructure and Specialization

We use the latest available US Census of Manufactures data at the 4-digit manufacturing level to obtain measures of the degree of specialization across US manufacturing industries at two dates: 1987 and 1992.[10] We proxy the degree of specialization by the total number of manufacturing establishments within an industry.[11] This provides us with 912 observations of the degree of specialization. Given that the core-infrastructure available to all industries is the same, while different industries may have different needs for infrastructure, we construct utilization rates using estimates of marginal benefits by Nadiri and Mamuneas (1998). This creates the degree of variation necessary to estimate the relationship between specialization and infrastructure. The data on infrastructure data are obtained from the National Income and Wealth Division BE-54 of the Bureau of Economic Analysis.

A simple OLS regression of the logarithm of the number of manufacturing establishments (LN) on the logarithm of the ratio of core infrastructure to GDP (LG) and twenty intercept dummies, representing 2-digit industries, yields the following result:

$$LN = \underset{(0.8083)}{0.3358}\, LG \qquad R^2 = 0.20 \qquad N = 912$$

where figures in parentheses represent heteroskedasticity-robust t-statistics. The correlation between infrastructure and the degree of specialization is, therefore, positive, albeit insignificant. However, equation (9) of our model suggests we should control for the resource constraint of the economy, which we proxy by the logarithm of aggregate private capital (LKK). This yields the following:

$$LN = \underset{(2.058)}{2.8613}\, LG - \underset{(1.897)}{1.3918}\, LKK \qquad R^2 = 0.20 \qquad N = 912$$

The relationship between infrastructure and the degree of specialization now strengthens and is statistically significant. However, the logarithm of aggregate private capital appears with a negative sign, even though it is statistically insignificant.

Infrastructure and output of intermediates

From the NBER-CES/Census Manufacturing Industry Productivity Database[12] we obtain data on average output per establishment at the 4-digit manufacturing level, which we use to measure the average output of intermediates (QN). This is clearly a very crude proxy because some of the gross output is likely to be for final consumption. With this limitation in mind, we estimate a relationship akin to equation (8), by introducing the average (utilized) core infrastructure per establishment (LGN) as a regressor, controlling for private inputs.[13] The latter are the logarithms of private capital (LKN) and labour (LLN) per establishment and are obtained from the same data set. An OLS regression on the logarithm of average output (LQN) yields the following results:

$$\underset{}{LQN} = \underset{(18.77)}{0.4818\ LKN} + \underset{(14.77)}{0.5650\ LLN} - \underset{(1.855)}{0.0250\ LGN} \qquad R^2 = 0.20 \qquad N=912$$

where, once again, there are twenty intercept dummies and the figures in parentheses represent heteroskedasticity-robust t-statistic. While the estimated relationship is broadly consistent with equation (8), which predicts a negative relationship between infrastructure and the average output of intermediates, infrastructure is significant only marginally (at the 6% level). This is perhaps the best that can be hoped for given the crude data approximations that had to be made.

Infrastructure and Economic Growth

Following Levine and Renelt (1992) and Levine and Zervos (1993) we run cross-country growth regressions of the form:

$$g^Y = \beta_i I + \beta_m M + \beta_z Z + u$$

where g^Y is per capita GDP growth, I is a vector of variables always included in the regression, M is the variable of interest - in our case infrastructure - and Z is a vector of variables chosen from a pool of variables identified by past studies as potentially explanatory variables for growth. The first step of EBA involves running a "base" regression where all Z variables are excluded. This is then followed by running regressions that include all possible combinations of up to three variables from the Z set. The next step involves identifying the highest and lowest estimates for β_m and associated standard errors. If these estimates are significant and of the same sign we conclude that the result is robust and define: (a) the extreme upper bound as the highest estimate of β_m plus two standard errors, and (b) the extreme lower bound as the lowest estimate of β_m minus two standard errors. We can say with a high degree of confidence that the true coefficient lies inside the interval defined by the two extreme bounds.

In our case, given the non-linear relationship predicted by the theory we expand the above analysis to allow for a non-linear term. Thus, the above equation is augmented as follows:

$$g^Y = \beta_i I + \beta_{m1} M + \beta_{m2} M^2 + \beta_z Z + u$$

According to the theory we expect β_{m1} to be positive and β_{m2} to be negative. Robustness in the case of two variables is clearly more demanding. Extreme bounds for *both* parameters must be significant and of the same sign.

We use the King and Levine (1993) version of the Summers-Heston data set, which covers 119 countries over the period 1960-1989. We augment this data set with physical measures of transport and telecommunications infrastructure obtained from World Development Report (World Bank, 1994). Specifically, we collect data on paved roads (kms) and telephone main lines. In the case of the first indicator the data relates to 1970 and 1980; in the case of the second indicator they relate to 1975 and 1980. In order to address possible time-series endogeneity, we therefore estimate the growth regressions that utilize the transport indicator on averaged data for the period 1970-75 and 1980-85. This ensures that the infrastructure indicators predate the dependent variable, which rules out the possibility of a spurious effect due to reverse causality.[14] Similarly, the regressions that use the telecommunications indicator are run on 1975-80 and 1980-85.

These indicators offer several advantages over other measures of infrastructure. Firstly, they are likely to have a more direct impact on production costs than other indicators, such as irrigation or sanitation measures. Specialization in production is clearly facilitated by a good system of roads and by the presence of a good telecommunications network (see World Bank, 1994, p.18). Secondly, they are more appropriate for our purposes than wider indicators like public capital, which includes government buildings, schools, hospitals and, in some cases, military capital. Thirdly, they are less susceptible to comparability problems across countries than other indicators, which may arise because of differences in national accounting practices and valuation methods, including exchange rate conversions. Finally, they are available for a larger number of countries than other indicators, which makes estimation feasible. There is no doubt, however, that both the length of paved roads and the number of telephone lines do not account for quality differences across countries, which are likely to affect their productivity. Unfortunately, however, quality-adjusted data on physical infrastructure do not exist for a sufficiently large number of countries.

The scale factors for the above measures of infrastructure are not immediately obvious. According to the theoretical model, they should be scaled by the level of economic activity to account for congestion. However, the theoretical model does not account for geographical heterogeneity. The needs for infrastructure differ substantially across countries and depend not only on the level of economic activity but also on factors such as country area, population, topography, etc. Natural candidates for scale factors are country-area, in the case of paved roads, and population in the case of telephone main lines. Summary statistics for the above infrastructure measures, scaled in this fashion, are presented in Table 1. The indicators exhibit considerable variation across countries, reflecting the lack of infrastructure in the least developed countries and its abundance in the richest countries.

Table 2 presents the correlation matrix between the infrastructure measures and growth of per capita GDP. Both infrastructure indicators are positively correlated with economic growth. The correlation is strongest in the case of the telephone lines - based indicator, taking the value 0.41. Furthermore, the indicators are positively correlated with each other. Thus, we use them individually in the regressions that follow, in order to avoid the possibility of multicollinearity.

Table 3 presents results of the base regressions, estimated by OLS and IV. The base variables are the log of initial GDP (LYO),[15] the log of initial secondary school enrollment (LSEC), which correspond to those used by Levine and Zervos (1993). We also include a time dummy, given that each of the samples includes two different time-periods. The table also reports Hausman's (1978) exogeneity test for the OLS regressions and Sargan's test for the validity of the instruments used in the IV regression, which are also listed.[16]

The OLS estimates are consistent with the theoretical predictions but the Hausman test suggests the presence of cross-sectional endogeneity. The IV estimates are qualitatively similar to the OLS ones, even though quantitatively there are some important differences. Importantly, the coefficients on the level and square terms of both infrastructure indicators have the expected signs and are highly significant. Thus, the results of the base regression are consistent with the predictions of our theoretical model. Furthermore, both models pass Sargan's test for the vailidity of the instruments.

Table 4 presents summary results from the Extreme Bounds Analysis. For each of the infrastructure indicators, IV regressions were run using all possible combinations of up to three *Z* variables. The set of *Z* variables comprises four variables: the inflation rare, measured by the average rate of change of the GDP deflator, the growth rate of inflation, the ratio of total trade to GDP, and the ratio of exports to GDP. Following Levine and Renelt (1992) the *Z* set includes variables identified by other studies as potentially explanatory variables for growth. However, as they did, we have excluded variables which, a priori, might measure the same phenomenon; e.g. the average rate of government investment expenditures.[17] Furthermore, by allowing the procedure to choose up to three *Z* variables we restrict the total number of explanatory variables in any one regression. Table 4 shows that the results are robust in the case of both infrastructure indicators, which provides strong support to our theoretical predictions.

Quantitatively, the estimated effects of infrastructure are plausible. For example, the implied output elasticity of transport infrastructure for the US is 0.129, which is comparable to the estimates obtained by Nadiri and Mamuneas (1998) using different methods. For other developed countries, the implied output elasticity of transport infrastructure turns ranges from 0.001 for Finland to 0.183 for Austria, and are comparable to the estimated output effects of public capital by Demetriades and Mamuneas (1998), who use duality methods. The estimated effects of transport infrastructure in poorer countries display more variation, and are sometimes negative, especially for sub-Saharan African countries. For example, the estimated output elasticity of transport infrastructure for China, Syria, Jordan, Taiwan, Egypt and Burundi are, respectively, 0.173, 0.133, 0.129, 0.043, 0.005 and –0.125.[18] The estimated effects of telecommunications infrastructure are, much smaller, sometimes in the order of one-tenth of those of transport infrastructure. The implied output elasticity for the US, for example, is 0.017, while for China, Syria, Jordan and Taiwan are 0.044, 0.028. 0.023 and 0.012, respectively. Once again, any negative effects are mostly found for sub-Saharan African countries.

We conclude that, in spite of data limitations and measurement constraints, both of which hamper the empirical investigation, the empirical evidence is consistent with the main predictions of our model. Furthermore, our empirical results demonstrate that the effects of infrastructure on output and economic growth are, with few exceptions, positive.

4. Concluding Remarks

In this paper we have put forward a plausible explanation of the mechanism by which infrastructure contributes to the process of economic growth. We have refrained from treating infrastructure as an input in the production of final goods, as is usually assumed in the literature. Instead we have argued that it is more natural to think of infrastructure as a technology which reduces costs in the production of intermediate inputs and, therefore, fosters specialization. In an endogenous growth model in which infrastructure accumulation entails a resource cost, we have shown that the relationship between the long-run growth rate of the decentralized economy and the rate of infrastructure accumulation (the "tax rate") is non-monotonic. Infrastructure accumulation is very productive when the tax rate is very 'low' and counter-productive at 'high' tax rates.

We have provided empirical results, using two different data sets, including US Census data from manufacturing industries and cross-country growth equations, which are consistent with our theoretical predictions. The US Census data suggest that there may well be a positive correlation between core infrastructure and specialization, as well as a negative correlation the average output of intermediates and infrastructure, both of which are unique predictions of our model. However, these results should be cautiously interpreted given that neither the degree of specialization nor the utilization rate of core infrastructure are directly observable.

Cross-country growth regressions utilizing physical measures of transport and telecommunications infrastructure published by the World Bank suggest an inverted-U shape relation between infrastructure and the rate of economic growth across countries, with most countries in the upward sloping segment of the curve. This relationship has been obtained after conditioning on variables that other studies have found important in explaining variations of growth across countries and controlling for endogeneity. Moreover, these results have been found to be robust to a wider set of conditioning variables.

Our results highlight the importance of infrastructure accumulation, especially for poor countries. Clearly, however, some caution must be exercised before policy implications are derived. Our theoretical model is one of a closed economy which relies on its own resources for infrastructure accumulation. There is, therefore, an implicit assumption that there exists a tax system which allows the government to put aside as many resources as it wishes for infrastructure accumulation. This assumption may be unrealistic in the case of poor countries which are lacking in terms of institutional infrastructure, for instance a well functioning legal system. In these countries, the formation of such 'soft' infrastructure may itself depend on the stage of economic development. Thus, modeling 'soft' infrastructure is likely to yield further important insights into the process of economic growth.

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Table 1: Infrastructure and Economic Growth

Summary Statistics				
Variable	*Mean*	*Standard deviation*	*Minimum*	*Maximum*
Per capita GDP growth	0.022	0.016	-0.013	0.064
Telephone lines per thousand inhabitants	121.5	150.2	0.543	560.8
Paved roads (km) per 1000 km	399.6	713.4	0.657	3437.9

Table 2: Correlations Between Infrastructure Indicators and Economic Growth

Variable	Per capita GDP growth	Telephone lines per thousand inhabitants	Paved roads (km) per 1000 km
Per capita GDP growth	1.0000	0.4148	0.3357
Telephone lines per thousand inhabitants		1.0000	0.5001
Paved roads (km) per 1000 km			1.0000

Table 3:Telecommunications Infrastructure, Transport Infrastructure and Economic Growth: Base Regressions

Dependent variable: Average growth rate of per capita GDP

	Telecommunication(1) (1975-80, 1980-85)		Transport Infrastructure(2) (1970-75,1980-85)	
	OLS	IV	OLS	IV
C	0.0097 (1.1046)	-0.0124 (1.0727)	0.0142 (1.7229)	-0.0467 (2.3688)
Y D	0.0180 (3.9323)	0.0088 (1.4831)	0.0283 (6.7364)	-0.0035 (0.3624)
LYO	-0.0070 (1.0665)	-0.0099 (0.6442)	-0.0017 (0.4606)	-0.0045 (1.1754)
LSEC	0.0076 (1.6870)	0.0002 (0.0265)	0.0070 (1.8092)	-0.0127 (1.8013)
M	0.1230 (1.8284)	0.8613 (2.8473)	0.0139 (1.9959)	0.7019 (3.7927)
M^2	-0.1853 (1.7373)	-2.0803 (3.1684)	-0.0043 (1.9389)	-0.3357 (-3.7583)
R^2	0.17	0.21	0.26	0.34
N	159	159	172	172
Hausman, χ^2(D.F.)*	10.44(2)		23.1(2)	
Sargan , χ^2(D.F.)**	4.27(2)		0.1(2)	

Note: Figures in parentheses are heteroskedasticity robust t-statistics; minus signs are omitted for simplicity.
*Degrees of freedom equal to the rank of the matrix of the differences of the covariance matrices.
** Degrees of freedom equal to the difference between the number of instruments and the number of explanatory variables.
Definitions: C: Constant; YD: Year Dummy; LYO: Logarithm of initial income (1960); LSEC: Logarithm of secondary school enrolment rate; (1) M: Telephone lines per million inhabitants; M^2: The square of telephone lines per million inhabitants, (2) M: Paved roads (km) per million km^2; M^2: The square of paved roads (km) per million km^2.
Instruments: Constant, YD: Year Dummy; GOV: Lagged values of government consumption share of GDP; LINV: Lagged values of investment share of GDP; GYP: Lagged values of growth of per capita GDP; GPO: Lagged values of growth of population.

Table 4: Infrastructure and Economic Growth: Extreme Bounds Analysis

Dependent variable: Average growth rate of per capita GDP

Infrastructure indicator	β_{M1}	β_{M2}	N	R^2	Z variables**	Robust/ Fragile
Telephone lines per million inhabitants (1975-80,1980-85)						
upper bound* for:						
β_{M1}	1.4663		159	0.21		
β_{M2}		-0.7730	159	0.21	X	
Base	0.8613	-2.0803	159	0.21	TRD	
lower bound* for:						Robust
β_{M1}	0.1083		159	0.24	PI, X, TRD	
β_{M2}		-3.4049	159	0.23	GPI	
Paved roads (km) per million km^2 (1970-75,1980-85)						
upper bound* for:						
β_{M1}	1.0616		172	0.36	GPI	
β_{M2}		-0.1204	172	0.35	TRD	
Base	0.7019	-0.3357	172	0.34		Robust
lower bound* for:						
β_{M1}	0.2637		172	0.35	TRD	
β_{M2}		-0.2106	172	0.36	GPI	

Z variables included: PI: Average inflation of the GDP deflator; TRD: Ratio of total trade to GDP; GPI: Growth of inflation rate, X: Export share of GDP.

*The upper (lower) bound is the largest (smallest) estimated coefficient plus (minus) two standard errors.

**These are the Z variables corresponding to the extreme bounds.

Appendix: Countries included in the estimation

Telecommunications infrastructure regressions

Afghanistan, Argentina, Bahamas, Bahrain, Bangladesh, Barbados, Belgium, Bolivia, Botswana, Burkina Faso, Burma, Burundi, Cameroon, Canada, Cape Verde, Central African Rep. Chad, Chile, China, Colombia, Comoros, Congo, Costa Rica, Denmark, Dominica, El Salvador, Equador, Egypt, Ethiopia, Finland, France, Gabon, Gambia, Ghana, Grenada, Germany (West), Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hong Kong, Hungary, Iceland, Indonesia, Iran, Ireland, Israel, Jamaica, Jordan, Kenya, Korea, Kuwait, Lesotho, Luxemburg, Madagascar, Malawi, Malaysia, Mali, Morocco, Mauritania, Mauritius, Mexico, Mozambique, Nepal, Niger, Nigeria, Pakistan, Panama, Peru, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Somalia, South Africa, Sri lanka, St. Lucia, St Vincent & Grens., Swaziland, Syria, Taiwan, Tanzania, Thailand, Togo, Trinidad & Tobago, Tunisia, Uganda, United States, Uruguay, Venezuela, Yemen (N. Arab).

Transport infrastructure regressions

Afghanistan, Argentina, Austria, Bahamas, Bahrain, Bangladesh, Barbados, Belgium, Benin, Bolivia, Botswana, Burkina Faso, Burma, Burundi, Cameroon, Canada, Cape Verde, Central African Rep. Chad, Chile, China, Colombia, Comoros, Congo, Costa Rica, Cote d'Ivoire, Denmark, Dominica, Dominican Republic, El Salvador, Equador, Egypt, Ethiopia, Finland, France, Gabon, Gambia, Ghana, Grenada, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, Hong Kong, Iceland, Indonesia, Iran, Iraq, Ireland, Israel, Jamaica, Japan, Jordan, Kenya, Korea, Kuwait, Lesotho, Liberia, Madagascar, Malawi, Malaysia, Mali, Morocco, Mauritania, Mauritius, Mexico, Mozambique, Nepal, Nicaragua, Niger, Nigeria, Oman, Pakistan, Panama, Peru, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Somalia, South Africa, Sri lanka, St. Lucia, St Vincent & Grens., Swaziland, Syria, Taiwan, Tanzania, Thailand, Togo, Trinidad & Tobago, Tunisia, Uganda, United States, Uruguay, Venezuela, Yemen (N. Arab).

Lead Footnote:

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[1] For a broad survey of the effects of infrastructure see World Bank (1994).

[2] Holtz-Eakin and Lovely (1996) also consider infrastructure as a cost-reducing input in a model with returns to variety.

[3] The resource costs of infrastructure are also modelled by Bougheas *et al* (1998, 1999) in an international trade context.

[4] This production function is analogous to the Dixit-Stiglitz utility function, which captures consumer preferences for product diversity. It exhibits constant returns to scale but labor is set to unity, as population growth is assumed zero.

[5] In his cost function, Romer sets the fixed component to unity, which conveniently achieves a minimum average cost of unity when output equals 1. In our case, the corresponding term is the first term in the numerator which, albeit invariant to the output of intermediates, varies inversely with the ratio G/Y.

[6] This is a standard assumption in the growth literature (see Barro and Xala-I-Martin, 1995). World Bank (1994) discusses a number of alternative possibilities involving the private sector. The international aspects of infrastructure financing are explored by Bougheas *et al* (1998).

[7] In a single period model the flow of government spending is equal to the stock of public capital.

[8] The LHS of (17) is increasing and convex in G/Y while the RHS is linear in G/Y. Both the intercept and slope of the latter are positive for admissible values of G/Y.

[9] Input-output tables for example, are not available at the individual firm level. Aggregate manufacturing tables, even at the 4-digit level, cannot accurately measure the degree of specialization within industries.

[10] The 1992 Census of Manufactures covers all establishements with one paid employee or more, primarily engaged in manufacturing as defined in the 1987 Standard Industrial Classification (SIC) Manual.

[11] Holtz-Eakin and Lovely (1996) follow a similar approach.

[12] Past updates of this data have been done by Wayne Gray and Eric Bartelsman. This update was carried out by Randy Becker at the Center for Economic Studies of the Census Bureau. This Database contains annual production and cost data for all manufacturing industries from 1958 to 1994. These data come primarily from the Annual Survey of Manufactures, but they have added some price deflators and real capital stock information.

[13] Our theoretical model makes the case that infrastructure must be normalized by economic activity to account for congestion. In this regression it is normalized by the number of establishments instead of GDP in order to prevent the possibility of a spurious inverse relationship between infrastructure and output. This could arise because GDP is positively correlated with manufacturing output, which appears on the LHS.

[14] We are grateful to an anonymous referee for bringing this problem to our attention.

[15] For simplicity, our theoretical analysis was restricted to balanced growth paths in which the tax rate is constant. As a result, the theoretical model lacks transitional dynamics. Nevertheless, empirical studies (see Barro and Sala-i-Martin (1995), ch. 12) have found a significant negative effect of the level of initial GDP on the long-run growth rate, reflecting conditional convergence. For consistency with these studies and to avoid the possibility of omitted variable bias we have added the initial level of GDP in our regressions.

[16] Note that the number of observations is not the same for the two sets of regressions, reflecting data availability. See the appendix for the list of countries included in the estimations.

[17] Trade variables may, arguably, be correlated with infrastructure. See Bougheas *et al* (1999) or Casas (1983).

[18] Note that output elasticities in developing countries need not be higher than in developed ones because M/Y tends to be larger in the latter. This may outweigh the marginal effects, which are usually larger for developing economies. The negative marginal effects for a small number of developing countries, mostly in sub-Saharan Africa, may reflect the high resource costs of infrastructure accumulation, which may be due to bureaucratic inefficiencies or corruption.

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