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INFRASTRUCTURE CAPITAL AND ECONOMIC GROWTH: HOW WELL YOU USE IT MAY BE MORE IMPORTANT THAN HOW MUCH YOU HAVE

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ABSTRACT

This paper shows that those low and middle income countries that use infrastructure inefficiently pay a growth penalty in the form of a much smaller benefit from infrastructure investments. The magnitude of this penalty is apparent when the growth experience of Africa is compared with that of East Asia: over one-quarter of the differential growth rate between these two regions can be attributed to the difference in effective use of infrastructure resources. At the same time, the difference due to new public capital formation is negligible. An even stronger impression is conveyed by the comparison of high and low growth rate economies. Here, more than forty percent of the growth differential is due to the efficiency effect, making it the single most important explanator of differential growth performance.

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I. Introduction

Most contemporary explanations of economic growth assign a prominent role to capital formation. However, the relevant literature has focused primarily on investment in new capital, and comparatively little attention has been given to the effective use of capital stocks once they are in place. This is a potentially important omission, since the very conditions responsible for economic backwardness may operate through the poor management of the means of production. If capital stocks are not used effectively, additional capital formation may be of little help in stimulating economic growth.

This problem may be particularly severe for social overhead capital (or "infrastructure"). Data presented in the 1994 World Development Report (WDR) suggest that $12 billion in timely road maintenance in Africa over the preceding decade would have avoided the need for $45 billion in reconstruction and rehabilitation. Moreover, "inadequate maintenance means that power systems in developing countries have only 60 percent of their generating capacity available at a given time, whereas best practice would achieve levels of 80 percent ... [and] water supply systems deliver an average of 70 percent of their output to users, compared with best-practice delivery rates of 85 percent (page 4)." The WDR goes on to note that these deficiencies often arise from inadequate management of the existing infrastructure assets, as distinct from inadequate levels of new construction. This is seconded by the remark by Easterly and Levine (1996) that, while Chad may have 15,000 telephones, 91 percent of all telephone calls are unsuccessful.

The existence of an infrastructure effectiveness problem is thus well-documented. What is not well known is the actual magnitude of the penalty that inefficiency imposes on economic growth. Assessing the magnitude of this penalty is the main goal this paper. To this end, an effectiveness indicator is developed and embedded in a growth model based on the study by Mankiw, Romer, and Weil (1992). The parameters of this model are then estimated using a cross-section of low and middle income countries, and the effectiveness indicator is found to be an important factor explaining differences in rates of real GDP growth between 1970 and 1990: indeed, a one percent increase in the infrastructure effectiveness parameter is found to have an impact on growth that is more than seven times larger than the impact of the same percentage increase in the rate of public investment.

In addition, those countries that use infrastructure inefficiently pay a growth penalty in the form of a much smaller benefit from new infrastructure investments. The magnitude of this penalty is apparent when the growth experience of Africa is compared with that of East Asia: over one-quarter of the differential growth rate between these two regions can be attributed to the difference in effective use of infrastructure resources. At the same time, the difference due to public capital formation is negligible. An even stronger impression is conveyed by the comparison of high and low growth rate economies. Here, more than forty percent of the growth differential is due to the efficiency effect, making it the single most important explanator of differential growth performance.

These results establish the importance of the effectiveness dimension of the infrastructure problem. However, the very strength of the efficiency effect invites the speculation that the infrastructure effectiveness variable is really a proxy for a more general productive efficiency. In this interpretation, it is the productivity with which all inputs are used that affects GDP growth rates, and not just the input of infrastructure. If this alternative interpretation is correct, it challenges the recent literature that suggests that differences in total factor productivity are not of central importance in explaining the success of the East Asian economies.

II. A Model of Infrastructure Effectiveness and Economic Growth

1. Development economists have long recognized that social overhead capital is a necessary input in the structure of production (e.g., Hirschman (1958)). Infrastructure was incorporated into formal growth theory by Arrow and Kurz (1970) and Weitzman (1970). Empirical studies of the importance of infrastructure as a source of growth gained prominence with the papers of Aschauer (1989a,1989b), which were followed by a large body of econometric research.[1] However, none of this research takes explicit account of the effectiveness with which infrastructure capital is used, and therefore cannot be used to assess the macroeconomic significance of the well-documented microeconomic problems associated with the ineffective delivery of infrastructure services.

The paper addresses this gap by introducing an explicit infrastructure-effectiveness variable into the Solow-Swan model of economic growth, as augmented by Mankiw, Romer, and Weil (1992), and extended by Knight, Loayza, and Villanueva (1993) and Holtz-Eakin and Schwartz (1995). Other models might have been selected, but the augmented Solow model is sufficient to establish the macroeconomic importance of the effectiveness variable.

The effectiveness with which infrastructure is used involves may dimensions and is not easily modeled (Hulten (1994)). Infrastructure facilities tend to be congestible public goods ("clubs") that are organized into capital-intensive networks (e.g., roads and bridges, railroads, air and water transport, water and sewer systems, electricity generation and distribution networks, telecommunications facilities). The efficiency of any one segment of the network depends on the size and configuration of the entire network, and complementarities may exist between some segments while others are substitutes. The richness of these possibilities is impossible to capture in any highly aggregative framework, but insights can be obtained by adapting the paradigm of embodied technical change to the problem of infrastructure effectiveness.

The embodied technical change model allows for differences in the productive efficiency of successive vintages of investment goods, and is therefore a natural starting point for the analysis of different degrees of productive efficiency among different network investments.[2] Two concepts of capital are recognized in the embodiment model. The first regards capital as the sum of past investments in capital goods, adjusted for physical depreciation, δ:

(1) $$G_t = \sum_\tau [(1-\delta)^\tau \sum_i I_{i,t-\tau}] \quad .$$

The $[I_{i0}, \ldots, I_{nt}]$ represent the physical (or constant price) quantities of capital investment in project i at time t, not adjusted for embodied differences in technology or effectiveness of use. That is, all investments are treated as perfect substitutes up to some average rate of depreciation. The summation occurs here over both time and network segments, whereas it is restricted to time in the standard embodiment model.

The second concept of capital (Solow's "jelly stock") adjusts each element of the investment vector, $[I_{i0}, \ldots, I_{nt}]$, for differences in productivity by assigning a quality factor, or weight $\psi_{i,t-\tau}$, to each individual investment. In the original embodied technical change model, differences in these weights arose from technological improvements in the design of capital goods, but in the present context, we will interpret them as effectiveness differentials. Full effectiveness can be viewed as the situation in which the investment (or infrastructure network segment) is maintained in mint condition and is operated with best practice efficiency. This case can be represented by an index value of ψ=1, and less effectively used infrastructure can be assigned a value less than one. In this formulation, the product $\psi_{it}I_{it}$ can be interpreted as the amount of fully-efficient investment that would be needed to replace I_{it} units of a capital good operated at the level of efficiency ψ_{it}. The total effective stock can then be represented as

$$(2) \qquad G^{e}_{t} = \sum_{\tau} \left[(1-\delta)^{\tau} \sum_{i} \psi_{i,t-\tau} I_{i,t-\tau} \right] \quad .$$

and is the equivalent quantity of efficiently-operated capital needed to replace the physical stock G in (1).

Since the ψ_{it}'s are implicit, the G^{e} concept of capital is not observable and the G concept of capital (or a close relative) is used in practice. This mismeasurement of G^e introduces the parameter θ into the analysis defined implicitly as $\theta = G^e/G$. The parameter θ can be shown to be a share-weighted sum of the individual $\psi_{i,t-\tau}$, and is termed in Hulten (1992) the "average embodied technical efficiency." However, in the present application, θ is the "average level of infrastructure effectiveness," and is the sum of the weighted-sum of the effectiveness with which each segment of an infrastructure work is operated.[3]

2. The average level of infrastructure effectiveness, θ, enters growth theory via the aggregate production function. In the augmented Solow model of Mankiw, Romer, and Weil used in this paper, the production function has the Cobb-Douglas form with constant returns to scale, and includes infrastructure capital, G, human capital, H, and physical capital, K (although MRW actually use a combined concept of physical capital, G+K, in their study). The resulting production function has the form

$$(3) \qquad y(t) = A\, k(t)^{\alpha} h(t)^{\beta} (\theta g(t))^{\gamma}$$

where (k,h,g) are the <u>per worker</u> magnitudes of private fixed capital, human capital, and public capital respectively.[4] Since output depends on the effective stock of capital in the production function, g^e is the appropriate argument in (3). But g^e is not directly observable, and is replaced with the potentially observable arguments θg.

The production function is a structural equation of the Solow growth framework. The capital stocks entering the production function are endogenously determined by accumulation equations for each type of capital, which have a form similar to (1), and by an investment equation I = sY for each type of capital (determined by s_k, s_h, s_g). A steady state growth path (y^*) is achieved when additions to the stock of each type of capital just match the amount needed to equip the expanding work force, which grows at a constant rate $n+\lambda$, and to replace depreciated capital, which is lost at a constant rate δ. When the production function has the Cobb-Douglas form (3), the steady-state equation for output per worker has an explicit form:

$$(4) \qquad y^* = \left\{\frac{A\ s_k^{\alpha} s_h^{\beta} (\theta s_g)^{\gamma}}{(n + \lambda + \delta)^{\alpha+\beta+\gamma}}\right\}^{\frac{1}{1-\alpha-\beta-\gamma}}$$

This equation relates the long-run (steady-state) growth of output per worker to the various rates of investment. Moreover, it shows that each percentage decline in effectiveness lowers steady-state output per worker by $\gamma/(1-\alpha-\beta-\gamma)$ percent. Thus, economies that make less efficient use of their infrastructure capital are constrained to have a lower level of real income per capita in the long run (all else equal). This is the penalty exacted by inefficiency.

However, it should be noted that the penalty affects the level of income per capital, but not necessarily the rate of growth. In fact, the Solow model has the well-known property that the <u>steady-state</u> growth rate of income per worker, y^* in (4), is constant at the fixed rate of labor-augmenting technical change, λ. Thus, countries with different levels of infrastructure effectiveness will have different levels of income per capita, but the same steady-state rate of growth.

3. The reduced form equation (4) characterizes the steady-state solution toward which the economy is converging, not the actual path followed by the economy. The economy actually moves along a transitional path from the initial level of output per worker to the steady state path, which, following MRW, can be defined by the following expression:

$$(5) \qquad \ln(y(t)/y(0)) = (1-e^{-\mu t})\ln(y*) + e^{-\mu t}\ln(y(0))$$

where y(0) is the level of output per worker in the initial year, y* the steady state value toward which the economy is moving, and μ the parameter determining the rate of convergence. The convergence rate is related to the other parameters through the relation $\mu = (n+\lambda+\delta)(1-\alpha-\beta-\gamma)$.

The transitional dynamics implied by (5) can be operationalized by combining this expression with the natural logarithm of first equation of (4). The resulting equation does not involve the unobserved steady-state, y*, but is instead a relation between observable variables that can, in principle, be estimated. Letting y(70) denote real GDP per efficiency of labor in 1970, and y(90) the 1990 value of this variable, this expression takes the form

$$(6) \quad \ln(y(90)/y(70)) = b_0 + b_k\ln(s_k/(n+\lambda+\delta)) + b_h\ln(s_h/(n+\lambda+\delta)) + b_g\ln(s_g/(n+\lambda+\delta)) + b_\theta\ln(\theta) + b_c\ln(y(70)) + \epsilon$$

The regression parameters (b_k, b_h, b_g) can be interpreted as the elasticities of growth with respect to the investments rates (s_k, s_h, s_g), b_θ as the growth elasticity of infrastructure effectiveness, and b_c as the elasticity of "catch-up."

These growth rate elasticities are not the same as the parameters of the production function (3), (α,β,γ), which are the output elasticities with respect to the capital stocks, (k,h,g). They are, however, related by the formulae: $\alpha = b_k/(b_k+b_h+b_g-b_c)$, $\beta = b_h/(b_k+b_h+b_g-b_c)$, and $\gamma = b_g/(b_k+b_h+b_g-b_c)$. In theory, the effectiveness elasticity is the same as the public capital elasticity, but as we will see below, this constraint will not hold in practice. The rate of convergence, μ, is derived from b_c. Estimation of the parameters (b_k,b_h,b_g,b_c) thus gives estimates of the output elasticities, (α,β,γ) and the rate of convergence.

It has been noted that the effectiveness indicator, θ, does not affect the rate of growth of output along the steady-state growth path (4). However, it is now apparent that it does affect the rate of growth along the transitional path (6). A country which uses infrastructure more effectively will converge to higher steady-state income per capita than a less efficient country, and if both start from the same initial level of income per capital, y(70), the former will have a more rapid rate of growth.

If the rate of labor-augmenting technical change (λ) is zero, then the left-hand side of (6) is the observed growth rate of real GDP per person. When λ is positive, the efficiency units in which labor is expressed must be removed from the denominators of y(90) and y(70) and expressed in the constant term β_0 which then includes the cumulative effects of this technical change. MRW assume that every country has the same λ, the constant is also the same and there is no country fixed effect. Knight, Loayza, and Villanueva (1993) model the efficiency term A in the production function (3) and allow it to vary across countries.

III. Data

The data used in this study are derived from four main sources: the Easterly-Rebelo (1993) data base, the World Bank's World Development Indicators, and the 1994 World Development Report, the Summers and Heston (1991) Penn World Tables. The analysis is restricted to low and middle income countries, and spans the years 1970 to 1990. A summary list of the variables is shown in Table 1, along with the data sorted by growth rate terciles. The statistics presented there refer to a sample of 42 countries (the smallest of the samples used in the analysis), but the estimates are similar to those of the largest (46) country sample (a list of countries is given in Appendix Table A).

The main income concept used in this paper is based on Summers-Heston real GDP per capita adjusted for purchasing-power parity, although unadjusted World Bank estimates of real GDP per capita were also used as a robustness check. These data are summarized in the top panel of Table 1. It is worth noting that the 1970 values of Summers-Heston income per capita are virtually the same in all countries, indicating a common starting point for growth in the 42 country sample. The dependent variable in all regressions is the growth rate of real GDP per capita between 1970 and 1990.

The basic right-hand side variables of the regression equation (6) are the investment rates of public capital/infrastructure, private capital, and human capital. Various alternatives are used for the public capital/ infrastructure variable, but only one private investment rate is used. Since no purchasing-power parity adjustment for public or private capital flows is available in the data bases, all investment rates are expressed as a fraction of unadjusted GDP, averaged over the period 1970 to 1990. Human capital is proxied by primary and secondary education enrollment rates, but expenditures on health and education as a fraction of GDP are also used. The investment rates are deflated by the average rate of population growth between 1970 and 1990, to which is added .05 (following MRW) to allow for the average rate of capital depreciation and labor-augmenting technical change.

The investment rates estimated by Easterly and Rebelo are shown in the second panel of Table 1. The measure of gross public investment is broadly encompassing, and includes investment by public firms that are similar in function to those in the private sector. The resulting ratio of public investment to GDP averages 9.7 percent for the 42 countries for which data is available. Private investment averages 10.2 percent in the sample of 42 countries, slightly larger than the public investment rate.

It is worth mentioning that the rate of public investment differs greatly from the rate of <u>infrastructure</u> investment, which is only 3.0 percent in the 24 countries for which this variable is available. Easterly and Rebelo note that their estimate of infrastructure investment may be biased downward because it excludes the infrastructure investments of publicly-owned and private firms.

The 1994 World Development Report presents information on the stock per capita of paved roads, telephone mainlines, electricity generation capacity, irrigation, and railroads. These data are largely physical indicators of the total stock, not perpetual inventory estimates. They are shown in the third panel of Table 1, expressed in 1980 dollars. There is apparently little difference among the three groups in the total amount of infrastructure capital, though the composition does change across groups. The most rapidly growing countries placed more emphasis on road transport than on rail, and had a larger stock of irrigation capital.

Measures of the effectiveness of the various infrastructure systems are also shown in the bottom panel of Table 1. One indicator was selected for each of the four main systems. These measures are representative of the efficiency of the various systems in 1990 (1988 for roads). The true situation is, of course, much too complex to be captured by a single index of indicator for each major system, so these data are, at best, approximations. Moreover, it is known that the relation between infrastructure condition and performance a non-linear.[5] And, the four World Bank series do not refer to a common set of countries (there are, for example, far fewer observations for telephone systems that for roads). Thus, they cannot be used separately in the regression analysis without a reduction in sample size or the omission of key infrastructure systems, but must instead be combined into an aggregate index.

The construction of an aggregate effectiveness index is, unfortunately, problematic. Each of the individual indicators is measured in its own units -- e.g., mainline faults per 100 telephone calls, electricity generation losses as a percent of total system output, the percentage of paved roads in good condition, diesel locomotive availability as percent of the total -- and there is no natural way of adding up the indicators in this form to arrive at a total. The 1994 WDR did not offer an aggregate measure of performance.

The procedure adopted in this paper attempts to deal with the aggregation and non-linearity problems by taking each World Bank performance indicator and sorting it into quartiles. The top quartile is assigned a value of 1.00, the second, 0.75, the next 0.50, and the bottom assigned a value of

0.25. This produces a quartile ranking for each of the four systems separately, and this is then converted into aggregate index by simple averaging. For some countries, all four quartile values are available, but for many countries, the average is taken over only two or three indicators (countries with only one value were dropped from the analysis). This averaging procedure retains as many countries as possible in the sample while making use of data for the different infrastructure systems. The resulting aggregate index provides a ranking of 46 countries according to qualitative performance in those infrastructure functions for which data are available.

IV. Results I: Gross Public Investment With Effectiveness Variables

1. The top panel of Table 2 reports the ordinary least squares estimates of the parameters of the regression equation (6) for the maximum number of countries for which complete data were available, along with the associated t-statistics.[6] The implied elasticities (α, β, γ) are computed from these estimates, and are shown in the lower panel. The first column shows the parameter estimates and implied elasticities without the effectiveness variable. The estimates of the output elasticities of capital are statistically significant, and their combined value is similar to the MRW estimate of 0.44 for the combined capital coefficient (MRW Table VI, 75 country sample). MRW's estimate for human capital is 0.23, while the combined human capital elasticity in Column (1) of this paper is 0.242. Finally, the estimated coefficient of the initial (1970) GDP per capita is statistically

significant, implying a rate of convergence of 0.024, which is close to the theoretical value $(n+\lambda+\delta)(1-\alpha-\beta-\gamma) = 0.020$. It is also close to the MRW estimate of 0.0186.

The second column of Table 2 shows the effect of including the effectiveness term in the regression (the "intercept" model in Column (2)). The effectiveness parameter, $b_{\theta'}$, is highly significant, but its addition reduces the public capital variable to statistical insignificance, and lowers the significance of private capital and primary education, while promoting that of secondary eduction. The rate of convergence is, again, reasonably close to its theoretical value (0.029).

The magnitude of $b_{\theta'}$, 0.794, implies that effectiveness has a strong impact on growth: a 10 percent improvement in effectiveness would lead to a 7.94 percent increase in 1990 GDP per capita relative to the 1970 value; spread over 20 years, this implies a 0.38 increase in the average annual growth rate. This is large compared to an equal percentage increase in the rate of public investment The estimated coefficient of public investment, b_g, is only 0.107, so the estimated magnitude of the effectiveness parameter is <u>more than seven times larger</u>.

In interpreting this result, it should be recalled that the last two estimates should both be equal if the true effectiveness index θ and the WDR indicator θ' are equal. The divergence between the two estimates, 0.107 and 0.794, indicates that the true effectiveness index θ and the WDR indicator θ' are not equivalent; in other words, the measured efficiency effect has two components, one corresponding to the theoretical benefit of an increase in the true θ and the other to the gap between the theoretical and actual indexes. This is not surprising given the approximate nature of the indicators and the way these indicators were aggregated. However, from the standpoint of policy analysis, it is the improvement in <u>measured</u> efficiency, the 0.794 estimate, that matters.

The output elasticities that correspond to the growth elasticity estimates are 0.837 and 0.118, respectively. The latter is the implied estimate of γ, and it is considerably less than the corresponding estimate in Column (1), 0.248, thus raising the possibility that the effect of omitting the efficiency variable θ from the analysis imparts an upward bias to the estimate of the public capital elasticity.

2. The preceding discussion is based on the assumption that infrastructure effectiveness affects growth only through the term $\ln \theta'$, implying that differences in effectiveness operate directly to lower steady-state output per worker. This, in turn, implies that the output elasticity of public capital is invariant to the degree of inefficiency, so that the percentage impact of new additions to the stock of infrastructure are the same in countries which use capital poorly as in countries where efficiency is high. This assumption is problematic[7] and can be relaxed by adding an interaction term to the regression analysis, $\theta' \ln s_g$, which is conceptually equivalent to adding a slope dummy variable to a model that already has an intercept dummy. The modified specification becomes

$$(6') \quad \ln (y(90)/y(70)) = b_0 + b_k \ln(s_k/(n+\lambda+\delta)) + b_h \ln(s_h/(n+\lambda+\delta)) + b_g \ln(s_g/(n+\lambda+\delta)) + b_\theta \ln \theta + b_{g\theta'} \theta' \ln s_g + b_c \ln y(70) + \epsilon$$

The results of this expanded model are shown in Column (3) of Table 4. The coefficient of public capital falls below zero, but the t-statistic is also close to zero. Other parameter estimates are not much affected, though the t-statistic on the effectiveness parameter of Column (2) -- the "intercept" effectiveness parameter -- is lowered. The statistical significance of the "slope" effectiveness parameter is low, although when it is appears by itself without the intercept parameter (in a regression not reported in the Table), it is significant.

One effect of adding the interaction term to the analysis is to change the output elasticity of public capital, γ, from a constant into a variable that depends on θ'. In the expanded version of the analysis, the elasticity of the growth rate of output with respect to log s_g is $b_g + \theta' b_{g\theta'}$. This elasticity takes on a value of 0.114 at the sample mean of θ', a value close to the magnitude of the corresponding estimate in Column (2). However, when this output elasticity is computed for those countries at the lowest level of infrastructure effectiveness, the estimate of γ is only 0.009. For those countries with the highest level of infrastructure effectiveness, this estimate is 0.244. This suggests that the impact of infrastructure investment depends on the efficiency with which it is used, and that those countries that use it inefficiently get a much smaller benefit for new infrastructure investments.

The addition of the interaction term to the analysis also causes the effectiveness parameter to vary according to the amount of public investment. The value of the effectiveness term in Column (3) is 0.892 at the mean value of public investment, but at one standard deviation below mean investment, the effectiveness term is 0.761, while it is 0.970 at one standard deviation above mean investment. Those countries with larger public capital investment rates also seem to use this capital more effectively. This probably reflects two factors: (1) the superior management of all aspects of infrastructure in "infrastructure-effective" countries, and (2) the fact that a low degree of infrastructure effectiveness can arise from inadequate investment in facility maintenance. For example, inadequate investment in road maintenance may lead to a low score on the "percentage of roads in good condition" indicator; also, too little investment in diesel locomotives may affect their availability, leading to a low score on this indicator, etc.

3. An interesting extension is obtained by interacting the effectiveness indicator, θ', with the rate of private investment ($b_{k\theta'}\ln s_k$) as well as the rate of public investment ($b_{g\theta'}\ln s_g$). This extension produces an estimate of $b_{k\theta'}$ equal to 0.819, with a t-statistic of 1.1637. When this variable appears alone, without $\ln s_g$, the t-statistic rises to 1.876. These results open up the possibility that the infrastructure effectiveness indicator is actually a surrogate for overall societal productive efficiency (or total factor productivity), not just the effectiveness of a country's infrastructure systems. In other words, it may control for the distance that each country is from the best practice production possibility frontier.

4. The initial level of GDP per capita ($\ln y(70)$), on the right hand side of the regression is, in effect, a lagged endogenous variable.[8] The use of ordinary least squares may thus introduce a bias into the estimates, if a random shock affects GDP per capita in both 1970 and 1990. To control for this problem, instrumental variables were used to obtain a fitted value for $\ln(y(70))$; these variables included the infant mortality rate in 1970, the primary enrollment rate in 1960, and energy consumption per capita in 1970. The results (not shown separately) indicate that the instrumental variables had a negligible effect on the parameters of interest -- the coefficients of the capital variables -- but did reduce the output elasticity of secondary

enrollments and the rate of convergence. Other sets of instruments produced a similar result. Since the rate of convergence is not the central focus of this paper, the instrumental variable approach was abandoned because it reduces the number of countries that can be included in the analysis.

A number of alternative definitions of the key variables were explored in order to check the robustness of the estimates in Table 2, and three deserve special mention. First, estimates were obtained using the World Bank unadjusted income concept in place of the Summers-Heston PPP-adjusted estimates. This has the theoretical effect of extruding the range of the dependent variable, and this was found have some impact on the elasticities of Table 2, but not so much as to change the general thrust of the results.

Second, the use of primary and secondary enrollments as proxies for the rate of investment in human capital was tested by using expenditures on health and education as a fraction of GDP to estimate the human capital elasticities. The result for health expenditures was found to be negative and statistically significant, a finding consistent with Devarajan et. al (1993). Education has a relatively large and significant elasticity with the World Bank income variant, but a smaller and insignificant elasticity with the Summers-Heston definition of income; however, the sample in this case was very small.

Third, Easterly-Rebelo estimates of investment in infrastructure, as opposed to investment in public capital, are available for a small number of countries. The latter averages approximately nine percent of GDP, while the rate of public infrastructure investment averages only about 3.0 percent. A shift from a broad to a narrow definition of infrastructure alters the results considerably, with a large decline in the elasticity of ln s_g. However, a further parsing of the infrastructure variable into "transportation and communications" and "other infrastructure" results in a large effect for the former, while "other infrastructure" is small and not significant. The importance of transportation and communications investment was noted by Easterly and Rebelo, but the size of the sample is so small that the results cannot be compared with the other results of this paper.

Finally, it should be noted that the analysis is sensitive to the composition of the sample. Subtracting Zambia from the sample has the effect, in Column (3) of Table 2, of increasing the public capital coefficient from 0.113 to 0.165, and reducing the elasticity of efficiency from 0.892 to 0.827. The procedure adopted in this paper is to present estimates for the maximum number of countries for which data are available.

V. Results II: Stock Measures of Infrastructure

1. The preceding analysis is based on the assumption that it is the rate of investment that is exogenously determined, not the capital stock. However, it is common to see the stock of infrastructure capital in the reduced form equation, presumably with the rationale that the stock, not the rate of investment, is the policy variable that the government seeks to control. This alternative assumption about policy poses no theoretical problem for the Solow reduced-form framework, since the model can be solved with the infrastructure stock as an exogenous variable instead of the investment rate, in which case the first equation of the reduced form (4) can be expressed in terms of the stock of infrastructure, g, rather than the investment rate s_g:

(7) $$y^* = \{\frac{\theta s_k^{\alpha} s_h^{\beta} (\theta g)^{\gamma}}{(n + \lambda + \delta)^{\alpha+\beta}}\}^{\frac{1}{1-\alpha-\beta}}$$

The rest of the steady-state model (4) is modified accordingly. This modification yields a variant of the basic estimating equation (6) in which the infrastructure stock replaces the investment rate.

This model was applied to the 1980 values of five types of infrastructure stock: telephone systems (proxied by telephone mainlines per capita), road networks (measured as kilometers of paved roads per capita), electric power systems (proxied by electric generating capacity per capita), railroads (kilometers per capita), and irrigated land area (thousands of hectares).[9] These stock measure are essentially indicators of physical capacity, unadjusted for quality or effectiveness difference. The expectation is thus that the addition of an effectiveness indicator to the analysis will have a larger impact than in Table 2.

The resulting estimates are shown in Table 3, which is similar to Table 2, except that the aggregate infrastructure stock replaces public investment as the measure of ln s_g. To bridge the gap between the two measures, Column (1) presents estimates based on the Table 2 measure of public investment and is comparable to Column (1) of that table, except that the analysis is now limited to the 42 countries for which complete infrastructure stock data is available (rather than 46). Nevertheless, the omission of four countries in passing from one to the next has only a small effect on the estimated parameter elasticities (a valuable robustness check). However, with Table 3, a large effect is recorded in jumping from the public investment variable of Column (1) to the aggregate infrastructure stock of Column (2). The estimate of b_g falls by a factor of ten, and the t-statistic falls from 2.706 to 0.254.

The importance of effectiveness-adjusted infrastructure as an explanator of cross-national growth thus disappears.

Some of the explanatory power is restored in Column (3) with the addition of the effectiveness indicator. As in Table 2, the efficiency effect is many times larger than the direct public capital effect. Indeed, a comparison of the estimated elasticities in the lower panels of the two tables reveals a high degree of similarity. Two differences should, however, be noted. As might be expected, given that the infrastructure stocks are physical indicators unadjusted for efficiency, the statistical significance of the effectiveness indicator increases relative to Table 2. Second, the possibility raised by Table 2 that the omission of the efficiency variable from the analysis imparts an upward bias to the estimate of the infrastructure elasticity is not evident with the physical stocks (perhaps because they are not adjusted for efficiency differentials).

Column (4) presents the results of having both "slope" and "intercept" effectiveness indicators in the analysis. The output elasticities are essentially unchanged from Column (3), as is the rate of convergence. The statistical significance of the effectiveness indicators falls dramatically, but this is, again, a matter of collinearity since the T-statistic of the slope term, $b_{g\theta'}$, is 5.673. The results of Column (4) are also quite similar to those of the last column of Table 2, with the notable exception of the coefficient of private capital.

2. Table 4 continues the analysis of infrastructure stocks, but with the data disaggregated into the four types of infrastructure and treated separately. The levels of significance are lower, here, than in Table 3. Roads and telephones have a small positive output elasticity, while electricity

generation and railroads have a (insignificantly) negative impact on growth. The positive value of telephones is consistent with Easterly and Levine (1996), and there is a rough consistency with similar variants of Canning and Fay (1993) for roads and Fay (1995) for electricity generation (although alternative estimation techniques in these last two studies did produce different results). None of these studies has an explicit treatment of the effectiveness indicators.

VI. Country Comparisons

It is clear from Tables 2, 3 and 4 that those countries that fail to use their infrastructure effectively pay a penalty in the form of lower growth rates. Just how large this penalty is can be illustrated by comparing the four East Asian countries in the 46 country sample with the 17 African countries.[10] The annual growth rate of the former averaged 3.26 percent between 1970 and 1990, while the African economies declined at an annual rate of -0.20 percent. The difference in these two rates can be allocated among the explanatory factors on the right-hand-side variables of Column (3) of Table 2 (which, in turn, are based on the regression equation (6)).

The result is shown in the top panel of Table 5. The first column of numbers reports the sources of growth allocation with the convergence factor subtracted from the differential growth rate. The difference in secondary school enrollment rates between Africa and East Asia is the most important source of differential performance, explaining 33.9 percent of the difference. The effectiveness indicator is second in importance, accounting for 25.9 percent of the difference. In other words, had the African countries in the sample operated their infrastructure stocks with the same effectiveness of the four Asian economies, their average growth rate would have been 0.75 per year rather than -0.20. Private capital formation is the third largest source of the growth differential, and public capital formation is of negligible importance.

When the rate of convergence is taken into account in Column (2), these effects are enhanced, since the convergence effect works in favor of Africa in comparison with Asia.

The importance of the infrastructure effectiveness indicator is even more pronounced when the data in the 46 country sample is sorted by rates of GDP growth per capita, and the top quartile of the sample is then compared with the bottom quartile. The former averaged 3.38 percent growth between 1970 and 1990, while the latter had an annual growth rate of -1.92 percent, and the sources of growth allocation of the implied differential is shown in the lower panel of Table 5. The difference in the effectiveness indicators is now the most important source of differential performance, explaining approximately 40 percent of the divergence. Secondary school enrollments are the second most important systematic factor, and public capital formation now has a slightly perverse effect. The popular idea that public capital formation is the deus ex machina of economic growth finds little support here or in the estimated elasticities of the preceding tables.

VII. Conclusion

Many qualifications must be placed on any conclusions and policy recommendations emerging from this paper. First, the infrastructure-effectiveness index developed above is, at best, a rudimentary representation of the underlying efficiency with which countries operate their infrastructure capital. Moreover, the results of the preceding section are perhaps too strong to be attributed to the effective use of public capital alone, and it is possible that the effectiveness index is a proxy variable for overall total factor productivity. If this is the correct interpretation, it has an interesting implication for the debate of the relative importance of total factor productivity as a source of economic growth. Young (1995) has argued that TFP growth played a much smaller role in the development of East Asia than is commonly supposed. If the results of this paper are given a TFP interpretation, they imply that the relative level of total factor productivity is an important correlate of growth in a broad range of low and middle income countries.

The robustness of the analysis to changes in sample composition is another source of concern. However, the conclusion about the importance of the effectiveness variable tends to hold up across different samples. And, confidence in this conclusion is greatly enhanced by the wealth of institutional analysis provided in the 1994 WDR. The WDR documents the importance of the infrastructure effectiveness variables -- recall the quotes cited in the introduction -- and the results of this paper can be regarded as a macroeconomic gloss for the micro analysis of the WDR. The implication for future research is clear: just as early studies of the sources of international growth inappropriately ignored infrastructure capital, it is no longer appropriate to ignore the efficiency with which this capital is used.

The implication for infrastructure policy is also clear: international aid programs aimed only at new infrastructure construction may have a limited impact on economic growth, and may actually have a perverse effect if they divert scarce domestic resources away from the maintenance and operation of existing infrastructure stocks.

NOTES

1. This large, and rapidly growing, body of literature is surveyed in the 1994 WDR (see also Levine and Renelt (1992) and Barro and Sala i Martin (1995) for reviews of the relevant growth literature). Recent contributions to the theoretical literature on the relation of infrastructure to the growth process include Barro (1990) and Baxter and King (1993).

2. The embodied technical change model was developed in the 1950s in a number of papers. The relevant literature is surveyed in the review article by Hulten (1990).

3. This application of θ differs from the original in one important respect: in the embodiment model, an individual ψ is fixed once the corresponding investment is made, and new investment brings larger values of ψ; in the current application, any individual ψ can rise or fall as management practices change or as new links are added to the infrastructure network.

4. Labor is expressed here in efficiency units, $e^{\lambda t}L(t)$, where λ is the rate of labor-augmenting technical change. Output per unit of (efficient) labor is then $\hat{y}(t) = Y(t)/e^{\lambda t}L(t)$, etc.

5. For example, a newly constructed road may deteriorate in condition without much penalty to road users, but a point is typically reached where further deterioration exacts an increasingly large penalty. Moreover, a few bad roads may not pose serious problems in a road network because substitute routes are available, but a large number of roads in poor condition may give rise to bottlenecks that erode the effectiveness of the whole network.

6. The regressions also include the "canonical" Easterly-Rebelo institutional variables: assassinations per million, revolutions and coups, and war casualties per capita. The estimates for these variables are omitted from the tables to save space, but their effects are included in the summary Table 5.

7. For example, new investment may alleviate a low degree of effectiveness and thus raise the output elasticity of capital. For example, investment in roads may reduce congestion and alleviate wear and tear (and thus depreciation). The opposite result may obtain in other situations: poor management practices may blunt the effect of new investment, as, for example, when additional telephone lines are added to a system in which few attempted calls are successful.

8. If the variable ln y(70) is subtracted from both sides of the regression equation (6), the resulting model is statistically equivalent to (6), except for a difference in the coefficient of ln y(70).

9. The stocks of five types of infrastructure stock are reported in the 1994 WDR, but as only four different effectiveness measures are available, the stock of irrigation capital was omitted from the

analysis.

10. The list African countries includes Burkina Faso, Burundi, Cameroon, Central African Republic, Cote, d'Ivoire, Gabon, Kenya, Mali, Mauritania, Mauritius, Mozambique, Nigeria, Rwanda, Senegal, Sierra Leone, Sudan, Togo, Zambia, and Zimbabwe. The four Asian economies are Indonesia, Malaysia, The Philippines, and Thailand.

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TABLE 1
Mean and Distribution of Key Variables

Growth Rate Rank	Summers-Heston GDP* Growth Rate 1970-90	Summers-Heston GDP* 1970	Summers-Heston GDP* 1990	World Bank GDP* 1970	World Bank GDP* 1990	Revoltn & Coups 1970-90
Top Third	0.044	$1651	$3145	$785	$1440	0.221
Mid Third	0.015	$1961	$2413	$935	$1084	0.187
Last Third	-0.014	$1958	$1674	$936	$920	0.347
Average	0.198	$1857	$2393	$885	$1144	0.256

	Public Inv Rate 1970-90	Private Inv Rate 1970-90	Populn Gr. Rate 1970-90	Primary Educ Rate	Secondary Educ Rate
Top Third	0.124	0.100	0.023	0.807	25.1
Mid Third	0.083	0.121	0.028	84.1	20.6
Last Third	0.086	0.087	0.026	67.7	17.8
Average	0.097	0.102	0.025	77.1	21.1

	Railroads* 1980	Paved* Roads 1980	Elect* Gener 1980	Telephone* Mainlines 1980	Irrigat.* 1980	Total* Infra. 1980
Top Third	36	81	82	10	68	278
Mid Third	42	57	112	12	54	277
Last Third	87	47	80	8	48	270
Average	56	62	90	10	57	275

	Electricity System Loss Index	Road Condition Index	Telephone Fault Index	Locomot. Avail. Index	Average Efficiency Index
Top Third	0.519	0.568	0.722	0.818	0.647
Mid Third	0.481	0.500	0.679	0.500	0.530
Last Third	0.423	0.467	0.469	0.417	0.446
Average	0.474	0.506	0.625	0.602	0.539

* Variable in per capita units

Table 2
OLS Estimates of Model Parameters
with Effectiveness Variables

	(1) Without Effectiveness Parameters	(2) With Intercept Parameter	(3) With Intercept and Interactive Parameters
Public Capital, b_g	0.355	0.107	-0.076
	(2.811)	(0.892)	(-0.186)
Effectiveness, b_θ		0.794	0.748
		(4.238)	(3.511)
Interactive Eff., $b_{\theta g}$			0.332
			(0.468)
Private Capital, b_k	0.344	0.180	0.185
	(3.603)	(2.052)	(2.067)
Primary Enrollment, b_{h1}	0.180	0.082	0.086
	(1.185)	(0.638)	(0.662)
Secondary Enrollment, b_{h2}	0.167	0.185	0.177
	(1.848)	(2.473)	(2.281)
1970 GDP per capita, b_c	-0.386	-0.350	-0.346
	(-3.566)	(-3.884)	(-3.379)
Constant	0.768	1.656	1.607
Implied Output Elasticities			
Effectiveness		0.837	0.892
γ	0.248	0.118	0.113
α	0.240	0.200	0.206
β_1	0.126	0.090	0.096
β_2	0.116	0.205	0.198
Converge. Rate	0.024	0.022	0.022
R Squared	0.558	0.705	0.707
# Observations	46	46	46

Dependent Variable: log difference in GDP per capita, 1970-90

Table 3
OLS Estimates of Using Total Infrastructure Stock
Instead of the Gross Public Investment Rate

	(1) Gross Public Investment w/o Eff Param	(2) Infrastructure Stock w/o Eff Param	(3) Infra Stock Intercept Eff. Param	(4) Infra Stock Both Eff Parameters
Public Capital	0.371	0.030	0.092	-0.043
	(2.706)	(0.254)	(1.074)	(-0.181)
Effectiveness			0.998	0.198
			(5.611)	(0.149)
Interactive Eff.				0.244
				(0.606)
Private Capital	0.287	0.161	0.106	0.106
	(2.491)	(1.388)	(1.251)	(1.246)
Pri. Enrol	0.219	0.184	0.067	0.090
	(1.331)	(0.972)	(0.490)	(0.623)
Sec. Enrol	0.184	0.204	0.210	0.200
	(1.812)	(1.519)	(2.173)	(2.013)
1970 GDP PC	-0.413	-0.418	-0.434	-0.441
	(-3.614)	(-2.840)	(-4.090)	(-4.092)
Constant	0.611	0.750	1.899	1.367
Implied Output Elasticities				
θ			1.097	1.006
γ	0.252	0.030	0.101	0.094
α	0.195	0.162	0.116	0.115
β_1	0.148	0.184	0.074	0.097
β_2	0.125	0.205	0.231	0.216
Conv. Rate	0.027	0.027	0.028	0.029
R-Squared	0.489	0.377	0.686	0.690
# Obs.	42	42	42	42

Dependent Variable: log difference in GDP per capita, 1970-90

Table 4
OLS Estimates of Individual Infrastructure Stock Parameters with Implied Elasticities

	(1) PAVED ROADS without Effectiveness	(2) PAVED ROADS with Effect.	(3) ELECT. GEN. without Effectiveness	(4) ELECT. GEN. with Effect.
Infrastructure Stock	0.057	-0.003	- 0.022	-0.236
	(0.642)	(-0.034)	(-0.210)	(-1.690)
Effectiveness		-0.075		-0.169
		(-0.199)		(-0.433)
Interactive Eff.		0.116		0.249
		(0.566)		(1.230)
Private Capital	0.255	0.233	0.237	0.248
	(2.270)	(1.963)	(1.943)	(2.001)
Primary Enrollment	0.221	0.224	0.175	0.127
	(1.255)	(1.254)	(0.814)	(0.620)
Secondary Enrollment	0.121	0.139	0.212	0.322
	(1.092)	(1.236)	(1.730)	(2.679)
1970 GDP per capita	-0.406	-0.426	-0.381	-0.305
	(-3.199)	(-3.304)	(-2.068)	(-1.773)
Constant	0.740	0.836	0.724	0.106
<u>Implied Output Elasticities</u>				
Effectiveness		0.146		0.404
γ	0.054	0.051	-0.023	-0.136
α	0.241	0.217	0.241	0.281
β_1	0.209	0.208	0.178	0.144
β_2	0.114	0.129	0.216	0.365
Converge. Rate	0.026	0.028	0.024	0.018
R Squared	0.406	0.435	0.386	0.512
# Observations	41	41	40	40

Dependent Variable: log difference in GDP per capita, 1970-90

Table 4 (continued)
OLS Estimates of Individual Infrastructure Stock Parameters
with Implied Elasticities

	(1) TELEPHONE ML without Effectiveness	(2) TELEPHONE ML with Effect.	(3) RAILROADS without Effectiveness	(4) RAILROADS with Effect.
Infrastructure Stock	0.070	0.054	- 0.080	-0.111
	(0.221)	(0.111)	(-0.810)	(-0.861)
Effectiveness		0.176		0.200
		(0.256)		(0.550)
Interactive Eff.		0.013		0.060
		(0.024)		(0.340)
Private Capital	0.354	0.328	0.383	0.320
	(1.972)	(1.520)	(3.132)	(2.850)
Primary Enrollment	0.010	-0.076	0.238	0.186
	(0.034)	(-0.237)	(1.105)	(0.961)
Secondary Enrollment	0.273	0.252	0.213	0.172
	(1.654)	(1.474)	(2.009)	(1.792)
1970 GDP per capita	-0.391	-0.324	-0.209	-0.201
	(-2.148)	(-1.627)	(-1.578)	(-1.652)
Constant	1.643	1.950	-0.684	-0.031
Implied Output Elasticities				
Effectiveness		0.218		0.445
γ	0.063	0.070	-0.083	-0.092
α	0.323	0.369	0.398	0.398
β_1	-0.009	-0.086	0.247	0.231
β_2	0.249	0.283	0.222	0.213
Converge. Rate	0.025	0.024	0.012	0.011
R Squared	0.522	0.562	0.664	0.762
# Observations	24	24	28	28

TABLE 5

Sources of the Difference in the Growth Rates of Real GDP Per Capita*

Right Hand Side Variable	Percentage Contribution Excl. Converge.	Percentage Contribution Incl. Converge.
Africa versus East Asia		
Civil Unrest	0.68%	0.81%
Public Capital	1.19%	1.41%
Private Capital	17.16%	20.44%
Prim Education	7.30%	8.69%
Sec Education	33.92%	40.38%
Inefficiency	25.92%	30.86%
Unexplained	13.83%	16.47%
Convergence		-19.06%
Total	100.00%	100.00%
Average GDP PC Growth Rate, Africa		-0.202%
Average GDP PC Growth Rate, Asia		3.261%
Difference		3.463%
High versus Low Growth Rate Countries**		
Civil Unrest	-2.83%	-2.89%
Public Capital	-1.69%	-1.72%
Private Capital	11.45%	11.67%
Prim Education	5.02%	5.11%
Sec Education	20.76%	21.16%
Inefficiency	39.55%	40.31%
Unexplained	27.74%	28.27%
Convergence		-1.90%
Total	100.00%	100.00%
Average GDP PC Growth Rate, Low Quartile		-1.923%
Average GDP PC Growth Rate, High Quartile		3.376%
Difference		5.299%

* Based on the estimates of Table 2, Column (3).

** Bottom versus top quartile of countries ranked by growth rate of GDP PC

APPENDIX TABLE A

Countries and Selected Data

	SH GDP PC 1990 (y90)	GDP PC AAGR 1970-90 $\Delta y/y$	Public Inv Rate 1970-90 s_g	Private Inv Rate 1970-90 s_k	Populn AAGR 1970-90 η	Primary Educ Rate h_1	Sec Educ Rate h_2
Algeria	2660	0.020	0.31	0.04	0.030	76	11
Argentina	3513	-0.011	0.07	0.11	0.015	105	44
Bolivia	1594	0.001	0.08	0.06	0.026	76	24
Burkina Faso*	533	0.015	0.12	0.19	0.024	13	1
Burundi	522	0.017	0.10	0.01	0.023	30	2
Cameroon	1235	0.009	0.13	0.08	0.029	89	7
Central Afr. Rep.*	554	-0.021	0.10	0.03	0.025	64	4
Chile	3992	0.001	0.07	0.08	0.016	107	39
Colombia	3186	0.014	0.06	0.10	0.021	108	25
Costa Rica	3618	0.009	0.07	0.15	0.028	110	28
Cote d'Ivoire	1179	-0.010	0.11	0.09	0.040	58	9
Dominican Rep.	2030	0.011	0.06	0.15	0.024	100	21
Ecuador	2793	0.021	0.08	0.12	0.028	97	22
Egypt, Arab	1838	0.042	0.18	0.06	0.023	72	35
Gabon*	3919	0.019	0.13	0.18	0.041	85	8
Guatemala	2077	0.001	0.04	0.12	0.028	57	8
Honduras	1298	0.007	0.07	0.13	0.034	87	14
India	1068	0.024	0.09	0.10	0.022	73	26
Indonesia	1942	0.044	0.09	0.12	0.021	80	16
Kenya	912	0.011	0.09	0.12	0.036	58	9
Malaysia	4904	0.035	0.11	0.15	0.025	87	34
Mali	522	0.011	0.08	0.11	0.023	22	5
Mauritania	810	-0.019	0.20	0.11	0.024	14	2
Mauritius	5655	0.049	0.08	0.16	0.013	94	30
Mexico	5379	0.014	0.08	0.13	0.025	104	22
Morocco	2021	0.018	0.11	0.10	0.025	52	13
Mozambique*	736	-0.046	0.15	0.01	0.026	47	5
Nigeria	775	-0.023	0.09	0.05	0.030	37	4
Pakistan	1360	0.008	0.09	0.07	0.031	40	13
Panama	3032	0.008	0.10	0.14	0.023	99	38

* Not in the 46 country sample.

APPENDIX TABLE A
(continued)

Peru	2041	-0.018	0.05	0.14	0.025	107	31
Philippines	1751	0.008	0.05	0.16	0.025	108	46
Portugal	6525	0.040	0.11	0.10	0.004	98	57
Rwanda	658	0.004	0.06	0.10	0.032	68	2
Senegal	1080	-0.005	0.05	0.10	0.029	41	10
Sierra Leone	835	-0.024	0.05	0.06	0.022	34	8
Sudan	960	-0.004	0.05	0.08	0.029	38	7
Syrian Arab	3993	0.025	0.14	0.05	0.034	78	38
Thailand	3532	0.043	0.07	0.16	0.023	83	17
Togo	624	-0.004	0.13	0.11	0.030	71	7
Tunisia	2860	0.024	0.15	0.12	0.023	100	23
Turkey	3711	0.024	0.11	0.10	0.023	110	27
Uruguay	4278	-0.003	0.04	0.08	0.005	112	59
Venezuela	5754	0.008	0.11	0.14	0.030	94	33
Zambia	701	-0.031	0.19	0.03	0.031	90	13
Zimbabwe	1287	0.012	0.08	0.10	0.031	74	7