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TRANSPORT RESEARCH CENTRE

TRANSPORT INFRASTRUCTURE INVESTMENT AND ECONOMIC PRODUCTIVITY

ROUND TABLE

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TRANSPORT RESEARCH CENTRE

REPORT OF THE
ONE HUNDRED AND THIRTY SECOND ROUND TABLE
ON TRANSPORT ECONOMICS

TRANSPORT INFRASTRUCTURE INVESTMENT AND ECONOMIC PRODUCTIVITY

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TRANSPORTATION INFRASTRUCTURE, PRODUCTIVITY AND EXTERNALITIES

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SUMMARY

College Park, August 2004

ABSTRACT

This paper summarizes the results of three studies linking investment in highway infrastructure to productivity growth in the manufacturing sector of the US, Spanish and Indian economies. The goal of this research is:

1) to trace the overall impact of highway investment on the growth of this strategic sector;

2) to examine the interregional effects of such investments, with particular attention to the issue of whether highway investment encourages regional convergence and relocation of economic activity; and

3) to assess the extent of the spillover externalities on manufacturing industry associated with such investments.

This last issue is of particular importance for infrastructure policy, since spillover externalities tend to go uncounted in formal project investment analyses, leading to the possibility of under-investment. The comparative study of three countries at different stages of economic development, using virtually the same model, allows a fourth issue to be examined: the possibility that the effects of infrastructure investment differ according to the level of development and the extent to which existing infrastructure networks have already been built up. These issues are first framed in the larger context of the literature on infrastructure and productivity.

1. TRANSPORTATION INFRASTRUCTURE AND PRODUCTIVITY: HISTORICAL BACKGROUND

The idea that transportation infrastructure is a type of capital investment distinct from other forms of capital is an accepted part of the fields of economic development, location theory, urban and regional economics and, of course, transport economics. In his classic treatise, Albert O. Hirschman (1958) classifies transport infrastructure systems as "social overhead capital (SOC)", to distinguish it from the type of capital that is used directly by industry to produce their goods and services (e.g. plant and equipment), which he calls "directly productive assets (DPA)"[1]. Hirschman points to four characteristics that distinguish SOC from DPA:

1) SOC is basic to (and facilitates) a great variety of economic activities;
2) it is typically provided by the public sector or by regulated private agencies;
3) it cannot be imported; and
4) it is "lumpy" in the sense of technical indivisibilities.

He also argues that the function of SOC investment is to "ignite" DPA, and that "*investment in SOC is advocated not because of its direct effect on final output, but because it permits and, in fact, invites DPA to come in* (p. 84)."

A more modern statement of these issues would perhaps modify these ideas, but not entirely reject them. The first two characteristics, for example, would now be framed in terms of spillover externalities and the economic theory of partial public goods, or "clubs". Roads and highways, for example, are joint-use facilities with many different simultaneous users and uses. Unlike "private good" DPA investments, the conditions for optimal provision involve the summation of benefits across the different users ("members of the club"), adjusted for congestion effects. Sorting out the complex structure of benefits involved in a club good is notoriously difficult, all the more so because of the "igniting" effect such a good has on the evolution of the economy. The example in the US of the intercontinental railroads, which opened up the western regions of the country in the middle of the 19th century, is a case in point: how can one assess the value of a project that shaped the history and evolution of the country?

A partial solution to the "club" problem is to limit attention to the production side of the economy, where the more-or-less immediate impact of SOC infrastructure on the growth of output is more easily quantified. This more limited objective is the general subject of this Round Table and the focus of the empirical research described in this paper. The first major empirical work implementing the production-side approach is usually attributed to David Aschauer (1989a, 1989b), who estimated aggregate production functions for the US that included a public capital variable. The result was a startling estimate of the infrastructure effect: the elasticity of output, with respect to the public capital variables used in these studies, ranges from 0.36 to 0.56, which, according to the estimates of Gramlich (1994), translates into a gross return of 100 per cent per annum or more, and a payback period of one year or less. These seemingly implausible results might have sunk under their own weight were it not for the fact that Aschauer's papers were soon followed by other studies that seemed to confirm these large estimates. Estimates of this magnitude are credible only if there are significant externalities that have gone uncounted by conventional micro-economic project evaluation procedures, and if this has produced a drastic under-investment in those systems. The building of the US intercontinental railroads was often mentioned as an example of how this might occur.

This literature was interpreted at the time as a validation of the idea that macroeconomic productivity studies could uncover what the micro studies of public infrastructure missed, though no explicit estimates of the magnitude of the presumptive externalities were offered. It is therefore not surprising that these results triggered a large amount of subsequent research, and Gramlich notes "*at least forty other econometric studies using different data and techniques*" in the five years between the first paper published by Aschauer and the appearance of the survey article. He also observes that, over this period, "*the bubble has happened and may even be beginning to burst* (p. 1177)", since the emerging research suggested that the econometrics of the macro-production function approach were fragile and not robust to changes in estimation technique, scope and data. For example, estimation using "first differences" in the data often produced far lower and sometimes statistically insignificant results, compared to "level" estimates; much the same was true when "panel data" with a regional dimension were employed. Moreover, the direct estimate of the link between infrastructure and output was subject to the problem of "reverse causality". While it is likely that transport and other infrastructure investment make possible ("cause") a larger volume of national output, it is equally clear that a growing volume of output leads to more investment in such systems. To assume that the statistical correlation between infrastructure and output is caused entirely by infrastructure is not only to commit the econometric sin of simultaneous equations bias, but also to invite an overstatement of the return to public infrastructure.

More recent econometric studies that have employed more flexible functional forms have obtained rates of return that are within a more normal range of experience. Nadiri and Mamuneas (1994), for example, use a flexible cost function approach to estimate an average annual "social" rate of return to infrastructure of around 7.2 per cent in US manufacturing industry for the period 1955-86, compared to a 8.7 per cent annual rate of return to private capital. In similar work, they report plausible rates of return to highway infrastructure investment that diminished as the Interstate Highway System programme matured.

However, the problem of model specification continues to present a significant challenge to the application of production function techniques. One challenge is to specify models in such a way that the externality effects are isolated. An even more formidable challenge is to allow for the fact that most forms of core infrastructure, including transport systems, come in the form of spatially distributed networks of individual investments, and that the total quantity (or stock) of network capital is therefore not a sufficient measure of productive capacity. Unlike most DPA capital, the marginal product of network capital depends on where in the system the incremental investment is made, and not just on how much capital is already in place (Hulten, 1994). Thus, the practice of adding an infrastructure stock variable to a production function, when it is measured in the same way as private DPA capital, results in model mis-specification.

The practical consequence of this mis-specification is that the parameter (elasticity) associated with the network capital will vary according to the evolution of the network, and may be very large at some times and zero at others. For example, incremental investments may have a very large payoff during a period in which a network is undergoing an "upsizing" in order to alleviate capacity and coverage constraints. However, cost considerations often dictate building capacity in advance of need during periods of upsizing, while investment in additional capacity has no immediate effect on output, and therefore appears to have a zero marginal product (gross rate of return). A similar outcome can arise in mature, built-up networks before capacity constraints (e.g. congestion, bottlenecks) set in: incremental investments in this situation tend to be made in links that substitute for other links, rather than complementing them as in the early stages of building, and will also tend to have a low marginal product. They may, on the other hand, have a significant effect on relocating economic activity from one point in the network to another with little or no net increase in overall output.

These considerations provide an intellectual backdrop for the body of empirical research described in the following chapters. This research is based on a model developed by Hulten and Schwab (1984, 1991, 2000), that attempts to avoid some of the econometric problems described above and, in particular, to isolate the externality effects. This approach focuses on manufacturing industry rather than on the entire economy, and has both a regional and a time dimension. Both features help reduce the problem of reverse causality, for reasons noted below. However, the principal difference between the Hulten-Schwab approach and the majority of the production function literature on infrastructure is the focus on total factor productivity rather than on real output as the left-hand variable of interest. This shift in focus reduces the dependence on econometric specification and the associated problems, further reduces the problem of reverse causality and, most importantly, provides a means for isolating infrastructure externalities as they affect manufacturing industry. Since this last issue is of considerable importance to infrastructure policy, it is developed in some detail in the following chapter, before turning to the description of the data and results.

2. INFRASTRUCTURE "CHANNELS" IN THE STRUCTURE OF PRODUCTION

The Hulten-Schwab approach to isolating externalities follows the general approach of Meade (1952) in assuming that the effects of infrastructure capital operate through two different channels in manufacturing industries[2]. In the first channel, the benefits to manufacturing industries from infrastructure investments are received *indirectly* in the form of inputs purchased from those sectors involved in the production of infrastructure services (for manufacturing, this is mainly transportation and various utilities). Roads and highways, for example, are combined with vehicles, workers, fuel, warehouses, etc., by the transport industry to produce transportation services sold to other sectors. Similarly, electric utilities combine the services of infrastructure networks with inputs of DPA capital, labour and fuels, and sell the output directly to other industries. From the perspective of the manufacturing sector, these infrastructure services appear as an intermediate input purchased from the upstream producing industry. In this process, the unpaid infrastructure inputs are converted to a *paid* factor of production in the downstream industry, and any improvement in the quantity or quality of the infrastructure network upstream appears as a reduction in the cost of the intermediate purchases of transportation services and electricity downstream, or as an improvement in the quality or scope of these services. In any event, upstream infrastructure externalities are internalised in the market for purchased services by the time they arrive at the downstream user.

If this were the only channel through which infrastructure affects manufacturing output, there would be little or no role for externalities in that industry. However, infrastructure may also affect manufacturing industries *indirectly* through a second channel: network externalities. The expansion of capacity at one point in an existing infrastructure system can have effects throughout the network, through the addition or extension of critical links, or the elimination of bottlenecks. These effects operate indirectly on industries like manufacturing in a variety of ways familiar in the field of location theory and economic geography (Krugman, 1998). Expanded transport systems may, for example, lead to expanded product and input markets, leading to efficiency gains through economics of scale and access to specialised inputs; they may also lead to a concentration of production at various points in the network that result in further economies of scope and scale; improvement in transport services may also cause a reallocation of production within the network to exploit specialised local resources, lower regional input costs (though this is perhaps a temporary effect) and a more favourable regulatory or tax climate; finally, these system effects tend to increase total productivity directly through improved technologies (e.g. just-in-time inventory management). These second-channel effects are external to the firms located at any point on the network and, unlike the first-channel effects, they operate largely outside the market place and are not mediated by prices.

The channels can be given a more precise analytical form in terms of the production functions underlying the descriptive analysis. Imagine an economy with only two products, transportation services, T, and a manufactured good, Q. The production of transport services is $T = T(D_T,B)$, where D_T is the primary input used by the sector and B is the transportation network; the technology for the manufactured good is $Q = F(D_Q,T)$, with D_Q as the primary input and T the transport service purchased from the other sector. The technology for manufacturing does not make use of the transport network as a direct input. The entire impact of transport infrastructure, on manufactured goods in this case, operates through the purchases of the intermediate transport good, T, by that sector, $\Delta Q/\Delta B = (\delta Q/\delta T)\Delta T/\Delta B)$. This is the first channel effect defined above, and there is no second channel effect ($\delta Q/\delta B$) in this case.

Second channel effects in the production of manufactured goods can be modelled by introducing a "shift" term, A(B), into the manufacturing production function. This alternative technological specification may then be expressed as $Q = A(B)F(D_Q,T)$. An increase in infrastructure now affects output indirectly by allowing the purchased inputs, D_Q and T, to be used more efficiently. Moreover, transport infrastructure now operates through both of the channels described above: $\Delta Q/\Delta B = [(\delta Q/\delta T)\Delta T/\Delta B)] + (\delta Q/\delta B)$, the first operating through the market and the second as an externality operating outside of it[3].

The model described in the following chapter is an elaboration of this rudimentary framework. The basic idea is to estimate the $F(D_Q,T)$ component of the manufacturing production function separately using non-econometric "index number" techniques, and thereby isolate the shift term A(B) function that embodies the second channel externalities.

3. EMPIRICAL RESULTS: INDIA

The empirical work for India and the USA is based on an elaboration of the model outlined in the preceding chapter. The production function for manufacturing output used for the analysis takes the form:

$$(1)\ Q_{i,t} = A_{i,t}(B)\ F^{i}(K_{i,t}, L_{i,t}, M(B)_{i,t})$$

where Q denotes gross output, M is intermediate inputs, L is labour input, K is privately owned (non-infrastructure) capital and B is the infrastructure stock. The variables and subfunctions can have both a time "t" and region "i" dimension. The shift term $A_{i,t}(B)$ is specified as:

$$(2)\ A_{i,t}(B) = A_{i,0}\, e^{\lambda,t} B_{i,t}^{\gamma i}$$

This specification treats productive efficiency as a multiplicative function of the initial level of efficiency in each region, $A_{i,0}$, the exogenously determined average annual rate of technical progress in each region, λ_i, and the second channel infrastructure externality effect whose elasticity, γ_i, is assumed to be constant over time but can vary among regions.

The multiplicative form of the specification (1) and (2) is a standard feature of the literature on the Solow residual, which allows the shift term to be estimated using index number techniques (as opposed to applying econometric techniques directly to the production function). Solow's "total factor productivity" is conventionally defined as the ratio of real output to total input, which, in terms of the production function above, is equivalent to $TP_{i,t} = Q_{i,t}/F(K_{i,t},L_{i,t},M_{i,t})$. Total factor productivity (which is really "total productivity" in this context because it is based on gross output and intermediate input)[4] is therefore directly related to the parameters of interest in $A_{i,t}(B)$. Expressing productivity in logarithmic form results in:

$$(3)\ \ln TP_{i,t} = \ln A_{i,0} + \lambda_i t + \gamma_i \ln B_{i,t}$$

The utility of this specification is that it isolates the parameter of interest, γ_i, in a form that can be estimated using regression techniques, given estimates of total productivity and of the stock of transport infrastructure, both of which can be measured. It forms the basis for the empirical results shown below.

The total productivity variable required for (3) is estimated in two steps. The growth rate is first estimated using the Solow residual method, which involves subtracting the growth rates of the inputs (L, K, M), each weighted by its shares in total income, from the growth rate of real gross output (Q)[5]. The resulting residual estimate of the *growth rate* of total productivity must then be converted to levels. This yields an estimate of variable $TP_{i,t}$ in the estimation equation (3) for each year and each region, and permits an analysis of the regional evolution of productivity as a by-product.

This approach is applied to the manufacturing sector of the Indian economy in Hulten, Bennathan and Srinivasan (2003), using data from India's Annual Survey of Industries for the years 1972-93. This source includes annual estimates (in current prices) of gross output, intermediate inputs, labour input and the book value of capital stocks for manufacturing firms registered under the Factory Act, which are the larger enterprises in the manufacturing sector. The estimates of output and input were then converted to constant (real) prices using a new output price deflator developed in the study, since previous approaches were deemed inadequate. The resulting growth rate estimates for the manufacturing sector as a whole are shown in the first columns of Table 1, and the productivity level estimates in Table 2.

Table 1 indicates that real gross output grew at a sustained rate of over seven per cent a year for the two decades of our sample. It also shows that the growth of inputs explained most of the growth in output, with productivity only a small contributor. Since this productivity estimate includes the externalities associated with transport infrastructure, γ_i, it would appear to leave little scope for this effect. However, while the 0.5 per cent annual growth rate of productivity may seem small, it appears so only because it measures the impact of innovation and infrastructure investment on a very broad base of inputs. When converted to a value-added basis, as shown in the second column of Table 1, the size of the productivity residual is a more conventional and very respectable magnitude of two per cent[6].

The Table 1 estimates of the annual growth rate of productivity (in both its measures) are for registered manufacturing across *all* the states of India combined, and it thus excludes the regional dimension. Since the ultimate goal is to isolate the infrastructure spillover component of manufacturing productivity, regional differences in productivity and infrastructure across geographical regions are a potentially important source of variation. A sources-of-growth table, similar to Table 1, was therefore calculated for each of the 16 states in the regional sample, and the results are summarized in Table 2 for Indian states grouped into terciles according to the initial level of productivity. The bottom five states ranked according to this criterion experienced a more rapid rate of both gross output and productivity growth, with the result that those states that started with the lowest levels of productivity narrowed (but did not eliminate) the gap with the leaders by 1992. This pattern of regional convergence was achieved with strong output growth in all regions, without major net relocations of manufacturing activity between the upper and lower groups of regions. These results stand in stark contrast to the experience in the United States.

Table 1. **Sources of output growth in three economies**
(Average annual rates of growth or ratios)

	Indian manufacturing 1973-92 Gross output basis	**Indian manufacturing 1973-92 Value added basis**	**US manufacturing 1970-86 Gross output basis**	**Spanish economy 1964-93 Value added basis**
Real product	7.3%[1/]	7.1%[2/]	2.5%[1/]	3.7%[2/]
Materials	7.4%	—	2.0%	—
Labour	2.1%	2.1%	-0.1%	-0.3%[3/]
Capital	6.8%	6.8%	2.5%	1.2%[3/]
Total input	6.9%	5.0%	1.1%	0.9%
Productivity	0.4%[4/]	2.1%[5/]	1.4%[4/]	2.8%[5/]

Sources: India: Hulten, Bennathan and Srinivasan (2003); US: Hulten and Schwab (2000); Spain: Mas *et. al.* (1998). Detail may not add due to rounding error.

Notes:
[1/] Real gross output.
[2/] Real value added.
[3/] Weighted by income shares.
[4/] Total productivity.
[5/] Total factor productivity.

Table 2. **Levels and growth rates by State**
(Ranked by terciles)

Rank by 1973[3/] level of total productivity	**AAGR[1/] Gross output Q**	**AAGR[1/] Total prod. TP[2/]**	**TP[2/] level 1973**	**TP[2/] level 1992**
Top 5	7.76%	0.42%	1.020	1.105
Middle 5	7.85%	0.45%	0.988	1.076
Bottom 5	9.30%	0.58%	0.927	1.035

Source: Hulten, Bennathan and Srinivasan (2003).

Notes:
[1/] AAGR is average annual growth rate.
[2/] TP is total productivity.
[3/] Ranking by tercile excludes Kerala.

4. CROSS-NATIONAL COMPARISONS

The results for India are based on the model first developed and applied to US manufacturing. The sources-of-growth results obtained by Hulten and Schwab (2000) for the US are reported in Table 1, based on data from the Census of Manufactures and the Annual Surveys of Manufactures for the years 1970-86. They show a different pattern of growth compared to India: the rate of growth of output is significantly lower in the US and it is driven primarily by productivity growth, while labour input growth was slightly negative.

The regional distribution of US manufacturing growth is summarized in Table 3. The results for the nine census regions in the original study are aggregated to the level of "Sun Belt" and "Snow Belt", to highlight the key fact exposed by the analysis: the shift in the manufacturing base from the older regions of the northeast and mid-west of the US (the "Snow Belt") to the south and west of the country (the "Sun Belt") that occurred after World War II. This shift attracted much comment in the 1970s and 1980s, for reasons that are apparent in Table 3, where Sun Belt growth rates of output and input are seen to be much larger. Labour input, in particular, shows a negative growth in the Snow Belt and no net growth overall, suggesting the presence of a significant relocation of manufacturing activity.

Some of the factors involved in this relocation are shown in this table. The rate of return to private capital was higher in the Sun Belt throughout the period and wages were lower, making these regions attractive from the standpoint of business. This was also a period of macroeconomic "stagflation", weakening the power of labour to resist the relocation of businesses to low-wage/high-return areas. Public capital, the measure of "infrastructure" used in this study, also grew significantly more rapidly in the Sunbelt. The public capital variable includes transport infrastructure as one of its most important components. In an earlier study, Hulten and Schwab (1991) estimated that the *growth rate* of highway expenditures was also much more rapid in the Sun Belt, and it is worth noting that the US Interstate Highway System Program, begun in the 1950s, was largely completed during this period and surely played a role in accommodating the regional shift in the manufacturing base (as predicted by location theory).

Significantly, productivity differences among the regions were *not* a factor determining regional growth differentials[7]. The level of total manufacturing productivity was basically the same across regions, at both the starting and end points of the period studied. Essentially, manufacturing firms functioned at the same average level of productivity efficiency throughout the US. This finding is consistent with a rapid rate of technological diffusion among the regions, but contrasts with the case of India, where productivity differentials existed and were compressed during the sample period.

The index number methodology used for the USA and India was applied to Spain by Mas *et. al.* (1998). The Spanish study focuses on the aggregate economy rather than on the manufacturing industry alone, so the second-channel externalities cannot be isolated as with the USA and India. However, the Spanish study does use productivity rather than output as the variable of interest, as do the US and Indian studies, so some insights can be obtained by a comparison of all three. The pattern of growth exhibited by the Spanish economy in Table 1 is, in fact, roughly similar to that of US manufacturing, in that productivity change is the most important source of output growth and the role of labour is insignificant. However, the level of productivity differed by region in Spain, and showed a tendency to converge over the sample period.

Table 3. **Regional sources of growth**[1/]
US manufacturing industry, 1970-86

	Sun Belt	Snow Belt	Total
Average annual growth rate of:			
Gross output	3.75%	1.53%	2.49%
Intermediate input	3.20%	1.02%	1.99%
Labour input	1.26%	-1.06%	-0.08%
Capital input	3.54%	1.57%	2.46%
Total productivity	1.30%	1.38%	1.34%
Total productivity level			
1970	0.9945	1.0027	1.0000
1986	1.2251	1.2505	1.2386
Rate of return to capital			
1970	16.4%	15.3%	15.9%
1986	10.7%	9.7%	10.3%
Index of wage level			
1970	0.937	1.012	0.970
1986	3.061	3.321	3.177
AAGR of public capital	2.09%	1.30%	1.70%
AAGR of highways	1.43%	0.69%	1.43%

Source: Hulten and Schwab (2000); “highways” estimates are taken from Hulten and Schwab (1991).

5. ESTIMATION OF THE INFRASTRUCTURE-PRODUCTIVITY LINK: INDIA

The results reported in Tables 1 and 2 provide the data with which to study the relation between the level of productivity and the stock of infrastructure, as set out in equation (3) above. Following Hall (1988), this equation was expanded to allow for the possibility of increasing returns to scale and to allow for the possibility of a bias in the Solow residual method, due to non-competitive pricing (a problem thought to be particularly characteristic of markets in developing economies). The externality parameter, λ_i, was assumed to be equal across regions in the variant of the econometric analysis reported in Table 4, and was estimated using a fixed effects model[8].

The results shown in the first column of Table 4 indicate a substantial and statistically significant externality effect. The implication of this estimate of "γ" for the gross return (marginal product) of transport capital is shown in Table 5: this rate of return increases from 2 per cent in 1974 to 5 per cent in 1993. While this is not a large number when compared to the overall return to private capital, 29 per cent, it is nevertheless impressive since it represents only the second-channel externality effect, over and above the direct return to transport infrastructure.

Table 6 provides another look at the importance of the infrastructure effect. This table allocates the overall total productivity residual (the 0.04 estimate in Table 1) into the four components shown in the rows of Table 6, with the result that the transport externality effect is found to account for almost a quarter of total productivity growth. When expressed on a value-added basis, as in the second column of Table 1, the transport externality is found to account for 0.25 percentage points per year, which is a very large effect in growth accounting terms.

The other regression estimates shown in Table 4 are statistically significant and of a conventional magnitude. The estimate of the scale effect implies mildly increasing returns to scale (3.8 per cent), and the markup parameter suggests an 8.2 per cent markup of price over marginal cost.

These results are but a subset of the results presented in Hulten, Bennathan and Srinivasan (2003), and an even smaller subset of the results underlying the complete paper. For example, the project also considered the role of electricity generating infrastructure, and found a large externality effect there, as well. The gross return to electricity was found to be 5 per cent in 1993, and the combined highway-electricity effect was 9 per cent. When translated into the decomposition framework of Table 6, the combined effect explains approximately half of the annual growth in total productivity. The magnitude of this effect may seem implausibly large (and it may well be), but it is fairly well established "on the ground" that inadequate road transport and electricity generating capacity have exacted a significant penalty on Indian economic growth.

Finally, this analysis has assumed that spillover effects occur within the boundaries of each state, with no allowance for spillovers to neighbouring states. When adjacent highway and electricity networks are included in the estimation, the implied spillover elasticities are much larger than in previous cases -- a combined 12.7 per cent -- although the levels of significance are marginal, due possibly to the presence of multicollinearity. These estimates should therefore be interpreted with care.

Table 4. **Parameter estimates of Basic Model[1/]**
Comparison of three studies (elasticities)

	India[2/]	**US[2]**	**Spain[3/]**
Infrastructure variable[4/]	0.044 (2.71)	-0.043 (0.58)	0.101 (2.08)
Time	0.004 (4.81)	0.014 (8.66)	0.024[5/]
Scale variable	0.038 (4.12)	-0.053 (1.24)	0.043 (0.66)
Markup variable	0.082 (7.31)	0.226 (4.14)	N/A
R-squared	0.809	0.794	0.978

Notes: [1/] t-statistics in parentheses; state fixed effects not shown.
[2/] Dependent variable is log total productivity.
[3/] Dependent variable is log total factor productivity.
[4/] Infrastructure variable is national and state roads and highways for India, and broader measures of public capital for US and Spain.
[5/] Arithmetic average over regions of Spain.

Table 5. **Comparison of gross marginal products**
All-India average for manufacturing industry
(Average gross return per rupee of capital)

	1974	**1993**
Highways	0.02	0.05
Private capital	0.29	0.29

Source: Hulten, Bennathan and Srinivasan (2003).

Table 6. **Decomposition of the growth rate of total productivity**
All-India average for manufacturing industry, 1973-92
(Average annual growth rates)

Core productivity	0.30%
Highways	0.09%
Subtotal:	0.09%
Scale effect	0.24%
Markup effect & residual error	-0.23%
Subtotal:	0.01%
Total productivity:	0.40%

Source: Hulten, Bennathan and Srinivasan (2003).

6. ESTIMATION OF THE INFRASTRUCTURE-PRODUCTIVITY LINK: THE UNITED STATES AND SPAIN

A similar but less elaborate analysis was carried out for the US manufacturing sector in Hulten and Schwab (2000). The key result appears in column (2) of Table 4, where the estimated elasticity associated with infrastructure, "γ", is not statistically different from zero. This is hardly surprising in view of Table 3, where the interregional differentials in the level of total productivity are effectively zero. Since total productivity is the dependent variable in the regressions reported in Table 4, there is little opportunity for infrastructure to matter in the cross-sectional dimension of the study.

The infrastructure variable used in the US study includes all public capital, and is therefore broader than the transport variable used in the Indian study. That said, the comparison of the two countries invites the surmise that the effect of infrastructure investment, and the extent of uncounted externalities, depends on the extent of pre-existing networks. Given the interconnected nature of networks discussed in the opening sections of this paper, it is plausible to expect that such investment has a different effect in built-up, infrastructure-rich environments than in situations where there are significant infrastructure deficits. A comparison of the Indian and US studies lends support to this hypothesis. The perceived inadequacies and needs underlying India's major effort to increase its highway network with the National Highway Development Project (the "Golden Quadrilateral") add verisimilitude.

The regression results for Spain do little to confirm or reject this last hypothesis, given the economy-wide focus of the analysis and the resulting non-comparability of the regression estimates. However, they confirm the general importance of the infrastructure productivity link at the aggregate level of economic activity in an economy that is in the later stages of development.

7. CONCLUDING REMARKS

The three studies reviewed in this paper shed light on the issues raised at the outset of the paper and have implications for infrastructure policy. The evidence suggests that investment in infrastructure networks does have an effect on the pattern of economic growth, and that the impact may depend on the stage of economic development. This evidence is by no means conclusive, but it does provide some support for the theoretical hypothesis that the effects of transportation network investments are highly non-linear: in built-up networks, as in the US, the primary effect of lowering transport costs is to relocate economic activity to lower-cost regions without a significant change in productivity or perhaps even system-wide output, whereas the addition of capacity to under-developed or capacity-constrained networks will tend to cause an improvement in productivity efficiency and lead to expansion in net output. The available evidence suggests that uncounted "second channel" externalities are important in the latter case and may be associated with systemic network under-investment. However, the three studies suggest that infrastructure investment is associated with convergence in regional growth in both built-up and infrastructure-poor networks, though to claim that the infrastructure causes convergence would be to over-interpret the evidence.

These conclusions are relevant for European transport policy, as the EU expands to incorporate lower wage regions in central and eastern Europe. Both the theory and evidence reviewed in this paper point to two important effects associated with improvements in the transportation systems which connect the new member states with existing EU members, and with improvements within the new members. On the one hand, a certain relocation of the existing manufacturing base toward the lower-wage regions can be expected. This is already occurring, according to Walter (2004), who writes:

> *"Still, the prospect of a larger Europe, encompassing tens of millions of new, low-income workers, has many western Europeans afraid that workers will migrate west in search of economic opportunities. In reality, the integration process is taking a different direction. Rather than workers moving west, it is investment capital that is moving east. This movement of capital, much more than the migration of people, is already shaping Europe's economic future."*

Substitute "north" for "west", "south" for "east" and "America" for "Europe" and this statement is reminiscent of the debate in the US over the growth of the Sun Belt relative to the Snow Belt. However, both theory and evidence also hold out the prospect of an expansion effect that benefits the EU as a whole. The relative strength of the two offsetting effects will be an important determinant in sorting out the net economic gains and losses by region. This is a matter for further study, where the focus should be on relative rates of productivity growth and levels among regions in comparison to wages and transport costs.

NOTES

1. "*SOC is usually defined as comprising those basic services without which primary, secondary and tertiary productive activities cannot function. In its wider sense, it includes all public services, from law and order through education, public health, to transportation, communications, power and water supply, as well as such agricultural overhead capital as irrigation and drainage systems. The hard core of the concept can probably be restricted to transportation and power* (Hirschman, 1958, p. 83)."

2. Meade distinguishes between unpaid factors of production and pure spillover externalities in the context of a production function, but does not deal with infrastructure capital *per se*. However, his model has a natural application to the production-side aspects of the infrastructure problem, since infrastructure can be expected to exhibit both of Meade's effects. The idea that infrastructure operates through different channels is certainly not uncommon in the transportation literature, with examples of different channel taxonomies appearing in recent papers presented at ECMT Round Tables by Berechman (2001) and Prud'homme (2001). The contribution of the current model is to show how to use these channels to estimate externalities in infrastructure-using industries.

3. This model can also be used to clarify the expansion and relocation effects that may be associated with an infrastructure investment, ($\Delta Q\ q/\Delta B$). Relocation occurs when production is induced by infrastructure investment to transfer from one place to another. The sum of these relocation gains and losses cancel in the aggregate. However, there may also be net expansion in the components of D_Q, labour and capital ($\Delta Q\ q/\Delta B) > 0$). These effects are related to Hirschman's "igniting" effects of infrastructure and are reflected in the debate over whether infrastructure "crowds out" or "crowds in" investment in private capital. A full analysis is complicated by the fact that infrastructure investment itself is determined endogenously in such a model (the source of the reverse causality noted above). It is sufficient for current purposes to note that all such effects refer to the $F(D_Q,T)$ segment of the production functions analysed in the following chapters, and that once this segment is removed from the analysis, the results obtained do not refer to this aspect of infrastructure investment.

4. Total factor productivity is expressed as a ratio of real value added to an index of the primary factors, labour and capital. It is used primarily for measuring productivity for the aggregate economy. Total productivity includes intermediate goods in both the numerator and denominator of the productivity ratio, and is used primarily at the industry level of detail. The survey of the productivity literature by Hulten (2001) provides a more complete description of this topic and, more generally, of the Solow productivity framework.

5. This procedure assumes that input prices are proportional to marginal products, the output elasticities of K, L and M are equal to the corresponding cost shares, and that the residual measures the shift in the production function. This pricing assumption is the characteristic limitation of the Solow residual method (Hulten, 2001). Its advantage is that it avoids the need to specify and estimate the "input" segment of the production function, $F(K_{i,t},L_{i,t},M_{i,t})$, and thus

avoids some of the econometric problems that have troubled the literature on productivity of transport infrastructure.

6. The two concepts of productivity are algebraically related: the growth rate of total factor productivity is equal to the growth of total productivity divided by the sum of capital's and labour's share of income (in effect dividing the latter by around 0.20). A two per cent growth rate for total factor productivity is quite respectable when compared to similar estimates by Young (1995) for some of the highly successful East Asian economies: the manufacturing sector of South Korea grew at an average annual rate of 3 per cent over the period 1966-90, while Taiwanese manufacturing grew at 1.7 per cent over this period.

7. The 1991 Hulten-Schwab study also found that the growth rates of productivity in the Sun Belt and Snow Belt regions are essentially the same. That study focused only on rates of growth and used real value added as the measure of real product, and therefore did not implement the full methodology of the 2000 study (on which the estimates reported in this paper are based).

8. The estimates of the transport infrastructure variable, B, were proxied by paved roads obtained from annual issues of the Ministry of Transport's "Basic Road Statistics of India". This measure consists of the lengths of the following categories of paved roads: national highways (arterial roads for interstate movement), state highways (arterial roads for inter-district movement, linking up with national highways and adjacent state highways) and district roads ("Other Public Works Roads"). Unfortunately, adequate data on road capacity (lanes) were not available, nor were data on capacity utilisation. State road lengths were normalised by state area.

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THE RATE OF RETURN TO TRANSPORTATION INFRASTRUCTURE

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SUMMARY

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This paper has been produced as part of a World Bank research project on Infrastructure and Growth: A Multi-Country Panel Study (RPO 680-89), sponsored by the Public Economics Division of the Development Research Group and by the Transport, Water and Urban Development Department. The findings, interpretations and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the World Bank, its Executive Directors or the countries they represent.

ABSTRACT

We estimate social rates of return to paved roads by looking at their effect on aggregate output using co-integration methods. Our results are driven by our finding that paved roads are highly complementary with physical and human capital, but have rapidly diminishing returns if increased in isolation. This produces an optimal mix of capital inputs and makes it very easy for a country to have too much, or too little, transportation infrastructure.

For policy purposes, we compare the rate of return to investing in transportation infrastructure with our estimated rate of return to capital as a whole. The strong complementarity we find between physical and human capital and lower prices of investment goods in developed countries, means that we calculate that rich countries have rates of return to capital just as high as those in the poorest countries, although the highest rates of return to capital are found in the class of middle-income countries.

We find that the rates of return to paved roads are on a par with, or lower than those on other forms of capital in most countries. However, in a limited number of countries we find evidence of very acute shortages of paved roads, and large excess returns to infrastructure investment. For paved roads, these countries with acute shortages are all middle-income countries. These excess returns are evidence of sub-optimal investment that, in the case of paved roads, appears to follow from a period of sustained economic growth, during which road building stocks have lagged behind investments in other types of capital. This effect is accentuated by the low costs of road construction we find in middle-income countries relative to poorer and richer countries.

While we find these positive effects using co-integration methods, using a more standard growth model gives similar results, with the returns to transportation infrastructure in general being the same or lower than the returns to capital as a whole, but with higher returns in a small number of middle-income countries.

Keywords: Aggregate production function – productivity - transport networks - electricity.

1. INTRODUCTION

Traditionally, the construction of infrastructure has had a large public sector component. For some kinds of infrastructure, the argument for public provision is that they represent non-rival public goods, as in the case of rural roads, or a natural monopoly, as in the case of electricity distribution systems and land-line telephone networks. Public sector provision, often in the absence of market pricing mechanisms, has led to projects being evaluated by the methods of cost-benefit analysis, as is the practice of the World Bank in its infrastructure projects. The average economic rate of return for World Bank projects evaluated over the period 1983-92 was 11 per cent for electricity projects and 29 per cent for road building (World Bank, 1994). Rates of that order might be described as adequate but not exceptional. Where they prevail, there is an argument for infrastructure provision but no indication of a serious shortage of the infrastructure.

There are, however, a number of well-known problems with rates of return based on cost-benefit analysis. Actual practice of such studies often departs far from the theoretically correct methodology (Little and Mirrlees, 1990). Even if performed correctly, however, microeconomic cost-benefit analysis is likely to miss important benefits of infrastructure if they occur in the form of externalities. Transportation infrastructure may have a profound impact on the extent of the market and the ability of producers to exploit economies of scale and specialisation. Widening the market then brings benefits in terms of increased competition and contestability in markets. Transportation infrastructure also allows greater dissemination of knowledge and technology. Models incorporating these ideas are now common in the "new economic geography" and there is increasing empirical evidence for these effects: see, for example, Krugman (1991, 1996), Borland and Yang (1992), Krugman and Venables (1995), Kelly (1997), Porter (1998), Gallup, Sachs and Mellinger (1999), Limao and Venables (1999).

Other infrastructure, such as electricity-generating capacity, should be important in the type of "big push" models of economic development proposed by Murphy, Shleifer and Vishny (1989). If the takeoff in developing countries relies on a co-ordinated bout of investment, the public provision of risky, large-scale infrastructure projects may provide a trigger for private sector investment and an escape from a poverty trap.

These arguments point to very large potential benefits from infrastructure which nevertheless elude identification and measurement by conventional cost-benefit analysis. Unless measured in a convincing way, however, we do not know whether the size of these effects provides a case for expanding infrastructure beyond current levels, or even perhaps for adopting a policy of infrastructure-led development. This remains true even under the current trend of providing infrastructure through the private sector, or at least having some form of pricing mechanism. While public or private pricing schemes can recover at least in part the costs of a project, prices can only capture private benefits. If infrastructure has large positive externalities, even under private provision we may wish to have a policy of subsidies to ensure provision on an adequate scale.

Our approach to finding the benefits of infrastructure is to estimate an aggregate production function for a panel of countries over the last 40 years, including as explanatory variables physical capital and human capital as well as our infrastructure variables, paved roads and electricity-generating capacity. We can then calculate the marginal product of infrastructure as its contribution to aggregate output. While this approach misses any benefits to infrastructure that do not appear in Gross Domestic Product (for example, time savings that lead to increased leisure), it should allow us to see if infrastructure has large output effects.

Using aggregate production functions to estimate the contribution of infrastructure has become quite common [for example, Andrews and Swanson (1995), Boarnet (1997), Carlino and Voith (1992), DeFrutos, Garcia Diez and Perez Amaral (1998), Garcia Mila, McGuire and Porter (1996), or Pinnoi (1994)]. The main problem with estimating this function is reverse causality. An increase in income leads to increased demand for infrastructure, and so a positive correlation between infrastructure stocks and output levels may be simply due to increased demand, and may not reflect any supply side productivity effect. To overcome this problem, we use the techniques developed in Canning (1999) based on a panel data, co-integration analysis, as outlined in 2.1 below. One appealing feature of our approach is that the estimates we get for the productivity of human and physical capital are close to those found in microeconomic studies of their private rates of return. This suggests that the procedure does indeed remove the bias introduced by reverse causality, which we suspect to be just as great for investment in physical and human capital as for infrastructure.

A major difference between the results in this paper and those in Canning (1999) is that here we base our approach not on a Cobb-Douglas production function but on a trans-log specification. The Cobb-Douglas production function imposes a declining marginal product of each type of capital as the capital-labour ratio rises. This virtually imposes a finding of a high rate of return to all capital goods in lower-income countries and a low rate of return in high-income countries, which is greatly at odds with observed private rates of return on physical and human capital and the pattern of capital flows between countries (Lucas, 1990). The trans-log specification, on the other hand, allows for flexibility in the pattern of rates of return across countries.

A further major reason for adopting this specification is to allow us to examine the pattern of complementarity and substitutability between inputs into the production function. We find that each type of infrastructure, on its own, has rapidly diminishing returns, which implies little support for a policy of purely infrastructure-led growth. However, infrastructure is found to be strongly complementary with both physical and human capital, giving it an important role in a process of balanced growth, with the possibility of acute infrastructure shortages if investment in other types of capital takes off but infrastructure investment lags behind. We explain these relationships in sections 2.2 and 2.3 below. Together with the cost of infrastructure (see chapter 3), these productivity relationships enter into the determination of the social rates of return to infrastructure (chapter 4).

For many countries, across the whole range of income levels, we estimate rates of return to infrastructure that are in line with, or actually lower than those found for physical capital as a whole. Given the extra costs caused by the distortions involved in raising taxes to fund public infrastructure projects, this gives little support for a general policy of increasing infrastructure stocks.

However, the rate of return to infrastructure is found to be highest in countries with infrastructure shortages, that is low levels of infrastructure relative to their levels of human and physical capital, and countries that have low costs of infrastructure construction. Among a subset of middle-income countries[1], we find evidence of an acute shortage of paved roads, coupled with very low costs of road building. This generates exceptionally high estimated rates of return to paved road building in these countries. We find similar evidence of high rates of return to electricity-generating capacity, but this time mainly in a subset of lower and lower middle-income countries.

It should be emphasized that for all higher-income countries, and for the vast majority of lower and middle-income countries, we find that the estimated rates of return to infrastructure are in line with or below those for capital as a whole. High rates of return to infrastructure are the exception rather than the rule, making the case for large-scale investment in infrastructure depend on an analysis of a country's characteristics rather than a blanket prescription or sector-specific rules or schemas.

2. THE EFFECT OF INFRASTRUCTURE ON AGGREGATE OUTPUT

2.1. Theory

We begin by examining the contribution of infrastructure to aggregate production. The approach used is to argue that there is a common world-wide production function given by:

$$y_{it} = a_i + b_t + f(k_{it}, h_{it}, x_{it}) + \varepsilon_{it} \quad (1)$$

where y is log output per worker, a is a country-specific level of total factor productivity and b is a time dummy capturing world-wide changes in total factor productivity, while k, h and x represent the log of per-worker inputs of physical capital, human capital and infrastructure capital, respectively. The term ε represents a random error.

By defining everything in per-worker terms, we rule out economies of scale at the aggregate level that may in fact be important for measuring the effect of infrastructure (Morrison and Schwartz, (1994). For simplicity, we include infrastructure as a normal factor of production, ignoring the possible effects of infrastructure on the long growth rate of technology and total factor productivity which are examined in Duggal, Saltzman and Klein (1999). We also assume random errors in output around our production function, rather than allowing for a stochastic frontier approach, as used by Mullen, Williams and Moonmaw (1996). The motivation for our straightforward approach to the production function is that it allows us to use techniques that control for reverse causality. Since it is reverse causality that is the major issue for the credibility of aggregate production functions, this seems worthwhile, even if it is at the cost of using a simple functional form.

We allow the production function, f, to take two different forms. Our first approach is to assume that the underlying production function is Cobb-Douglas, so that, in logs, we have:

$$f(k_{it}, h_{it}, x_{it}) = \ \ k_{it} + \ \ h_{it} + \gamma x_{it} \quad (2)$$

A second approach is to assume a more complex functional form given by:

$$f(k_{it}, h_{it}, x_{it}) = {}_1 k_{it} + {}_1 h + \gamma_1 x_{it} + {}_2 k_{it}^2 + {}_2 h_{it}^2 + \gamma_2 x_{it}^2 + \psi_{kh} k_{it} h_{it} + \psi_{kx} k_{it} x_{it} + \psi_{hx} h_{it} x_{it} \quad (3)$$

This variant of the trans-log production function allows for different degrees of substitutability and complementarity between the different types of capital. However, by using capital per worker variables we again impose constant returns to scale and are ruling out the interaction effects between each type of capital and labour that would appear in a standard trans-log specification. The larger the number of variables to be estimated, the lower will be the precision of our estimates, so that (3) represents a trade-off between a more general model and the parsimonious specification that one would like to have for estimation purposes.

A major problem in estimating the production function as set out above is the potential for reverse causation. If capital investments depend on income (for example, through a savings function s_i) we can write:

$$\Delta K_{it} = s_i(Y_{it}) - dK_{it} \quad (4)$$

where K is the capital stock, Y is the total GDP and d is the depreciation rate. This gives the steady state relationship:

$$K_{it} = \frac{s_i(Y_{it})}{d} \quad (5)$$

This implies a feedback from income to the capital stock, making it difficult to identify the results of regressions such as (2) or (3) as a production function relationship. There is also obvious potential for a feedback from income to a demand for infrastructure. If we follow a country through time, output will grow as capital accumulation proceeds, but capital accumulation will follow income, making it very difficult to establish the causal links in each direction. The positive feedback from higher income to greater capital accumulation in infrastructure might lead us to expect an over-estimation of the coefficients in a production function regression.

While this problem of reverse causality usually precludes simple, direct estimation of the production function, there are circumstances under which we can estimate a relationship such as (1) using simple methods. As shown in Canning (1999), each of the series that appear in (1) is non-stationary. We can, therefore, think of (1) as a long-run, co-integrating relationship. Note, however, that in each country (5) may also be a co-integrating relationship, holding even when we divide through by the number of workers. It follows that when we estimate the "production function" as a co-integrating relationship we will in practice estimate a mixture of a production function and an investment relationship[2].

However, in panel data the problem disappears, provided the long-run relationship (1) is homogeneous across countries while the investment relationship (5) differs across countries. In a panel, we can pool data across countries and, while (1) remains a co-integrating relationship, when we pool the data and estimate a homogeneous form of equation (5),

$$K_{it} = \frac{s(Y_{it})}{d} + u_{it} \quad (6)$$

we find that the error term, due to actual investment behaviour in each country being different from the world average relationship, is given by:

$$u_{it} = \frac{s_i(Y_{it}) - s(Y_{it})}{d} \quad (7)$$

It follows that the error term in each country is non-stationary and eventually becomes very large, because the error produced by using a pooled relationship, rather than the true country-specific relationship, depends on the income level, which is non-stationary. Even if we have a long-run relationship between income and investment for each country, pooling the data across countries allows us to identify the long-run production function relationship. This argument, of course, depends on the assumption that our model (1) is correct and holds across countries. It also depends on the relationship between income and investment being heterogeneous across countries but, as Chari, Kehoe and McGratten (1996) point out, differences in the security of property rights and tax policies are likely to produce very different investment rates, even for countries at the same level of income.

If we accept this argument, we can estimate equation (1) consistently by ordinary least squares (OLS). However, OLS has poor small-sample properties in this framework and its reported t-values are not appropriate, even asymptotically. Banerjee (1999) and Phillips and Moon (1999) each give an overview of recent techniques for estimating long-run relationships using panel data that overcome these problems. In this paper, we follow Kao and Chiang (1999), who argue that a dynamic OLS estimator that includes leads and lags of the first differences of the explanatory variables, has good small-sample properties and gives a method (based on the long-run variance-covariance matrix of the innovations and residuals) of estimating consistent t statistics.

The method used by Kao and Chiang (1999) is appropriate when we estimate a Cobb-Douglas production function relationship, as in equation (2), since all the variables appear to be I(1)[3], and we postulate that the production function is a co-integrating relationship[4]. However, estimation of the more complex production function (3) is somewhat more problematic. The difficulty is that if capital stock and infrastructure variables are I(1), the higher order squared and cross-product terms cannot be I(1). However, Chang, Park and Phillips (1999) show that estimating non-linear functions of I(1) variables does not affect the consistency properties of the standard OLS estimator, though it does affect the speed of convergence of the estimates[5]. In addition, while we report adjusted t-statistics in the same way as for the linear case, it is not clear that these are asymptotically consistent for the non-linear case. Therefore, while we have a consistent estimate of the parameters of equation (3), and regard these as our “best estimates” of the long-run relationship between inputs and aggregate output, we do not carry out hypothesis testing of the significance of the estimates.

2.2. Cobb-Douglas production function estimates

Data for output per worker and capital stock per worker are from the Penn World Tables 5.6 (see Summers and Heston, 1991). For output per worker, we use purchasing power parity GDP per worker (chain index). Our physical capital measure is constructed using a perpetual inventory method: assuming a capital-output ratio of three in the base year (usually 1950), we update each year’s capital stock by adding investment (from Penn World Tables 5.6) and subtracting 7 per cent depreciation from the previous year’s capital stock. Since our estimation only starts in 1960, this gives a reasonable period of time for our capital stock estimates to lose their dependence on the arbitrary initial condition. The results of this procedure for producing capital stock estimates are remarkably robust to variations in the initial choice of capital-output ratio and the depreciation rate. Human capital per worker is measured by the average years of schooling of the workforce (from Barro and Lee, 1993).

The two infrastructure stock variables used are kilowatts of electricity-generating capacity and the length of paved roads (including urban paved roads), both taken from the processed data in Canning (1998). These physical measures do not reflect quality differences in infrastructure across countries and over time. These differences may occur at the time of construction; roads differ enormously in terms of their capacity (number and width of lanes) and durability. Electricity-generating capacity comes in many forms (e.g. oil-fired, coal-fired, nuclear, hydroelectric) with different construction costs and running costs. In addition, the effectiveness of infrastructure may depend crucially on its quality, both initially and in terms of maintenance (see Hulten, 1997). In particular, there is evidence of wide variation in the quality of roads in different countries due to different climatic conditions, as well as different levels of maintenance and repair. The lack of comprehensive quality data means we use our simple quantity measures in our estimation; however, it is worth noting that the fixed effect specification we use to capture cross-country differences in total factor productivity tends to net out any cross-country infrastructure quality differences that are constant over time.

In Table 1, we report the results of our estimates using the Cobb-Douglas production function. All regressions in this paper include country-specific intercepts and world-wide year dummies (which are not reported). The regressions also include the value, current as well as one lead and one lag, of the growth rate of each capital input per worker (the first differences of the capital stock variables). The short-term effects of these growth rates are estimated separately for each country, to allow for country specific business cycle multiplier/accelerator effects. Estimating the short-run coefficients separately for each country uses up a large number of degrees of freedom, but may improve the small sample properties of the estimators considerably.

The first column reports results for a standard Cobb-Douglas production function specification including only capital per worker and human capital per worker. Both coefficients are statistically significant; they can be interpreted as the elasticity of output with respect to each input. The coefficients found are consistent with what emerged from the calibration of a Cobb-Douglas model using microeconomic studies on private rates of return to physical and human capital (Klenow and Rodriguez-Clare, 1997). We take that as indicating that any externalities to physical and human capital are small on average. On the other hand, our results contrast with the finding in some macroeconomic studies of much higher elasticities, particularly for human capital (e.g. Mankiw, Romer and Weil, 1992). However, these earlier studies may be contaminated by a feedback from income to savings (or savings rates) which biases their estimates upwards; the similarity between our macroeconomic estimates and those based on micro-evidence on private returns suggests that our econometric methods have overcome the feedback problem.

When we add electricity-generating capacity (column 2 of Table 1) we find a significant, positive coefficient. Since electricity-generating capacity is already included in total capital, we have a double-counting problem in interpreting regression 2: an increase in electricity-generating capacity will have two effects, increasing the capital stock as well as the stock of generating capacity. The coefficient on log electricity-generating capacity can be thought of as the effect of increasing generating capacity while holding capital stock constant; that is, it is the effect of diverting resources from other types of capital to investment in generating capacity. As shown in Canning (1999), a positive coefficient implies a gain in output from shifting resources to generating capacity, provided that the reallocation is carried out at world average prices. In general, therefore, a positive coefficient on generating capacity implies a higher rate of return to generating capacity than that for other types of physical capital, though this may not hold in countries where the cost of generating capacity is relatively high compared with that of other types of capital.

We find a similar result for paved roads (column 3 of Table 1), suggesting that paved roads have, in general, higher rates of return than other types of capital. These positive results retain their statistical significance when we add both types of infrastructure together (column 4 of Table 1).

The result that paved roads and electricity-generating capacity have higher returns than found for capital in general is at odds with the results reported in Canning (1999), where no evidence of significant excess returns was found. One difference between the two studies is that here we use paved roads instead of transport routes (which include railway line length). In addition, we drop Singapore and Hong Kong from the roads sample. These city states have very high incomes, despite having very low road lengths, and including them in the data set tends to produce a much lower estimate for the effects of roads, since they suggest that roads are not required to generate a high income level. We remove them from our estimation when we include paved roads as an explanatory variable, on the grounds that, as city states, their unusual geography, in particular their high population densities, make them unrepresentative of the development process.

However, the main difference between the two studies is that in this paper, when estimating the effect of paved roads and electricity-generating capacity on output, we do not include telephones as an extra explanatory variable. The difficulty with including telephones in the regressions is that it has a very large estimated coefficient, and tends to swamp the effect of the other variables. The large coefficient would still not justify exclusion if it were a true reflection of the productivity of telephones, but the estimated productivity effects are implausibly large (giving rates of return of over 10 000 per cent per year) and may well reflect the fact that the number of telephones is demand-determined to a greater extent than the other types of infrastructure we are considering[6]. To avoid this difficulty, we exclude telephones from our inputs in this study.

We could use the result in Table 1 to compute the marginal product, and rate of return, to infrastructure. However, the Cobb-Douglas production function imposes the assumption of a constant elasticity of output with respect to each type of input and ignores the possibility that the elasticity may vary across countries. In Table 2, we report the result of splitting the sample into two equal sub -samples, based on each country's income per worker in 1975[7]. We find that the coefficients on the infrastructure terms in poorer countries are very small, and statistically insignificant, but that they remain large and significant in richer countries. This implies that infrastructure in the poorer countries appears to have the same effectiveness in raising output as other types of physical capital, while having a greater effectiveness than other types of capital in richer countries.

2.3. Trans-log production function estimates

We can investigate the production function relationship in greater detail by adopting the more complex trans-log style of production function set out in equation (3). The results of these trans-log regressions are shown in Table 3. In the first column, we report results for capital and human capital on their own. In column 2, we add electricity-generating capacity, while in column 3 we add paved roads. In all three regressions we add short-run adjustment terms, including current, lagged and a lead of each capital stocks growth rate, again estimated separately for each country[8].

In the trans-log specification, the important points are the size and sign of the higher power terms. In our base specification (column 1), the squared term in capital is positive. The elasticity of output with respect to capital is therefore rising, giving capital a greater effectiveness in countries that already have a great deal of it. On the other hand, the squared term for human capital is negative, implying rapidly diminishing returns to investment in human capital. The interaction effect between human capital and physical capital in column 1 is positive, suggesting that the two are complements, which is consistent with the complementarity between capital and skilled labour found by Berndt and Christensen (1974).

In column 2 of Table 3 we add electricity-generating capacity, EGC, to the specification. The squared term in EGC is negative, indicating rapidly diminishing returns to investment in electricity taken in isolation. However, the interactive terms between electricity and physical capital and electricity and human capital, are both positive. This implies that electricity-generating capacity is complementary to physical and human capital, with its effectiveness increasing in their presence. Since we measure the various capital stocks each per worker, the effectiveness of EGC is found to be rising with capital deepening.

We find the same pattern for paved roads, with the squared term in roads being negative, but both interaction terms, between roads and the other forms of capital, being positive. These results, for both kinds of infrastructure, indicate that infrastructure investments are not sufficient by themselves to induce large changes in output. However, infrastructure can be a productive investment in economies with high levels of physical and human capital, and infrastructure itself, in turn, raises the productivity of investment in those other types of capital.

A clearer picture emerges from calculating the elasticity of output with respect to each capital input. Since the elasticities vary with the amount of each input, we begin by doing this for three fictitious countries, one with median inputs of physical capital and human capital and infrastructure per worker, one with each input at the lower quartile and one with each input at the upper quartile. The results, using input measures taken in 1985, are reported in Table 4. Notice that, in general, the actual country with a median amount of physical capital in that year will not be the one with median levels of human capital or infrastructure. The table therefore does not represent elasticities in actual countries but in the hypothetical ones that we construct to represent an average, i.e. a moderately poor and a moderately rich country.

For physical capital we find a consistent pattern of rising elasticities. Based on the results in column 1 of Table 3, we find that the elasticity of output with respect to capital would be 0.5 for a country at the first quartile in terms of its input levels of human and physical capital, rising to 0.65 in a country that was at the third quartile. On the other hand, the elasticity of output with respect to human capital is fairly steady as we change input levels. Turning to the regressions that include our infrastructure variables, we find that the elasticity of output with respect to infrastructure seems to be higher in middle-income countries that have input levels per capita around the world median, than in countries with higher or lower input levels. This reflects the fact that infrastructure in middle income countries benefits from the presence of complementary inputs in the form of physical and human capital, but is not yet extensive enough to have entered the phase of rapidly diminishing returns (reflected in the negative coefficients on infrastructure squared in Table 3).

In Figures 1 through 4 we plot the elasticities of output with respect to each input, estimated using each country's actual input mix in 1985, and plot the result against its income per capita (at purchasing power parity, from the Penn World Tables) in that year. Figures 1 and 2 are based on regression 1 in Table 3. Figure 1, for the elasticity of output with respect to physical capital, tells the same story as Table 4, with poorer countries having low elasticities while richer countries (with higher levels of input per worker) have high elasticities. For education, shown in Figure 2, there is some evidence of a U-shaped relationship, with elasticities higher in poorer and richer countries and lower in middle-income countries. However, the non-linearity in the relationship is not statistically significant.

Adding together the elasticities of output with respect to these two types of capital produces a figure that rises with income, and is close to 0.9 in the most developed countries. This implies that, while we have diminishing returns to capital as a whole over the entire income range, this diminishing return may occur very slowly in developed countries. If this is so, then the developed world may have self sustaining “endogenous growth” while developing countries live in a neoclassical paradigm.

Figures 3 and 4 (based on regressions 2 and 3 of Table 3, respectively) plot the estimated elasticity of output with respect to our two kinds of infrastructure for each country against that country's income per capita in 1985. In both cases we see an inverted U shape, with elasticities being higher in middle-income countries and somewhat lower in the poor and rich extremes of the income distribution. It is notable that in Figures 3 and 4 we find a relatively large number of countries that have negative elasticities of output with respect to paved roads or electricity-generating capacity. This does not imply that adding to the stock of these types of infrastructure reduces output; as before, the elasticities refer to the effect of adding to the stock of infrastructure while holding total capital constant. That is, we have the effect of diverting spending away from other physical capital and into the relevant infrastructure; the negative coefficient therefore means that infrastructure spending is less productive than spending on other types of capital (at world prices).

This heterogeneity in the response of output to increases in infrastructure, holding the total capital stock constant, agrees with the results found in Canning and Pedroni (1999), who use a different technique to estimate the sign of this elasticity on a country-by-country basis. It is notable that in both Figures 3 and 4 the heterogeneity of the estimated elasticities is higher for the lower-income countries than for the higher-income countries. Variations in the elasticity are caused by differences in the relative proportions of physical capital, human capital and infrastructure capital across countries, so that the greater heterogeneity implies that the mix of capital varies more among the less-developed countries. We see this as a characteristic of countries in the process of development, that they are in general further from the optimal mix of capital than the richer countries (or just the mix characteristic of developed countries), though the way in which the mix varies differs between countries.

The production function estimates allow us to calculate the impact of infrastructure investment on output, and indeed the marginal product of infrastructure. To calculate rates of return, however, we need data on construction costs.

3. THE COST OF INFRASTRUCTURE

3.1. Measuring the cost of infrastructure

Cost data on infrastructure investment are relatively scarce. Our two main sources are electricity-generating capacity costs from the World Bank study by Moore and Smith (1990) and the cost of constructing transportation routes, from the United Nations International Comparison Project (ICP). In addition, we compared the cost of constructing transport routes from the ICP with data from World Bank projects.

There are several difficulties involved in measuring the cost of constructing infrastructure to go alongside our physical measures of infrastructure stocks. One fundamental problem with comparing data across countries is differences in the type and quality of the infrastructure being built. For electricity-generating capacity, the figures give averages over many different types of capacity that may reflect different combinations of capital and running costs.

In theory, the ICP data for the cost of construction of transport routes are for a common basket of goods and so should adjust for quality differences. However, in practice, the adjustment may not be complete. Our World Bank project data are superior in that they measure road-building costs (rather than transport routes in general), but they are not adjusted for road quality. For these projects we count kilometres of road, not lane-kilometres, nor can we distinguish between roads according to the strength of the surface or the width of the lane. A kilometre added in a high-middle-income country is likely to be of higher quality than a kilometre in a low-income country, which may introduce a systematic bias into the data. In addition, the coverage of the ICP data set is much broader than that from World Bank projects and in what follows we rely exclusively on the ICP data, though it is worth noting that the ICP and World Bank data, when we have data on both, are in broad agreement.

There is the additional problem for paved roads that our cost figures refer exclusively to construction, without any allowance for the cost of the land. Land costs are one reason why Hong Kong and Singapore are such outliers in terms of their road stocks: not only is the productivity of transport systems likely to be different in such a densely populated environment, but these city states also have notoriously high land costs.

As with cost-benefit analysis, the cost of infrastructure construction we use should be the real resource cost. However, our data are actual costs, including any price distortions caused by the tax system or import controls. If we were to take the view that most of the cross-country differences in infrastructure projects are due to such distortions, it would be appropriate to take a common world cost for each type of infrastructure as its real resource cost. On that view, the elasticity results in Table 4, and in Figures 1 to 4, would indicate whether there is an excess return to paved roads over and above that found for other forms of capital. However, while this type of assumption may be appropriate for internationally traded goods, infrastructure projects often involve large-scale labour inputs in the country concerned. This makes the real resource cost depend on the productivity of labour in other employment, which can vary dramatically across countries. In what follows we use the actual costs as indicative of the real resource cost.

A problem specific to our data on the cost of electricity-generating capacity is that these are measured in US dollars, while our marginal productivities are measured in constant international (ICP) dollars. The value of the international dollar is normalized so that the GDP of the United States is the same in either unit. However, in other countries the two are not equivalent. In poorer countries, where prices (measured at the nominal exchange rate) tend to be lower than in the US, the real purchasing power of a US dollar, and so the real resource costs of spending on infrastructure, is high. Before carrying out our rate-of-return calculations, we therefore convert our costs from US dollars to international dollars by dividing through by the country's 1985 price level (its purchasing power parity exchange rate divided by its nominal exchange rate), taken from Summers and Heston (1991).

3.2. Exploring the data

Table 5 reports our data on costs by country. We take 1985 as the base year for comparisons because this gives us a fairly wide range of data in nearby years that can be deflated to 1985 values. Column (1) of Table 5 gives data on the cost of construction of transport routes from the 1985 International Comparison Project. These price indices represent the nominal price of a basket of transport routes deflated by the country's purchasing power parity price level. The indices have been converted into a dollar cost per kilometre of paved road by taking a figure of $627 580 for the USA. While transport routes are a more general category of infrastructure than paved roads, roads make up a large component of transport routes and these figures do reflect the price of a common basket of routes, which tends to lessen the problem of measuring costs for different infrastructure qualities. For a small number of countries, we also have data on the cost of road construction from World Bank projects. These data are roughly in line with those from the International Comparison Project, but more vulnerable to differences in road quality between countries.

Summers and Heston (1991) show that there is a tendency for capital goods to be relatively more expensive in developing countries than in developed countries. When we plot the data on the cost of transport routes in Figure 5, we see some evidence of a U-shaped relationship, with costs being high in the poorer developing and in the developed countries, but substantially lower in middle-income countries. Regressing log cost on log income per capita and the square of log income per capita gives the result:

$$\text{Log cost per km} = \underset{(4.66)}{25.9} \; - \underset{(2.59)}{3.517 \log y} \; + \underset{(2.76)}{0.226\ (\log y)^2} \qquad (8)$$

$N = 53$, $R^2 = 0.26$

This gives a minimum cost at an annual income level of around $2 300 (in 1985 international dollars) per capita, which lies in the bottom half of the income range spanned by the 40 countries classified as lower-middle income in 1985 by the World Bank. The World Bank data on costs of paved road construction give a similar picture of U-shaped costs. In our calculations of rates of return, we use the larger data set, based on the cost data we have calibrated from the ICP costs of route construction.

One reason for this U-shaped cost structure would be that middle-income countries have lower labour costs than developed countries, but also more of the skills and industry required to produce construction materials and equipment than the majority of the low-income countries. Where road construction and paving depend on importing equipment and even raw materials, costs in the poorer countries can rise to levels found in industrialised countries.

Our cost data for electricity-generating capacity come from Moore and Smith (1990). Cost, in 1989 US dollars, per kilowatt of electricity-generating capacity and the corresponding extension of transmission and distribution, is shown in column (2) of Table 5. The figures are deflated to 1985 values using the GDP deflator and then converted to international dollars using the country's purchasing power parity price level, before being employed in our rate-of-return calculations. These figures are reported in column (3) of Table 5.

Looking at the costs in US dollars, there is clearly an outlier: Senegal has construction costs in excess of US$13 000 per kilowatt, which is substantially higher than for any other country. In fact, the next two most expensive countries, also in Africa, are Niger and Mozambique, with costs that are about half those found in Senegal. However, when we look at the costs in international dollars we find high real costs of generating capacity in many developing countries due to their low price levels relative to their exchange rate. The relative consistency of prices at nominal exchange rates suggests that developing countries are not, in general, able to exploit their low wage costs to achieve low costs of installing electricity-generating capacity.

Once again, there is evidence that the cost of installing electricity-generating capacity falls with the level of income. A regression of log cost per kilowatt of capacity on log income per capita (both in international dollars) gives the result:

$$\text{Log cost per kW.} = \underset{(16.4)}{11.18} - \underset{(3.58)}{0.287} \log y \qquad (9)$$

N=63 R^2 =0.061
t statistics in parentheses

For both electricity-generating capacity and paved roads the difference in construction costs between the cheapest and most expensive countries is a factor of almost 10, while cost differences in the order of a factor of 3 are not unusual. Cost differentials are therefore likely to play an important role in determining rates of return to infrastructure investment.

4. THE RATE OF RETURN TO INFRASTRUCTURE

4.1. Rate-of-return estimates and infrastructure policy

The rationale for our approach is that there may be externalities to infrastructure projects that are not caught in micro-economic cost-benefit studies. The inclusion of these externalities potentially allows us to capture the total social rate of return to infrastructure. There are, however, a number of caveats that must be borne in mind when looking at our results.

Firstly, our approach is to look at the impact of infrastructure on aggregate output as measured by GDP. This measure of aggregate output has the potential to capture some of the externalities that microeconomic cost-benefit analysis may miss, yet it has conceptual drawbacks of its own. For example, cost-benefit analysis can estimate the travel time saved by a road project and calculate the value of this time. An analysis using aggregate output will only pick up the time saved if it is devoted to productive uses; time saved that is spent in leisure activities will not be accounted for. In addition, as Haughwout (1998) points out, an analysis which relies on aggregate output may neglect relative price effects of infrastructure construction that can have a significant welfare impact.

A second problem is that our estimate of the effect of infrastructure on output is its long-run steady state effect. In calculating rates of return, we assume that this long-run effect occurs immediately and lasts for ever, and we depreciate infrastructure stocks at 7 per cent a year to allow for the cost of maintaining the infrastructure in the long run. This creates a difficulty because, when calculating rates of return, the discounting of future flows means that returns in the early years tend to dominate the calculations. It follows that, if it takes several years for infrastructure to reach its full potential, we may be overestimating its rate of return. However, a similar consideration applies to our estimates of the rate of return to private capital, so that when we compare infrastructure rates of return to those found on general capital, we might expect both to be overestimated in similar proportions. While both are probably overestimates, the problem may be worse for infrastructure where there is considerable evidence that construction may sometimes lead demand for infrastructure services, either due to its “lumpy” nature, or to over-optimistic demand projections (World Bank, 1994).

Our macroeconomic estimates of the rate of return to infrastructure also ignore any "crowding in" effects that it may have on other types of capital. While an increase in infrastructure raises the return to other forms of capital, and can lead to an increase in investment, with consequent effects on output and economic growth, these induced changes in investment may have only a very small impact on welfare. As Baldwin (1992) points out, if the marginal product of capital is close to the rate of discount, the marginal benefit and marginal cost of extra investment are roughly the same, implying little or no gain in welfare from the extra investment[9].

However, there are two cases in which this negative result does not hold. If, instead of a small increase in infrastructure, we are analysing a large change, then marginal analysis is no longer appropriate, since the new infrastructure may raise the marginal product of capital substantially above the discount rate. Alternatively, if we have reason to believe that the marginal product of capital already exceeds the discount rate, owing, for example, to a tax wedge, induced increases in investment can have large welfare effects. In our calculation, we ignore any "crowding in" effect, implicitly assuming that we are analysing relatively small infrastructure projects and that the existing allocation of resources to other forms of capital is reasonably efficient (though we do in fact present evidence that in some countries the rate of return to capital is considerably in excess of any reasonable discount rate).

There are also several caveats about the use of our rate-of-return estimates for policy purposes. First of all, for evidence of externalities to infrastructure to emerge, we have to subtract from our figures the private returns to infrastructure projects. Only if all the returns to infrastructure captured in cost-benefit analysis are private benefits (and none are externalities) would we arrive at a measure of externalities by subtracting those benefits that are measured in aggregate GDP (private benefits not measured in GDP should be added to aggregate productivity estimates to find social rates of return).

However, it is not clear that we ought to focus on externalities: when the government is the main supplier of infrastructure there is no presumption that it will be setting infrastructure at the optimal level in terms of private benefits. There may be capital misallocation in infrastructure even without externalities. Instead, we shall focus on the rate of return to infrastructure relative to that on other forms of capital. Where this ratio exceeds one, there is a case for arguing that there should be a reallocation of resources to infrastructure.

Note that this is somewhat different from the normal cost-benefit approach, which looks at the rate of return to a project in relation to a threshold level that is set by the cost of funds. We find that, in many countries, the rate of return to capital as a whole appears to be considerably higher than the commonly used threshold levels (or test discount rates). In this case there is an argument for encouraging investment in general and, in particular, for removing any distortions that are keeping investment rates low. However, if the rate of return to infrastructure, while high, is lower than that for other capital, the optimal policy is to encourage investment in capital other than infrastructure. Infrastructure investment in those circumstances is very much a second-best policy, and would depend on an argument that investments in other types of capital are not feasible for some reason.

4.2. Calculating rates of return

In order to estimate the marginal product of infrastructure, we must take account of the fact that it appears twice in our production function, once on its own in the form of X, but also as a part of aggregate capital, K. Let Z be non-infrastructure capital, then we can write:

$$K_{it} = \frac{Z_{it} p_z + X_{it} p_x}{p_k} \qquad (10)$$

The aggregate capital stock is the value of total capital (we sum the volume of each type of capital times its price) divided by the price of capital. To construct these volume measures we use world prices of investment goods; all prices are expressed relative to output, which is taken to be the numeraire. For simplicity, we use the approximation $p_z = p_k$, taking the price of non-infrastructure capital as equal to the price of capital as a whole. Given that infrastructure capital is a relatively small component of the total capital stock (certainly less than 20 per cent of the total in each case), this approximation seems reasonable.

Using equation (3), it is easy to derive the country- and time-specific elasticities:

$$e_k = {}_1 + 2\ {}_2 k_{it} + \psi_{kh} h_{it} + \psi_{kx} x_{it} \qquad (11)$$

$$e_x = \gamma_1 + 2\gamma_2 k_{it} + \psi_{kx} k_{it} + \psi_{hx} h_{it}\,. \qquad (12)$$

The elasticity of output with respect to infrastructure that we estimate is actually the elasticity found when increasing infrastructure but holding aggregate capital (including infrastructure) constant. It can therefore be interpreted as the result of diverting a unit of physical capital from other purposes to infrastructure. From these elasticities, and the definition (10), we can calculate the marginal products of a unit of physical and infrastructure capital - MPK and MPX, respectively – as:

$$MPK_{it} = e_k \frac{Y_{it}}{K_{it}}, \quad MPX_{it} = MPK_{it} \frac{p_x}{p_k} + e_x \frac{Y_{it}}{X_{it}} \qquad (13)$$

Note that the marginal product of infrastructure consists of two terms, the first representing the effect of infrastructure on aggregate capital and a second representing the distinctive infrastructure effect.

These equations for marginal productivity highlight an important feature of using aggregate data. To find the marginal product per dollar spent on an input, the estimated elasticity must be multiplied by the ratio of output to the stock of the relevant capital, each measured in dollar terms. For capital as a whole this ratio is quite small (typically less than one-third), but for sub-categories of capital this ratio may be large. Multiplying the estimated elasticities by a large number also multiplies up any errors in estimation.

It follows that this method is unlikely to be good for determining the marginal product of small components of the capital stock. Paved roads and electricity-generating capacity, valued at replacement cost, each make up around 20 per cent of the capital stock on average, implying that they should have observable effects on aggregate output. Not so, however, telephone main lines which make up less than 2 per cent of the capital stock by value. For reasons stated in 2.2 above, we omitted telephone main lines from our analysis. A further reason for that decision is their low share in the total capital stock. We would, therefore, expect to see them have only a small effect on aggregate output; and to find their marginal product, we would have to multiply a badly estimated elasticity by a huge number (the ratio of output to the value of the telephone stock).

The marginal products measure the output effect of an extra unit of capital. In the case of infrastructure this is the marginal product of an extra kilowatt of electricity-generating capacity or an extra kilometre of paved road. To find the rates of return, we need the information on the cost of a unit of capital, its marginal product and its rate of depreciation. We take the price of investment goods from the Penn World Tables (Mark 6.5) as the price of capital goods and measure both marginal products and costs in a common unit, 1985 international dollars.

Formally, we can find the rates of return to infrastructure type x in country i, given by r_{ix}, by solving for the internal rate of return in the formula:

$$\sum_{t=1}^{\infty} \frac{MPX_{it} - dp_{ix,t}}{(1+r_{ix})^{t}} = p_{ix,0} \tag{14}$$

The left-hand side of this equation is the discounted flow of benefits from a unit of infrastructure, minus depreciation (or maintenance costs) which occur at a rate d per unit of infrastructure per year. The right-hand side represents the cost of the unit of infrastructure. Assuming that the marginal product of infrastructure and the price at which depreciation is replaced (or maintenance costs), $p_{ix,t,}$ are constant over time and, taking a depreciation rate of 7 per cent per annum[10], equation (14) simplifies to:

$$r_{ix} = \frac{MPX_{i}}{p_{ix}} - 0.07\,. \tag{15}$$

An equivalent simple formula holds for the rate of return to capital as a whole.

In the following two chapters we use these equations to estimate the rate of return to electricity-generating capacity and paved roads. It is, nevertheless, worth noting that if the relative price of capital and infrastructure are the same in every country, equation (15) simplifies to:

$$r_{ix} = r_{ik} + e_{x}\frac{Y_{it}}{p_{x}X_{it}} \tag{16}$$

In this case, the infrastructure has an excess return over and above that found for capital in general, if and only if it has a positive elasticity, as given by equation (12). As pointed out by Prittchett (1996), however, and as is evident in our data, the relative prices vary enormously across countries. We should therefore use equation (15), based on our two-stage procedure of estimating the marginal product of a physical unit of infrastructure and then relating this to its price. We could still use equation (16) and Figures 3 and 4 to indicate the pattern of the sign of excess social returns to infrastructure, so long as we were to believe that our cost data reflect rents and distortions, while the real resource costs of infrastructure relative to other forms of capital are roughly constant across the world. However, in what follows we shall concentrate on the rates of return using actual cost data for the construction of infrastructure. Estimates based on this approach are reported in Tables 6 and 7. All data refer to 1985.

4.3. Estimates of the rate of return to electricity-generating capacity

Table 6 reports the estimated rate of return to electricity-generating capacity, physical capital in general and the ratio between the two rates of return in all countries for which we have the necessary data. The elasticity estimates that underlie these calculations – that is, the elasticities of both electricity-generating capacity and capital in general – come from regression (2) in Table 3. There is a wide range of rate-of-return estimates, from well in excess of 100 per cent a year (in 1985, for Bangladesh, Kenya, Bolivia and China) to quite low figures (Brazil and Zimbabwe) and even a negative rate of return for Mozambique. Note that a small negative rate of return does not imply that infrastructure does not benefit output, only that its benefits do not cover the costs of depreciation or maintenance.

One might simply use these rates of return to indicate whether or not investment in electricity-generating capacity was a good use of funds. However, the real issue being the allocation of investment between projects, it is more relevant to compare the estimated rate of return to electricity-generating capacity with that of physical capital in general. The rate of return to capital [again based on regression (2) of Table 3] is reported in column (2) of Table 6, while column (3) gives the ratio of the rate of return on electricity-generating capacity to the rate of return on capital in general. This ratio takes on a wide range of values. In Figure 7, we plot the estimated ratio of rates of return against log income (in purchasing power parity terms) per capita in 1985. There is a clear downward trend in the relationship; the poorer countries, on average, have much higher rates of return for electricity-generating capacity than for other capital, while the middle-income countries show rates of return to electricity-generating capacity that are roughly the same as for capital in general. Unfortunately, our cost data are all for developing countries, so that we cannot see how the relationship changes as one moves to high-income levels.

Just as the average rate of return is higher in the poorer countries than in middle-income countries, the variation in the rate of return to electricity-generating capacity, as seen in Figure 7, is also greater in the poorer countries. High rates of return in the poorer countries are based on low stocks of electricity-generating capacity relative to the stocks of complementary inputs, that is, physical and human capital. A line is drawn across Figure 7 at a ratio of one; at this point, the returns to infrastructure are equal to those on capital in general. As we can see, it appears to be quite possible for a developing country to have an excessive investment in electricity-generating capacity, relative to its stocks of other physical capital and of human capital, driving its rate of return down below that on other forms of capital.

On average, therefore, we find a tendency for returns to electricity-generating capacity in the poorer developing countries to exceed the returns to other forms of capital. The *heterogeneity* of the rates of return in the poorer countries suggests independently that these countries tend to be further from an optimal mix of investment than middle- or higher-income countries, perhaps reflecting greater market failure, possibly externalities or state failure, and thus prime issues for country analysis.

4.4. Estimates of the rate of return to paved roads

Our cost data for paved roads cover a wider incomes span of countries, especially high-income countries, than those for electricity-generating capacity. The first column of Table 7 reports the rates of return to paved roads, based on regression 3 of Table 3. For some developing countries (in 1985, notably South Korea, Colombia, Bolivia and the Philippines) we find exceptionally high rates of return to paved roads. In some others (such as Tunisia and Botswana, again in 1985), rates of return are low. Low rates of return are also found in most developed countries, with negative returns being present in Austria and Australia.

Rates of return to capital (this time based on the productivity effects from the same regression 3 of Table 3) are reported in column 2 of Table 7. These estimated rates of return show much less variation than those for paved roads, partly, no doubt, because of the much larger value of the total capital stock, which makes for greater accuracy in the macroeconomic estimates of the marginal product.

In Figure 7, we plot the estimated ratio of the rate of return to paved roads to that found on capital in general in each country, against the country's log income per capita. The first point to note is that in most countries, notably in all the developed and high-income countries, but also in the poorer developing countries, the ratio is less than one. In these countries, the rate of return to paved roads is lower than that on capital in general. However, in a group of middle-income countries, the ratio exceeds one by a long way. These countries get the benefit of a high marginal product of roads coupled with a low cost of road building. However, even among middle-income countries, the rates of return to roads are sometimes lower than the rates of return to capital as a whole.

Once again, we find a great deal of heterogeneity across countries in rates of return to paved roads relative to other forms of capital, and once again the heterogeneity is greatest among the low to upper middle-income countries. However, if we are looking for high rates of return to investment in paved roads, it is in that very class of middle-income countries that we have to look.

4.5. The rate of return to capital

The rate of return to capital as a whole has been used extensively in the last two sections as a benchmark by which to judge the attractiveness of infrastructure investment. We now take the rate of return to capital on its own, basing our estimates on regression 1 (with physical and human capital as the only independent variables) in Table 3. Plotting this in Figure 9 against log income per capita for a cross-section of countries in 1985, we obtain a graph with an inverted U shape. The highest rate of return is found in middle-income countries; and the maximum on the curve corresponds to an income per capita of $3 600 (international dollars) which is in the top half of the 1985 lower middle-income class. This result contrasts starkly with the very steeply downward sloping graph for the rate of return to capital that we obtain from a Cobb-Douglas specification.

The relationship we find is consistent with the observation that actual private returns to capital are quite low in the poorer developing countries and that capital does not flow from the rich to the poor (see Lucas, 1990) but rather to middle-income countries. In developed countries, diminishing returns to capital set in quite slowly because they can keep their marginal productivity of capital up by having large amounts of human capital. We nevertheless find some evidence that returns to capital are higher in middle-income developing than in the developed (industrialised) countries, a finding that makes the very high relative returns to paved roads even more interesting.

5. CONCLUSION

The use of an aggregate production function allows us to calculate rates of return to infrastructure that should capture any externalities that escape microeconomic cost-benefit studies. The model could be improved upon, in particular by estimating a more general production function, including, for example, the effects of industrial structure and geography on the productivity of infrastructure.

Though our results depend on a number of simplifying assumptions, they appear plausible. They suggest that, as a rule, infrastructure shortages – signalled by high social rates of return to electricity-generating capacity or paved roads – relative to other capital, are symptomatic of limited groups of countries identified by the income per capita class that they belong to, essentially the lower-middle and upper-middle income classes of developing countries. To the extent that such high rates of return are not detected by a microeconomic cost-benefit analysis, they point to macroeconomic externalities associated with infrastructure.

NOTES

1. Our country groups are based on World Bank definitions measured in US dollar Purchasing Power Parity terms; Low Incomes (43 of 123 countries) have an upper limit of (1985) $1 690 p.c.; Lower Middle-Income (40 countries) range from $1 890 to $4 735 p.c.; Upper Middle-Income (16 countries, from Venezuela to Romania) from $4 904 to $6 764 p.c.; and 24 High-Income countries (from Saudi Arabia to Switzerland) from $6 765 to $17 000 p.c.

2. Even if we adopt Johansen's (1991) technique, which allows the estimation of multiple co-integrating vectors, the results depend on an arbitrary normalisation and provide a basis for the subspace spanned by the co-integrating vectors rather than the structural relationships themselves.

3. I(1) means integrated of order one; that is, non-stationary but stationary when first differenced. The tests for non-stationarity are reported in Canning (1999). Here we use paved roads rather than paved roads plus railway lines, but this change makes little difference to the time series properties of the series.

4. When estimating a single time series relationship with non-stationary variables, it is important to test for co-integration because the time trends in non-stationary variables can lead to a "spurious" regression, suggesting a close relationship when in fact none exists. However, Phillips and Moon (1999) point out that this does not occur in panel data, and we can safely estimate long-run relationships by OLS, even without co-integration.

5. The speed of convergence of a parameter estimate to the true parameter value depends on the range of variation of the explanatory variable, relative to the variance of the error term. Non-stationary variables tend to have much greater variance than stationary variables, giving much faster convergence of parameter estimates in co-integrating relationships than in standard regressions (so called "super-consistency"). Our higher power terms exhibit an even greater range of values than I(1) variables, indicating that their parameter estimates will converge to the true value even more quickly.

6. Formally, the problem may be that the feedback from income level to the number of telephones is fairly homogeneous across countries, so that this is what our estimation procedure picks up, while the institutional structures of road building and installing electricity-generating capacity are more varied across countries, and so do not bias our results.

7. Splitting the sample on the basis of income tends to bias the results slightly because of the correlation between sample selection and the disturbance terms. However, Table 2 is intended for illustration purposes only and is not used in calculating rates of return.

8. As noted above, it is unclear that we should put much weight on the estimated t statistics in Table 3 because of the non-linearities in the specification. In addition, it should be noted that the large increase in the R squared between Table 1 and Table 3 is an artifact of the fact that in Table 3 we include in the R squared the explanatory power of the country-specific fixed effects and the

worldwide time trend, while in Tables 1 and 2 these effects are removed from the data before estimation.

9. This is simply an application of the envelope theorem.

10. The simple path of initial expenditure, followed by positive returns to the project, ensures the existence of a unique internal rate of return for the project. The result is exactly the same if, instead of replacing depreciation as it occurs, we assume that we let the capital stock decay to zero over time with proportional reductions in the benefits of the project.

ANNEX

Table 1. **The Cobb Douglas Production Function with Infrastructure**

Dependent variable: Log GDP per worker 1960-90

Total factor productivity	**Year dummies, fixed effects**	**Year dummies, fixed effects**	**Year dummies, fixed effects**	**Year dummies, fixed effects**
Short-run dynamics	2 lags, 1 lead	2 lags, 1 lead	2 lags, 1 lead	2 lags, 1 lead
Log capital per worker	0.455 (14.7)	0.404 (14.6)	0.417 (11.7)	0.392 (11.9)
Log human capital per worker	0.125 (3.73)	0.051 (1.43)	0.079 (1.77)	0.059 (1.54)
Log electricity-generating capacity per worker		0.085 (5.83)		0.057 (3.13)
Log paved roads per worker			0.083 (4.06)	0.048 (2.30)
R squared adjusted	0.729	0.678	0.716	0.685
Countries	97	90	67	62
Observations	2 674	2 473	1 671	1 534
Average T	28	27	25	25

Note: t ratios in parentheses are calculated based on the long-run auto-covariance matrix and are asymptotically N(0,1).

Table 2. **The Cobb Douglas Production Function with Infrastructure In Low Income and High Income Countries**

Dependent variable: Log GDP per worker 1960-90

	Full sample	**Low-income countries**	**High-income countries**
Total factor productivity	**Year dummies, fixed effects**	**Year dummies, fixed effects**	**Year dummies, fixed effects**
Short run dynamics	2 lags, 1 lead	2 lags, 1 lead	2 lags, 1 lead
Log capital per worker	0.392	0.371	0.365
	(11.9)	(8.58)	(6.41)
Log human capital per worker	0.059	0.035	0.112
	(1.54)	(0.64)	(1.57)
Log electricity-generating	0.057	0.012	0.117
capacity per worker	(3.13)	(0.50)	(3.73)
Log paved roads per worker	0.048	0.003	0.134
	(2.30)	(0.12)	(4.05)
R squared adjusted	0.685	0.582	0.478
Countries	62	31	31
Observations	1534	781	753
Average T	25	25	24

Notes: t ratios in parentheses are calculated based on the long run auto-covariance matrix and are asymptotically N(0,1).
Sample split on the basis of income per capita in 1975.

Table 3. **The Translog Production Function with Infrastructure**

Dependent variable: Output per worker

Regression	**(1)**	**(2)**	**(3)**
Log input (per worker)			
Capital	0.072	-0.038	0.017
	(0.70)	(0.20)	(0.10)
Human capital	-0.151	0.992	0.569
	(1.39)	(6.31)	(3.27)
Electricity		-0.869	
		(7.47)	
Paved roads			-0.398
			(2.98)
Capital squared	0.026	0.034	0.027
	(3.57)	(3.50)	(2.75)
Human capital squared	-0.064	-0.114	-0.062
	(5.78)	(5.76)	(2.92)
Electricity squared		-0.061	
		(10.9)	
Paved roads squared			-0.054
			(6.36)
Capital*Human capital	0.049	-0.049	-0.039
	(3.81)	(3.13)	(1.89)
Capital*Electricity		0.069	
		(6.07)	
Capital*Paved roads			0.044
			(2.87)
Human capital*Electricity		0.152	
		(9.31)	
Human capital*Paved roads			0.101
			(6.12)
R squared adjusted	0.993	0.995	0.996
N	2674	2473	1671
Countries	97	90	67
Number of short-run parameters	582	810	603

Table 4. **Elasticity of Output**

Regression No.	**Elasticity of output with respect to:**	**Inputs per worker in 1985**		
		Lower quartile	**Median**	**Upper quartile**
(1)	Capital	0.50	0.59	0.65
	Human capital	0.09	0.11	0.11
(2)	Capital	0.35	0.52	0.65
	Human capital	0.08	0.08	0.13
	Electricity	0.06	0.09	0.07
(3)	Capital	0.43	0.52	0.61
	Human capital	0.14	0.09	0.14
	Paved roads	0.05	0.09	0.04

Table 5. **Unit Costs of Construction**

Infrastructure units Year	Paved roads International $ per kilometre 1985	Electricity US$ per kilowatt 1989	Electricity International $ per kilowatt 1985
Algeria		2 347	2 193
Angola		3 400	3 257
Argentina	80 223	1 902	2 780
Australia	869 154		
Austria	506 012		
Bangladesh		2 815	17 833
Belgium	402 887		
Bolivia	180 458	1 740	3 177
Botswana	256 089		
Brazil	639 203	2 655	5 447
Cameroon	278 808		
Canada	500 760		
Central African Rep.		7 786	15 407
Chile	143 840	1 924	4 126
China		1 502	4 695
Colombia	169 987	2 564	5 401
Congo		2 429	4 934
Costa Rica	131 966	2 301	4 143
Cyprus		2 655	3 982
Denmark	400 378		
Dominican Rep.	253 455	1 914	4 850
Ecuador	366 371	2 439	4 581
Egypt		1 590	3 498
El Salvador	540 362	3 971	7 127
Ethiopia	712 160	2 689	6 128
Fiji		2 923	4 924
Finland	477 889		
France	386 139		
Gambia		1 769	3 929
Germany, West	443 177		
Ghana		2 460	3 274
Guatemala	631 965	4 719	6 785
Honduras	771 088	2 144	3 006
Hong Kong	305 218		
Hungary	159 311	3 439	7 878
India	143 306	2 061	6 504
Indonesia	200 008	1 829	4 736
Ireland	399 348		
Israel	337 680		
Italy	296 089		
Ivory Coast	288 277	1 680	3 048
Jamaica		2 023	4 196
Japan	339 714		
Jordan		1 797	2 846

Table 5. **Unit Costs of Construction (continued)**

Infrastructure units **Year**	**Paved roads** **International $ per kilometre** **1985**	**Electricity** **US$ per kilowatt** **1989**	**Electricity** **International $ per kilowatt** **1985**
Kenya	285 128	1 717	3 779
Korea, Rep.	92 072	2 990	4 651
Lesotho		2 918	14 928
Liberia	426 839		
Luxembourg	402 887		
Madagascar	176 712	4 882	11 174
Malawi	282 163	1 990	5 499
Malaysia		1 746	3 057
Mali		1 957	6 145
Mexico		1 949	3 729
Morocco	270 454	2 145	6 040
Mozambique		6 250	15 957
Myanmar		2 719	7 646
Nepal		4 346	22 989
Netherlands	529 989		
New Zealand	456 604		
Nicaragua		3 229	5 280
Niger		7 000	14 977
Nigeria		2 793	2 560
Norway	438 496		
Pakistan	434 650	1 390	4 550
Panama	187 551	3 417	4 423
Papua New Guinea		1 925	3 737
Peru		3 393	8 273
Philippines	111 343	2 043	4 708
Poland		1 851	3 404
Portugal	236 770	2 330	4 858
Senegal	306 742	13 600	32 856
Sierra Leone		3 038	6 304
Somalia		3 268	5 413
Spain	236 990		
Sri Lanka	65 277	4 451	19 930
Sudan		2 422	5 293
Sweden	522 244		
Syria		1 539	3 458
Tanzania	221 723		
Thailand		2 034	5 823
Tunisia	313 404	1 189	2 415
Turkey	228 506	1 849	4 555
UK	777 133		
USA	627 580		
Uruguay	95 440	1 778	3 776
Yugoslavia		1 702	3 591
Zambia	144 577		
Zimbabwe	277 287	1 927	3 660

Table 6. **Rates of Return to Electricity-generating Capacity and Capital**

	Rate of Return to EGC	Rate of Return to Capital	ROR EGC/ ROR K
Algeria	0.63	0.15	4.20
Argentina	0.46	0.29	1.59
Bangladesh	0.61	0.80	0.77
Bolivia	0.92	0.19	4.74
Brazil	0.10	0.58	0.16
Central African Rep.	0.40	0.12	3.25
Chile	0.41	0.73	0.56
China	0.54	0.41	1.31
Colombia	0.28	0.55	0.50
Congo	1.14	0.25	4.58
Costa Rica	0.25	0.36	0.69
Cyprus	0.36	0.31	1.19
Dominican Rep.	0.25	0.61	0.42
Ecuador	0.45	0.50	0.91
Egypt	0.45	0.50	0.90
El Salvador	0.17	0.42	0.40
Fiji	0.32	0.30	1.06
Gambia	1.05	0.23	4.49
Ghana	0.25	0.18	1.37
Guatemala	0.18	0.34	0.52
Honduras	0.95	0.27	3.56
India	0.24	0.53	0.44
Indonesia	1.06	0.62	1.70
Jamaica	0.11	0.20	0.54
Jordan	0.40	0.42	0.96
Kenya	1.25	0.19	6.63
Korea, Rep.	0.31	0.45	0.68
Malawi	0.54	0.18	3.00
Malaysia	0.77	0.44	1.76
Mali	0.51	0.24	2.16
Mexico	0.51	0.52	0.98
Mozambique	-0.07	0.17	-0.42
Myanmar	0.34	0.33	1.03
Nepal	0.40	0.56	0.72
Nicaragua	0.20	0.30	0.67
Niger	0.12	0.13	0.92
Pakistan	0.18	0.95	0.19
Panama	0.21	0.38	0.55
Papua New Guinea	0.06	0.24	0.26
Peru	0.21	0.40	0.51
Philippines	0.44	0.35	1.25
Portugal	0.07	0.46	0.14
Senegal	0.06	0.24	0.27

Table 6. **Rates of Return to Electricity-generating Capacity and Capital** (continued)

	Rate of Return to EGC	**Rate of Return to Capital**	**ROR EGC/ ROR K**
Syria	0.35	0.80	0.44
Thailand	0.42	0.61	0.69
Tunisia	0.40	0.37	1.07
Turkey	0.32	0.72	0.45
Uganda	0.80	0.02	46.26
Uruguay	0.30	0.51	0.59
Yugoslavia	0.24	0.34	0.72
Zimbabwe	0.05	0.38	0.14

Table 7. **Rates of Return to Paved Roads**

	Rate of return to paved roads	Rate of return to capital	ROR Paved Roads/ ROR Capital
Argentina	3.85	0.29	13.33
Australia	-0.01	0.30	-0.02
Austria	0.00	0.29	-0.02
Belgium	0.06	0.40	0.14
Bolivia	7.96	0.21	37.09
Botswana	0.20	0.58	0.34
Brazil	0.61	0.57	1.07
Cameroon	1.88	0.35	5.31
Chile	5.24	0.73	7.15
Colombia	9.47	0.54	17.53
Costa Rica	1.96	0.37	5.24
Denmark	0.12	0.30	0.40
Ecuador	1.97	0.51	3.85
El Salvador	1.11	0.47	2.38
Finland	0.15	0.22	0.68
Germany, West	0.16	0.29	0.55
Guatemala	0.76	0.38	2.01
Honduras	0.39	0.34	1.15
India	0.74	0.78	0.96
Indonesia	2.03	0.83	2.45
Ireland	0.06	0.36	0.15
Italy	0.26	0.34	0.76
Japan	0.62	0.20	3.05
Kenya	0.53	0.35	1.51
Korea, Rep.	15.76	0.43	36.95
Liberia	1.04	0.15	6.82
Malawi	0.60	0.40	1.50
Netherlands	0.15	0.32	0.46
New Zealand	0.08	0.36	0.23
Norway	0.02	0.21	0.08
Pakistan	0.52	1.17	0.45
Panama	2.18	0.38	5.76
Philippines	7.19	0.40	17.99
Senegal	0.48	0.45	1.07
Sweden	0.06	0.29	0.21
Tunisia	0.16	0.43	0.36
Turkey	1.58	0.78	2.03
UK	0.13	0.39	0.32
USA	0.07	0.29	0.26
Zambia	0.65	0.24	2.69
Zimbabwe	0.15	0.45	0.33

Figure 1
Elasticity of Output with Respect to Capital

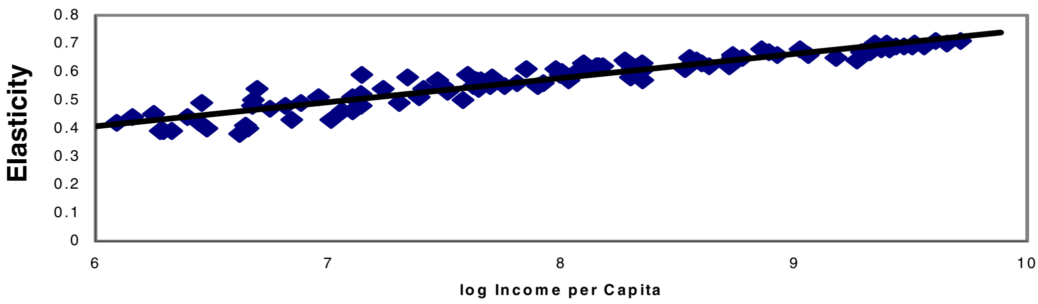


Figure 2
Elasticity of Output with Respect to Education

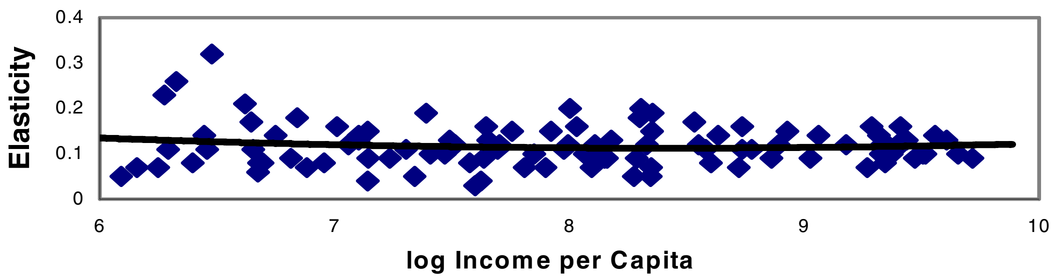


Figure 3
Elasticity of Output with Respect to EGC

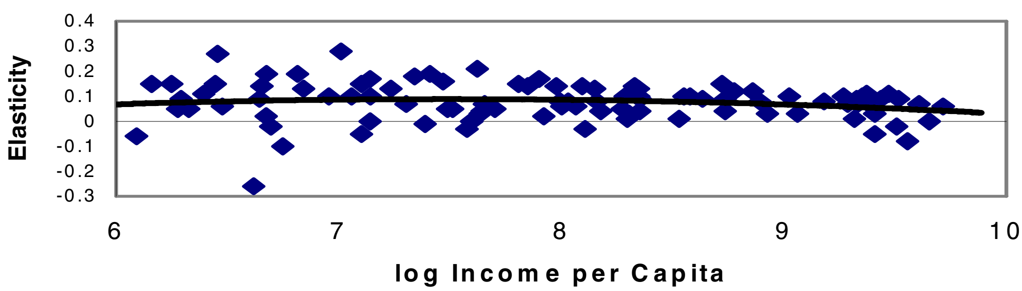


Figure 4
Elasticity of Output with Respect to Paved Roads

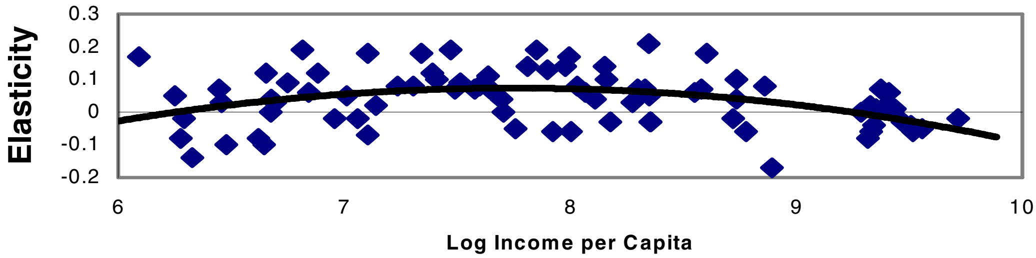


Figure 5
Cost of Paved Roads

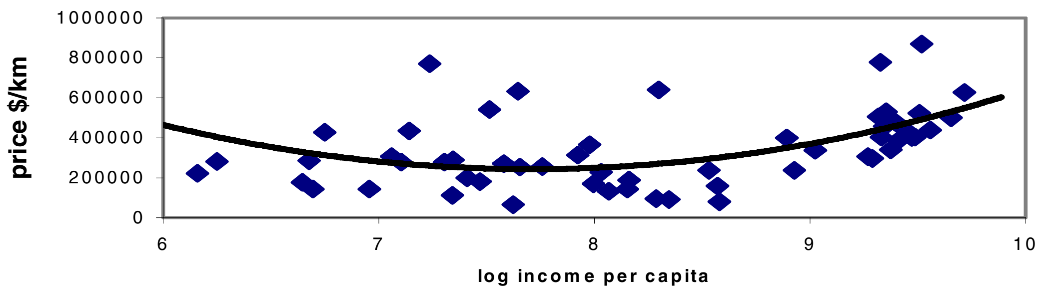


Figure 6
Cost of Electricity Generating Capacity

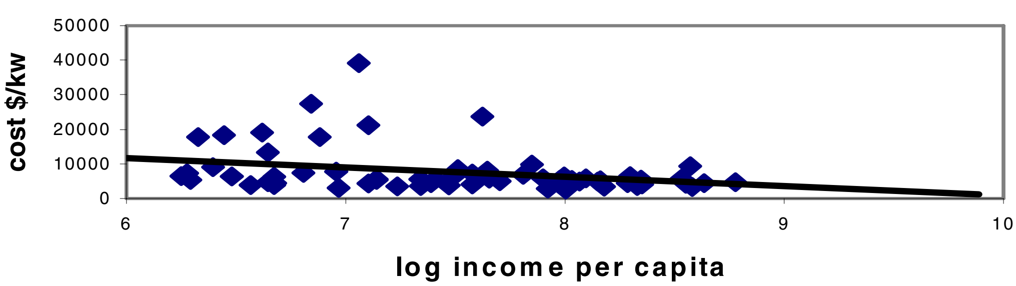


Figure 7
The Rate of Return to EGC Relative to Capital

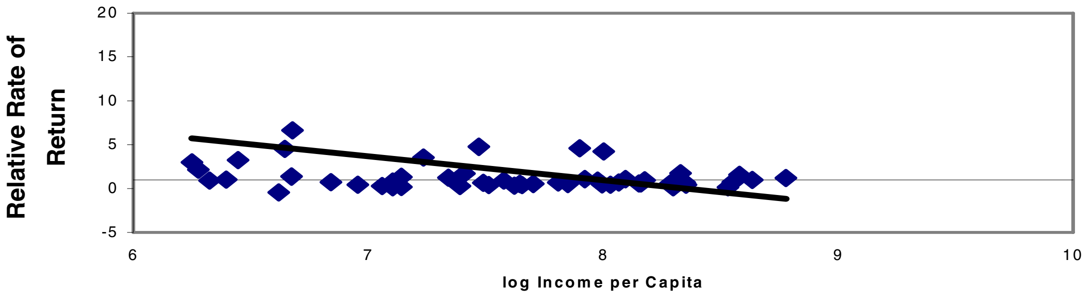


Figure 8
Rate of Return to Paved Roads Relative to Capital

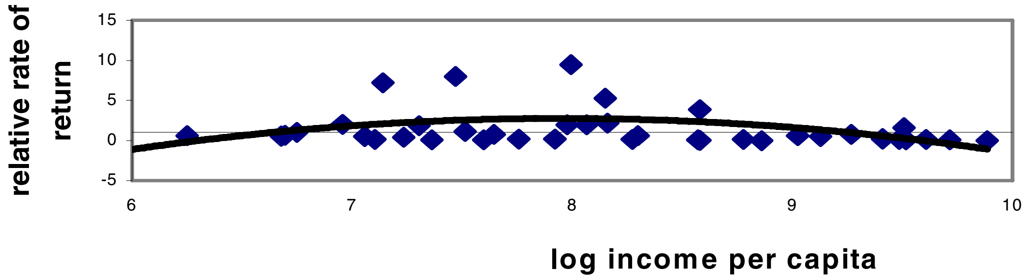
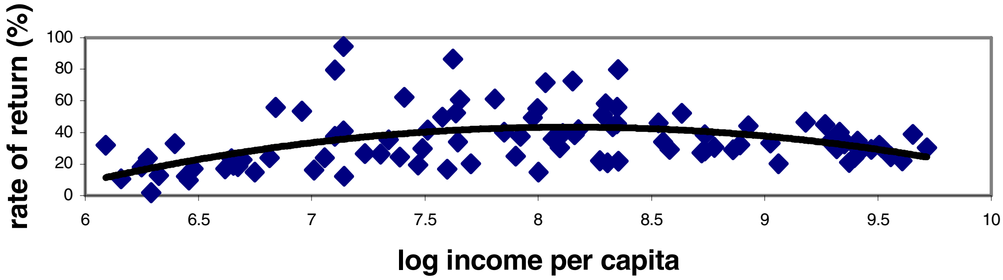


Figure 9
Rate of Return to Capital



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MACROECONOMIC PRODUCTIVITY EFFECTS OF ROAD INVESTMENT – A reassessment for Western Europe

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SUMMARY

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ABSTRACT

An understanding of the productivity effects of infrastructure would allow more informed decisions to be taken on the overall budget allocations for infrastructure investment in general and transport infrastructure in particular. This paper analyses the macroeconomic productivity effects of road investment in 13 western European countries. It reviews the previous attempts to measure the macroeconomic effects of infrastructure investment, which often suffer from an unresolved endogeneity problem. The production theory framework used explicitly includes the modelling of national transport intensities, and the fact that transport services depend on private capital investment and government investment in roads. The endogeneity bias is addressed by introducing an estimation breakdown which combines national productivity effects with overall productivity effects for the country group as a whole, to make residuals of the estimation orthogonal to the explanatory variables. Productivity is measured by the Toernquist productivity index. The productivity effects depend on the sign of the ratio of vehicle stock to the road stock elasticity of production. The fixed-effects panel data analysis shows that transport infrastructure has a positive effect on macroeconomic productivity. The variance of road infrastructure investment in the panel explains, however, only a small part of the macroeconomic productivity development.

Keywords: Road investment - macroeconomic productivity - panel data analysis.

1. INTRODUCTION

Transport infrastructure investment and road infrastructure investment in particular are seen, by a major part of the general public and by many political decision-makers, as a central instrument for promoting regional or national economic growth. Large-scale investment in the road network formed part of long-term growth policies in the US under the Dwight D. Eisenhower System of Interstate and Defence Highways, which was launched in 1956 and led to the creation of over 80 000 miles of highways by 1980 (Federal Highway Administration, 1976). In 1998, the Transportation Equity Act was signed, assigning US$203 billion to the improvement of the national highway infrastructure. Of this amount, US$176 billion were allocated for highway construction (cf. Chandra and Thompson, 2000).

The European Council of October 2003 called on Member States to "...*promote investment in networks and knowledge*." It highlighted *"the importance of speeding up the roll-out of European transport, energy and electronic communications networks and of increasing investment in human capital. These are crucial steps to boost growth, better integrate an enlarged Europe and improve the productivity and competitiveness of European businesses on global markets* (Commission of the European Communities, 2003)." The Community budget contributes 700 million euros annually to fund up to 10 per cent of Trans-European Network (TEN) projects. The Structural Funds are foreseen to provide 29.2 billion euros for transport infrastructure, while Cohesion Fund resources can mobilise up to 1.5 billion euros per year for infrastructure investment. Furthermore, the Commission is considering setting up an innovative Guarantee Instrument to facilitate private sector funding in PPPs for TEN transport projects. The European Investment Bank supports the Growth Initiative with a 50 billion euro TEN Investment Facility to be allocated to TEN's priority projects. In addition, the EIB reinforces its financing capacity under the Structured Finance Facility which, *inter alia*, supports the TEN projects. On the national level, transport infrastructure investment is considered to be of equal importance to increase economic growth.

The strong role assigned to transport infrastructure investment as a vehicle for economic growth appears to be worth critical examination for at least two reasons:

- There is no strong growth theory foundation for the hypothesis that an increase in transport infrastructure investment would lead to an immediate and lasting increase in *growth rates* of economic activity. Rather, according to the exogenous growth theory, an increase in the investment rate (which does not necessarily result from an increase in transport infrastructure investment) leads to an increase in the income *level* (Barro and Sala-i-Martin, 1995). Some variants of endogenous growth theory do provide a link between transport infrastructure investment and growth rates. The link is established by the effects of transport infrastructure investment on urban form and the size distribution of cities, and the resulting agglomeration economies (Lucas, 1988; Black and Henderson, 1999; Lucas, 2001; Lucas and Rossi-Hansberg, 2002). However, the links from transport infrastructure investment to economic growth are less direct than claimed in public debates, and related arguments are rarely used in policy discussions.

- There is no clear, empirical evidence that transport infrastructure investment leads to higher growth or even to a higher level of income. Some authors interpret the strong correlation between public capital and macroeconomic productivity, which was found for the USA, as evidence that infrastructure generally provides valuable services to the private sector and that, in particular, the slowdown in US public investment after the early 1970s explains a substantial proportion of the concomitant productivity slowdown[1]. Other authors have argued that public capital is endogenous, in that higher public investment is due to the public sector response to an increased demand for infrastructure services, resulting from higher aggregate income[2]. Sectoral and regional disaggregation have led to smaller, positive but more robust effects (see the review in Cohen and Morrison Paul, 2004). A number of studies have looked into issues which complicate the estimation of public infrastructure investment effects, such as the existence of spatial spillovers from public infrastructure investment in geographically linked areas and the temporal dependence of estimated infrastructure effects. Kelejian and Robinson (1997) allowed for spatial lags of dependent and independent variables along with spatial correlation of the error terms. Holtz-Eakin and Schwartz (1995) consider interstate spillovers in a production model based on long lags to accommodate long-run adjustment, and Boarnet (1998) measured cross-county spillovers using a Cobb-Douglas production function approach.

Among the studies which addressed the more specific question of whether road infrastructure investment increased productivity, Carlino and Voith (1992) found that the productivity of US states was higher the greater the density of highways. Holtz-Eakin and Schwartz (1995) could not confirm the strong positive productivity effects of transport infrastructure on the state level. Holtz-Eakin and Lovely (1996) succeeded in relating output growth to the positive effect transport infrastructure investment had on the number of firms in the manufacturing industry, without observing a direct effect on manufacturing productivity.

Within the production function approach, Canning (1999) and Canning and Bennathan (n.d.) have used a different method to solve the problem of the endogeneity of public capital. It is based on the non-stationarity of the data for output per worker and capital stock per worker. This means that the production function may represent a long-run, co-integrating relationship. They use this fact to apply the panel data co-integration methods of Kao and Chiang (2000). Using this method, and the assumption that production functions are identical for all countries, while the relationship between investment and income varies across countries, allows each country in the sample to have its own short-run investment dynamics, to give consistent estimates of the parameters of the production function which are robust to reverse causality.

This paper is related to the study of Fernald (1999). He tried to give an answer to the question of how changes in road stock affected the relative productivity performance of US industries from 1953 to 1989. His argument is based on the hypothesis that if roads contribute to industries' productivity, industries which use roads intensively should benefit more from their expansion. Given the complementarity between vehicle use and road use, and the lack of direct measures for industrial road use, vehicle use is employed as a direct measure of road intensity. The basic result of Fernald's study is that changes in road growth are associated with larger changes in productivity growth in industries which are relatively vehicle-intensive. This finding supports the hypothesis that industries with more than average vehicles benefited more than proportionately from road building. This result, in turn, suggests that the correlation between aggregate productivity and infrastructure reflects causation from changes in road stock to changes in productivity. If roads did not contribute to aggregate productivity at the margin, but governments just built more roads as aggregate income rose, one would not expect any particular relationship between an industry's vehicle intensity and its relative productivity performance when road growth changes. The results do not, however, support the idea that public investment offers a continuing route to increasing income. The US industry data are consistent with the view that the massive road building of the 1950s and 60s offered a one-off boost to the level of productivity, rather than an instrument to continuing rapid growth in productivity.

In this paper a similar approach is taken. We distinguish the western European countries by their transport intensity, as well as their use of labour and capital. The next chapter sets out the conceptual framework for the empirical analysis. Chapter three explains some data and econometric issues, and the results of the empirical analysis are presented in chapter four. In chapter five we make some concluding remarks.

2. THE MODEL

In this chapter, we develop the background of the estimation equation. We formalize the notion that countries which have relatively transport-intensive industries benefit more from an increase in road infrastructure investment than countries with a relatively low transport intensity. We consider a set of n countries. The growth accounting with road infrastructure starts out from national production functions. For each country i, the production of gross output Q_i depends on non-transport capital stock K_i, employment L_i and transport services T_i. Output also depends on the economy's technological level

U_i, which is assumed to progress in a Hicks-neutral way. Transport services depend on the services of road stock G_i as well as the national stock of transport equipment V_i. Omitting time subscripts, we have the following national production functions:

$$Q_i = U_i F^i\left(K_i, H_i, L_i, T[G_i, V_i]\right) \tag{1}$$

for $i = 1,\ldots,n$.

Equation (1) represents the gross production function of the representative firm using the primary inputs, capital *K*, labour *L* and transport services *T*, as the only intermediate input. The transport services are produced using road services *G* and the services of the vehicle stock *V*. The firms do not choose input *G* but the number of vehicles, which is *V*.

Taking logarithms of (1) and forming the total differential, we obtain:

$$\frac{dQ}{Q} = \frac{dU}{U} + \frac{1}{F}\left(F_K dK + F_L dL. + F_T T_V dV + F_T T_G dG\right), \text{ or} \tag{2}$$

$$\frac{dQ}{Q} = \frac{dU}{U} + \frac{F_K K}{F}\frac{dK}{K} + \frac{F_L L}{F}\frac{dL}{L} + \frac{F_V V}{F}\frac{dV}{V} + \frac{F_G G}{F}\frac{dG}{G}. \tag{3}$$

F_j denotes the derivative of the production function with respect to input *j*, while the coefficients $\frac{F_J J}{F}$ indicate production elasticities, i.e. the percentage increase of gross output if the input *J* is increased by one per cent. Firms do not take input decisions with respect to road services. However, input decisions with respect to vehicles are not independent of the road services provided by the existing road capital stock. The output elasticity with respect to road services can be expressed relative to the elasticity with respect to vehicles:

$$\frac{F_G G}{F} = \left(\frac{\frac{F_G G}{F}}{\frac{F_V V}{F}}\right)\cdot\left(\frac{F_V V}{F}\right) = \phi\cdot\left(\frac{F_V V}{F}\right) \tag{4}$$

The parameter ϕ equals the ratio of output elasticities of roads and vehicles. The production elasticity of vehicles measures the transport elasticity of the national economy. Hence the parameter links the observed transport intensity of the economy to the indirect input road use. We expect ϕ to be positive, i.e. we expect economies which are relatively transport-intensive to be relatively road-intensive. Due to the separability assumption implicit in (1), ϕ also equals the ratio of the elasticities with respect to *G* and *V* in producing transport:

$$\phi_i = \frac{T_G G_i}{T_V V_i} \tag{5}$$

The formal derivation of the estimation equation and the interpretation of results are now greatly simplified by assuming that the ϕ_i are identical for all countries *i*, that is, we assume that the function for transport services *T* has the form of a Cobb-Douglas function. Assuming that the manufacturing industries of all countries are price-takers in factor markets, cost minimization implies that the production elasticities can be interpreted as factor shares and shares of intermediate goods in the value of gross production. Denoting the share of factor *j* in gross output of country *i* by:

$$s_{ij} = \frac{\partial F^i}{\partial J_i} \cdot \frac{J_i}{F^i} = \frac{F_j^{\,i} J_i}{F^i}, \tag{6}$$

adding country subscript i; we can then rewrite (3) by:

$$\frac{dQ_i}{Q_i} = \frac{dU_i}{U_i} + s_{Ki}\frac{dK_i}{K_i} + s_{Li}\frac{dL_i}{L_i} + s_{Vi}\frac{dV_i}{V_i} + \phi \cdot s_{Vi}\frac{dG_i}{G_i}. \tag{7}$$

To express the productivity increase as the Solow residual, i.e. as the increase in *value added* minus the contributions of the private factors of production, we have to take account of the following identity:

$$\frac{dQ}{Q} = \frac{dY}{Y}(1 - s_I) - \frac{s_I}{1 - s_I}\frac{dI}{I} \tag{8}$$

where *Y* denotes value added, *I* real intermediate goods and s_I the share of nominal inputs of intermediate goods *I* in the value of gross output[3].

We then have, as the expression for the Solow residual:

$$\frac{d\rho}{\rho} = \frac{dY}{Y} - s_K^*\frac{dK}{K} - s_L^*\frac{dL}{L} - s_V^*\frac{dV}{V} \tag{9}$$

with $s_j^* = s_j(1/(1-s_I))$ denoting the share of factor *j* in value added. Given (7), we have for country *i*:

$$\frac{d\rho_i}{\rho_i} = \phi s_{Vi}^*\frac{dG_i}{G_i} + \frac{dU_i^*}{U_i^*} \tag{10}$$

In other words, the observed growth in productivity is the sum of the technology shock in terms of value added and the percentage increase in production which is due to the relative increase in road services.

The road services enjoyed by country *i* do not only depend on the road investment in country *i* but also on:

- the road services and road investment on the trading partners' territory, depending on trade intensities and the transport intensities of bilateral goods trade[4];
- congestion in the individual countries, which determines the level of road services provided by national road stocks.

To account for bilateral trade, the road service consumed by country *i* is defined as its own and the trading partners' road stock multiplied with the share of domestic consumption and the share of bilateral exports in the value added of country *i*:

$$\frac{dG_i}{G_i} = \frac{dg^i}{g^i} + \sum_{J=1}^{N} \frac{e_{ij}}{Y_i} \frac{dg^j}{g^j} \text{, for } i \neq j = 1,..., N \tag{11}$$

Road services do not only depend on the stock of road capital but also on collective road use or, more specifically, on congestion. To account for congestion, the national road service supply g^i is defined as the real road stock value divided by the number of vehicles registered in country *i*. By measuring congestion in this way, we implicitly assume that car usage does not change much over time or, in particular, that it does not go down. By dividing road stock by the number of vehicles, we adopt the assumption of Barro and Sala-i-Martin (1995) and Mankiw (1992). With this specification, any individual producer takes road use by others as given.

With (10) as the estimation equation, there is still the problem of endogeneity. If reverse causality and public investment depended on aggregate income rather than the other way around, then country productivity shocks would affect road growth. To address the endogeneity problem, we consider the following regression breakdown:

$$\frac{dU_i^*}{U_i^*} = \frac{d\bar{U}^*}{\bar{U}^*} + \varepsilon_i \tag{12}$$

with $\bar{U}$ denoting the overall shock of the group of countries. The residuals ε_i of equation (12) are, by construction, orthogonal to the national productivity shocks and hence to the changes in national government expenditure on transport infrastructure. The Solow residual for the country group as a whole is defined as:

$$\frac{d\bar{\rho}}{\bar{\rho}} = \phi s_{\bar{V}}^* \frac{dG}{G} + \frac{d\bar{U}^*}{\bar{U}^*} \tag{13}$$

where *G* denotes the overall growth of road services, i.e. the ratio of real road stock to the number of vehicles and $s_{\bar{V}}$ is the share of vehicle cost in nominal value added.

Both Solow residuals, for the country group and the individual countries, are computed as Törnquist indices of value added growth. That is, the discrete changes in productivity are expressed as:

$$\begin{aligned} \ln(\rho_t) - \ln(\rho_{t-1}) = \ln(Y_t) - \ln(Y_{t-1}) &- 1/2\left(s_{Kt}^* - s_{Kt-1}^*\right)\left(\ln(K_t) - \ln(K_{t-1})\right) \\ &- 1/2\left(s_{Lt}^* - s_{Lt-1}^*\right)\left(\ln(L_t) - \ln(L_{t-1})\right) \\ &- 1/2\left(s_{Vt}^* - s_{Vt-1}^*\right)\left(\ln(V_t) - \ln(V_{t-1})\right) \end{aligned} \tag{14}$$

To derive the estimation equation and substituting for the overall productivity shock, we have:

$$\frac{dU_i^*}{U_i^*} = \frac{d\bar{\rho}}{\bar{\rho}} - \phi s_{\bar{V}}^* \frac{dG}{G} + \varepsilon_i \tag{15}$$

The expression for the national growth rate of productivity is then:

$$\frac{d\rho_i}{\rho_i} = \phi s_{Vi}^* \frac{dG_i}{G_i} + \frac{d\bar{\rho}}{\bar{\rho}} - \phi s_{\bar{V}}^* \frac{dG}{G} + \varepsilon_i \tag{16}$$

and we have:

$$\frac{d\rho_i}{\rho_i} - \frac{d\bar{\rho}}{\bar{\rho}} = \phi s_{Vi}^* \frac{dG_i}{G_i} - \phi s_{\bar{V}}^* \frac{dG}{G} + \varepsilon_i = \phi\left(s_{Vi}^* s_i^g - s_{\bar{V}}^* \right)\frac{dG}{G} + \varepsilon_i \tag{17}$$

where s_i^g denotes the share of road services of country *i* in total road services of the country group.

The left-hand side of (17), the difference between the national growth in productivity and the productivity growth of the country group, is positive if country *i* has a higher productivity increase than average. The share of G_i in G, i.e. s_i^g, is higher, the higher the road stock of country *i* relative to the road stock of the country group and/or the higher the trade intensity of country *i*. If road infrastructure investment is productive, we would expect countries with an above-average road stock and an above-average vehicle intensity to benefit more than average from investment in road stock. Therefore, we would expect ϕ to be positive. Recall that ϕ equals the ratio of output elasticities of roads and vehicles, linking observed decisions on investment in vehicles to unobserved road use. A positive ϕ then captures the idea that vehicle-intensive countries are, or should also be, more road-intensive.

3. DATA AND ECONOMETRIC ISSUES

The empirical analysis includes western European countries for which data on all the variables involved are available. The largest gaps in the data were found for transport infrastructure investment, and for the real value of vehicle stock. The countries in the sample are Austria, Belgium, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Spain, Sweden and the United Kingdom.

A major part of the data used were taken from the OECD's STAN (Structural Analysis) database (OECD, 2004e). This holds for gross production figures, for value added, gross capital stock figures and the data on labour compensation. The employment figures in terms of hours worked have been taken from the OECD Productivity database (OECD, 2004d). The changes in vehicle stock were computed from the STAN figures on the production of motor vehicles, trailers and semi-trailers, subtracting exports and adding imports. The vehicle stock figures were calculated by applying the permanent inventory method and using the depreciation rate of 25.37 per cent proposed by Joergensen and Yun (1991). The long-term interest rate reported in the *OECD Economic Outlook* (OECD, 2004c) is used as the required rate of return on capital. Lacking information on the relevant taxes and subsidies, the user cost of capital is approximated by the sum of the discount rate and the required rate on return to capital. The total cost of vehicle capital, divided by nominal value added, gives the share of the vehicle capital cost in value added which is used to compute the Törnquist index of productivity growth. Nominal figures have been deflated using the deflator for private capital investment provided by the *OECD Economic Outlook* (*op. cit*.).

Very few ECMT member countries provide data on transport infrastructure stocks. The road stock figures are computed by applying the permanent inventory method to the ECMT data (ECMT, 2004b) on transport infrastructure investment. Following Boskin *et al.* (1991), it is assumed that roads depreciate geometrically at a rate of 1.98 per cent per year. Constant national currency values for road stock are calculated by using the deflator for government investment, reported in the OECD *Economic Outlook* (*op. cit*.). As mentioned above, the variable “road services” takes account of international trade relations and congestion. Bilateral trade coefficients are based on the bilateral trade data provided by the STAN Bilateral Trade Data Base (OECD, 2004a, 2004b)[5]. Congestion is depicted by dividing the constant currency value of road stock by the number of vehicles. The data on the number of vehicles are collected in the ECMT Statistical Report on Road Accidents (ECMT, 2004a).

Wherever absolute national currency values have had to be added up or compared, they have been made commensurable by using the PPP conversion factors of the *OECD Economic Outlook* (*op. cit*.).

4. RESULTS

For all the countries in the sample, the Toernquist index of productivity increased during the period from 1975 to 2000 (see Figure 1), Portugal, Finland and Sweden having the greatest overall increase of total factor productivity. The increase in the index was highly volatile, but decreased on average over the whole period, as can be seen from Figure 2.

The transport infrastructure investment data show that the absolute numbers for transport infrastructure investment, and road infrastructure in particular, are highly volatile. They do show a continuous increase in road stock which is, however, unable to keep pace with GDP growth. That is, the share of transport infrastructure investment in GDP is secularly decreasing for the western European countries. For road stock, this implies continuous growth, as shown by Figure 3, but at substantially decreasing rates (see Figure 4).

Figure 1: Toernquist index of real productivity

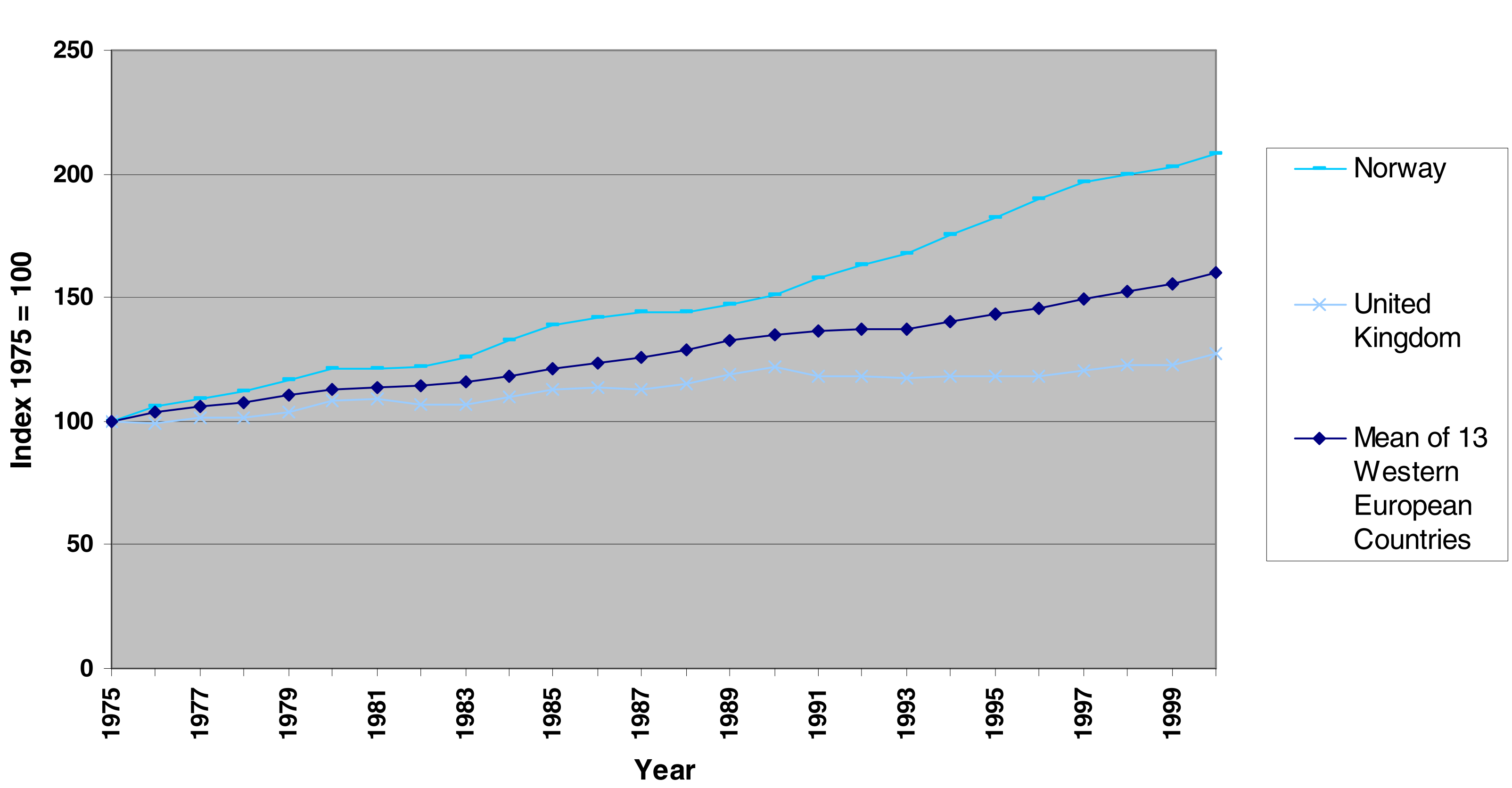


Figure 2: TFP growth

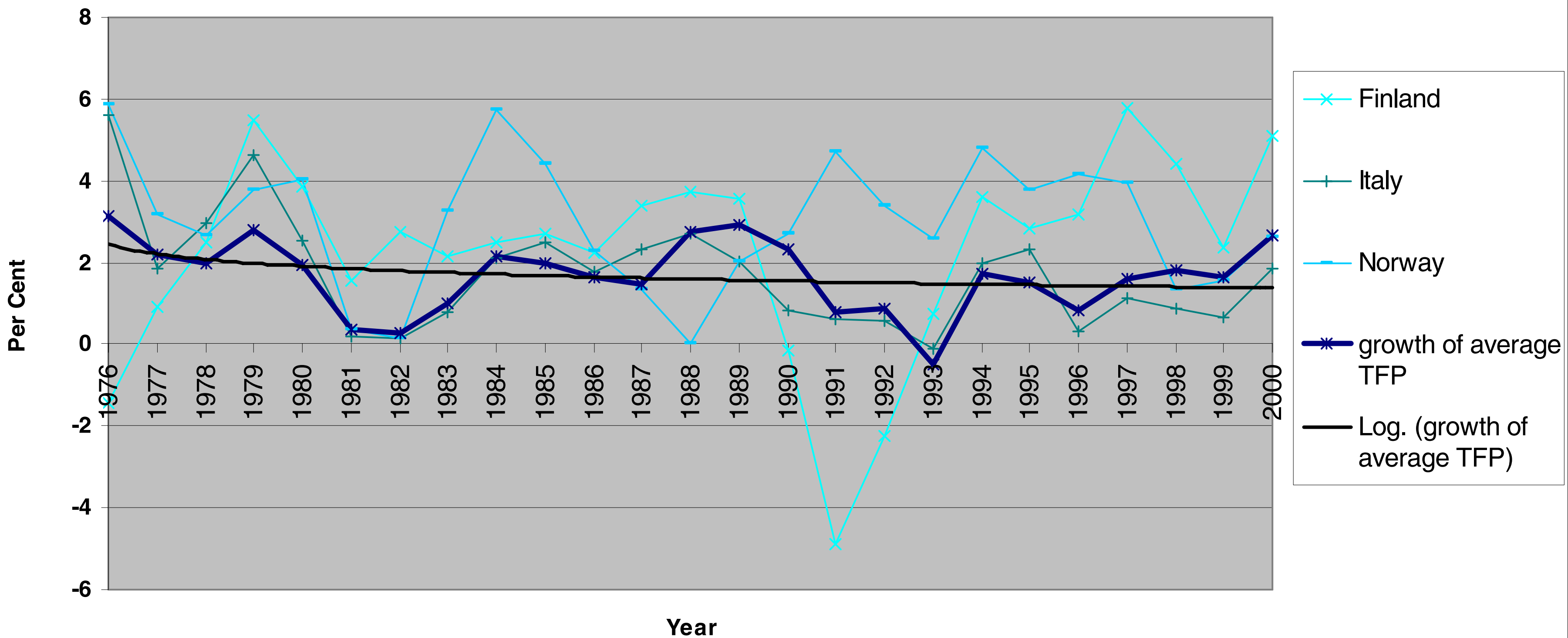


Figure 3: Road stock in 1995 international dollars

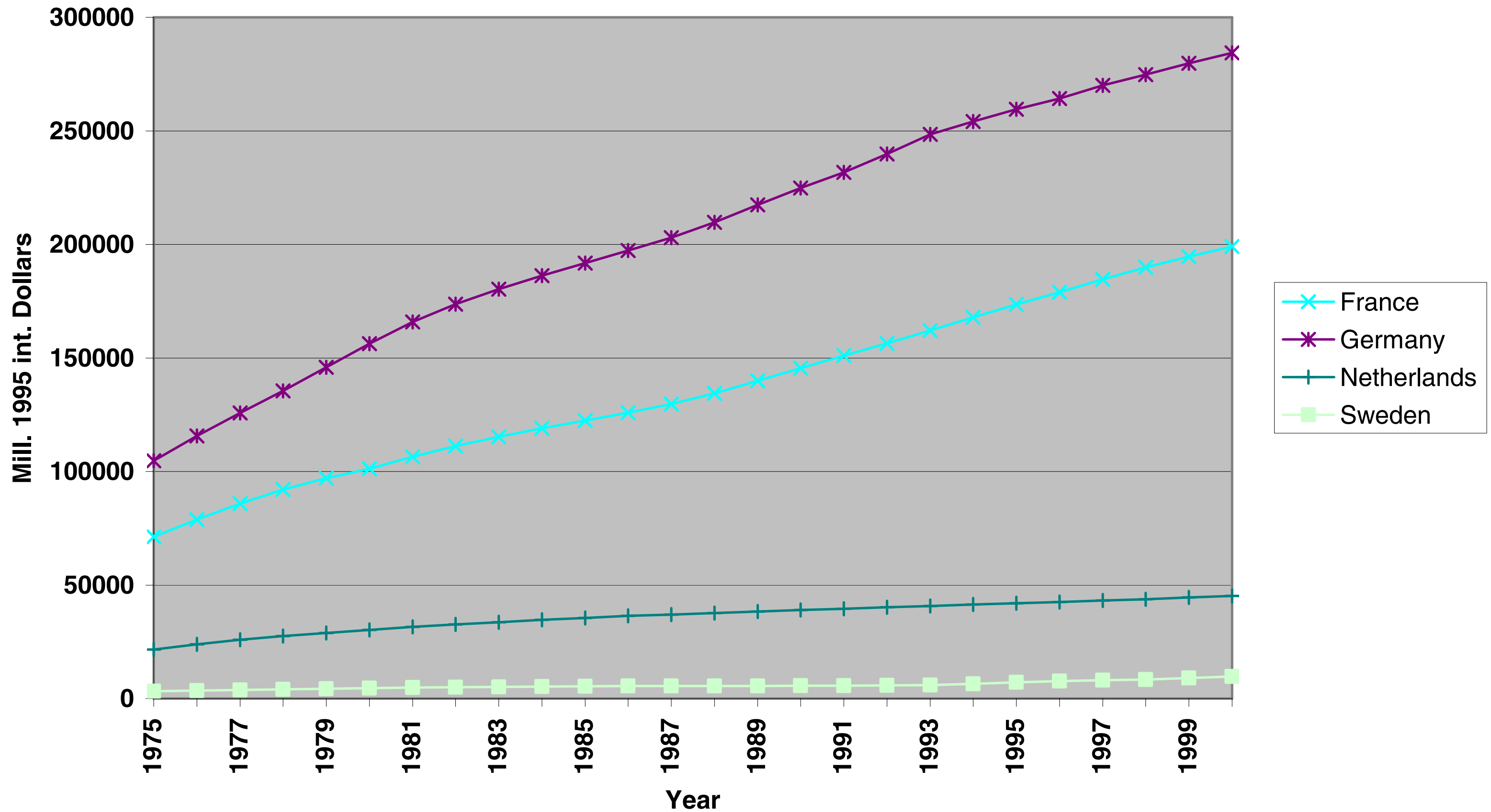
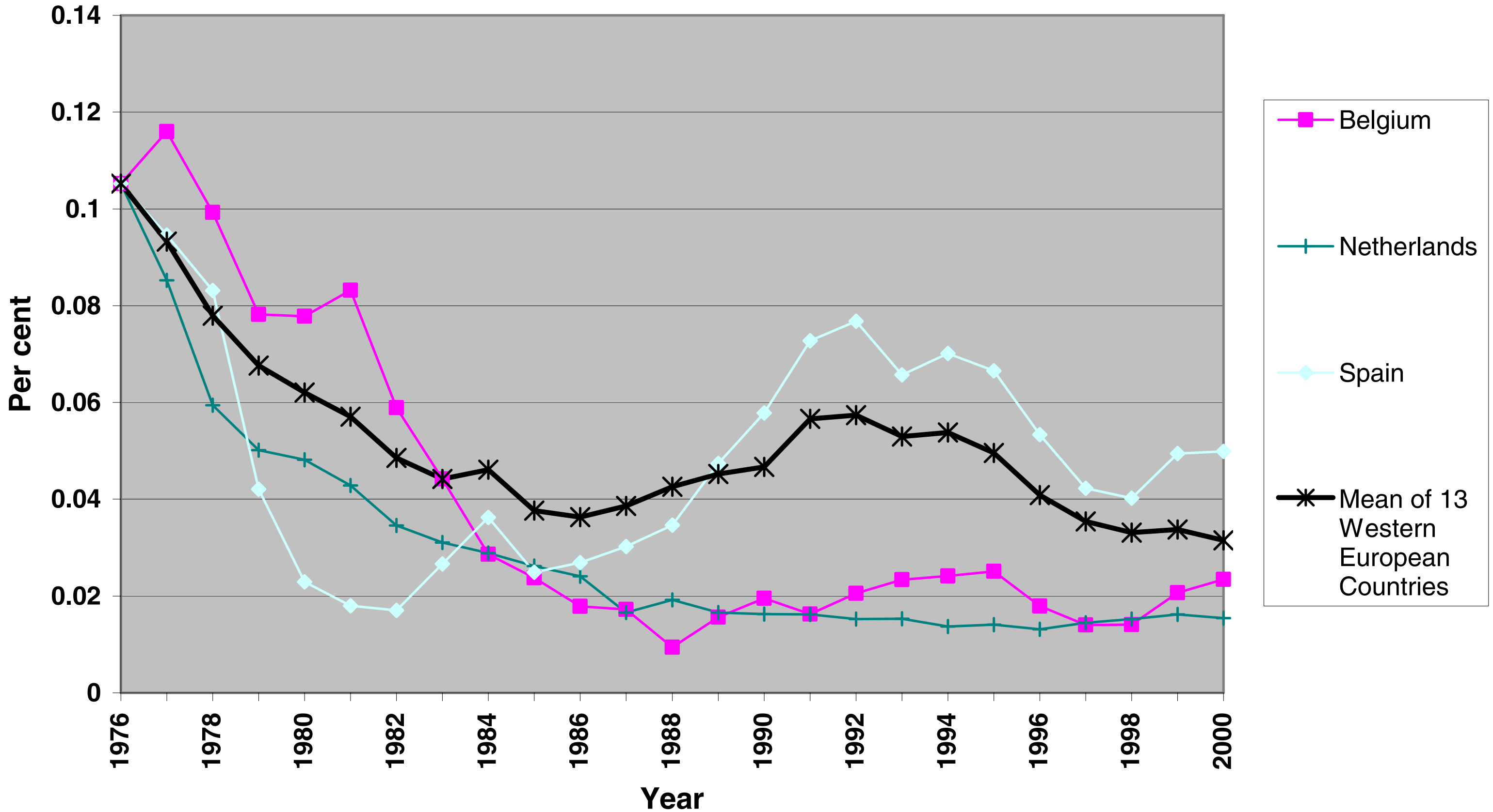


Figure 4: Growth rates of capital stock



We estimate the relationship between the growth of road services and the change in the Toernquist index by using a fixed-effects model. That is, we allow for country-specific, unobserved characteristics influencing the relationship between road infrastructure investment and macroeconomic productivity effects, which are assumed to be constant over time.

Estimating the difference between national productivity growth and productivity growth as a function of the product of national vehicle intensity and national road services, and the product of overall vehicle intensity and overall road services, we obtain the results given in Table 1.

Table 1. **Fixed effects regression 1, Independent variables for national and international road stock**

Number of observations = 300

difftfp	**Coefficient**	**Standard Error**	**t**	**P > $\|t\|$**	**95 p.c. Confidence Interval**
prod1	.7143729	.1921074	3.72	0.000	.3362493 1.092497
prod2	-2.478365	.49504	-5.01	0.000	-3.452749 -1.503981
constant	.2947857	.0294078	10.02	0.000	.2369025 .352669

R-sq: within = 0.0882
between = 0.0266
overall = 0.0458
F test that all $u_i = 0$: $F(11,286) = 53.41$ $Prob > F = 0.0000$

The table shows difftfp as the independent variable, and prod1 and prod2 as the explanatory variables, the estimation coefficients of the latter, the t values, the P values and the 95 per cent confidence interval. The table shows that the estimation coefficients have the expected signs, i.e. ϕ is positive, as the coefficient of the product of national vehicle share and national road services is positive, and negative for the product of overall vehicle share and overall road stock. An increase in national road services by investment in national road infrastructure improves, *ceteris paribus*, national productivity growth relative to the productivity growth of the country group. All coefficients are highly significant and the F-test shows desired results. However, as can be seen from the reported coefficients, the share in the variation of productivity growth explained by road investment is very low.

Estimating the difference in productivity growth on the national and country group levels as a function of the difference between the products of vehicle shares and road services on the national and international levels, does not affect the fundamental results, as can be seen from Table 2. The ratio of production elasticities of road stock to vehicle stock, ϕ , remains positive. The significance of the estimation coefficient is, however, slightly decreased and the regression coefficients are even worse than in the first model.

Table 2. **Fixed effects regression 2,**
Difference between vehicle share weighted national and international road stock

Number of observations = 300

difftfp	Coefficient	Standard Error	t	P > $\|t\|$	95 p.c. Confidence Interval
diffprod	.6563709	.1964768	3.34	0.001	.2696527 1.043089
constant	.2159342	.0223437	9.66	0.000	.1719559 .2599126

R-sq: within = 0.0374
between = 0.0266
overall = 0.0282
F test that all $u_i = 0$: $F(11\ 287) = 50.81$ $Prob > F = 0.0000$

The third estimation model adds a time dummy to estimation model 2. This improves the performance of the estimate in that the statistical significance of the estimated ϕ is improved and the regression coefficients are increased. The low coefficient for the time variable suggests that there is no problem of spurious correlation, due to the independent and dependent variables following the same time trend.

Table 3. **Fixed effects regression 3**,
Difference of vehicle share weighted national and international road stock and year dummy

Number of observations = 300

difftfp	Coefficient	Standard Error	t	P > $\|t\|$	95 p.c. Confidence Interval
diffprod	.7982335	.1919924	4.16	0.000	.4203362 1.176131
year	.0139947	.0029731	4.71	0.000	.0081427 .0198466
constant	-27.6085	5.911197	-4.67	0.000	-39.24347 -15.97353

R-sq: within = 0.1066
between = 0.0266
overall = 0.0528
F test that all $u_i = 0$: $F(11,286) = 54.46$ $Prob > F = 0.0000$

5. CONCLUDING REMARKS

This paper has argued that investment in road infrastructure indeed has positive macroeconomic productivity effects. The results of the paper do not, however, justify a general conclusion that national road infrastructure investment levels should be increased.

- The rate of return implied by the above analysis does not seem to be high (for many countries around 5 per cent)[6]. A relatively low rate of return might not necessarily be due to too high a level of investment but could be due to a misallocation at the local level. As demand for transport services is highly unequally distributed over space and even over time, local road infrastructure investment projects might have high expected rates of return, even if the overall implied rate of return is low.

- The greater income that can be achieved with the given resources may be associated with greater external costs, in particular in the form of environmental damage. On the other hand, the under-provision of transport infrastructure services leads to external costs in the form of time costs, which are not reflected in the national accounts data used here. While it is certainly true that GDP is an imperfect welfare measure, further research is required to identify how the impact of transport infrastructure on income differs from the impact on welfare.

An analysis such as the above can, however, give a broad indication as to an appropriate level of infrastructure investment, at least based on the hypothetical assumption that the assignment of investment resources to individual projects is rational. The linking of the above macroeconomic analysis to planning tools, to allocate regional infrastructure resources and cost-benefit analysis at the project level, is a matter for future research.

NOTES

1. Aschauer (1989, 1990) started the discussion on the productivity effects of public investment. His finding of large positive productivity effects being caused by public investment has been confirmed by Munnel (1990, 1992), Nadiri and Manuneas (1994), Kocherlakota and Yi (1996a), Morrison and Schwartz (1996b) as well as Duggal *et al*. (1999a).

2. See, for example, Aaron (1990), Hulten and Schwab (1991), Holtz-Eakin (1994) as well as Sturm and de Haan (1995).

3. On measuring the productivity increase by the Solow residual, see Hall (1990) and the discussion in Basu and Fernald (1997).

4. On the implications of international trade for the incentives to invest in transport infrastructure, cf. Bougheas *et al.* (2003).

5. Road investment might have an impact on trade coefficients. Given the resulting concern about the potential endogeneity of the weights, the average values for the sample period are used. In this we follow an approach proposed by Case *et al.* They provide the argument that, when using average values over several years for the weights, the weights and the explanatory values are orthogonal. Thus the introduction of the weights does not lead to a correlation of the independent variables and residuals.

6. It is calculated by multiplying the share of vehicle capital costs in value added by the ratio of value added to the value of road stock, and multiplying this product by ϕ.

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SUMMARY OF DISCUSSIONS

SUMMARY

1. INTRODUCTION

This Round Table was part of a sequence of research events to discuss tools to improve transport planning. It was chaired by Hilde Meersman (University of Antwerp). Background papers were contributed by David Canning (Harvard University), Charles Hulten (University of Maryland) and Andreas Kopp (OECD/ECMT Transport Research Centre).

The motivation to study the macro-economic effects of transport infrastructure investment was two-fold. First, fiscal and transport policy allocate major shares of national budgets to transport infrastructure investment, usually without the budget figures being an aggregate of project and programme plans from the bottom up. The Round Table discussions aimed at identifying the scope of macroeconomic methods to roughly indicate how many financial resources should be spent on transport infrastructure. If expenditure plans are based on a quantitative analysis at all, crude measures, like the share of transport infrastructure investment in GDP in comparable regions or time periods, are often used to develop an idea about the volume of required resources. The joint effort of the United Kingdom's Chancellor of the Exchequer and the Secretary of Transport to initiate the Eddington Transport Study (2006) may be seen as a strong signal of the public interest in developing sound estimates of transport infrastructure investment needs at the macro level.

The macroeconomic analysis of the productivity effects of transport infrastructure investment provides a summary measure of the outcomes without being able to indicate the channels through which the additional capacity of the transport sector helps to use the resources available to society more effectively. The Round Table discussed to what extent this is a weakness or an advantage of macro studies relative to other planning tools. On the one hand, all infrastructure investment project planning starts out from micro effects of the investment, on which the macro studies are uninformative. On the other hand, micro and meso planning methods lead to an incomplete picture of the overall impact, due to their methodological limitations.

Section 2 of this summary will review the mechanisms by which the income effects of transport infrastructure investment are translated into higher aggregate income, in order to outline the context in which macro studies have to be seen. Section 2 will set out the microeconomic, regional and growth channels through which transport infrastructure investment affects aggregate economic performance. Section 3 will report discussion on the empirics of the productivity effects. It will start out from an account of the early debate that centred on a number of studies which claimed to have identified very strong effects from public infrastructure investment in general and transport infrastructure investment in particular. The Round Table discussed the criticism of these studies and which methods have been developed to respond to this criticism.

The results of the background papers show that, in most cases, there is no basis for claiming drastic underinvestment in transport infrastructure. Such underinvestment would be reflected in computed rates of return which exceed the rate of return of private investment. The Round Table discussed the systematic differences of the results of the productivity studies in different regional contexts and for different phases of national economic development.

2. TRANSMISSION MECHANISMS OF TRANSPORT INFRASTRUCTURE PRODUCTIVITY EFFECTS

A first reason for a particular interest in the productivity effects of transport infrastructure derives from the partial public good character of transport infrastructure. A defining characterisation of infrastructure is the fact that, historically, or more generally at low levels of demand, infrastructure facilities can be used by several users without restricting each other's benefits. In other words, under these demand conditions, consumption of infrastructure services is "non-rivalrous", which is the constitutive element to define a "public good". With high levels of demand, infrastructure facilities start to get congested and additional use has a negative impact on the benefits for other users, and the costs of additional use can exceed its extra benefits. The appropriate supply of infrastructure services and the corresponding provision of infrastructure stock has to sum the benefits across the different users, adjusted for congestion costs (Hulten, 2007). The distribution of benefits and the assignment of costs to users present enormous challenges to transport policy. The Round Table confined itself to looking at the production side of the infrastructure effects.

2.1. Microeconomic effects

On the microeconomic level, investment in transport infrastructure might help to increase the productivity of individual firms. Depending on the market structure, the increased productivity leads to increased profits or, in markets with price competition, to lower goods prices and greater consumer benefits. The basis of the micro-economic effects is a reduction of the inbound and outbound transport costs.

The reduction in transport costs can be for two reasons: first, an expansion of the transport infrastructure network increases the density of links, reducing the distances of point-to-point trips. The more developed the network, the smaller will be the gains in reduced distances (Hulten, 1996).

Second, the addition of new roads and capacity expansion on existing roads may decrease congestion and reduce travel times. As congestion implies that fewer trips can be achieved with the same level as other inputs, and since fuel efficiency is lower in congested driving conditions, reduction in congestion also leads to reduced monetary transport costs.

A third reason may be due to a productivity effect at the level of the individual firm: if manufacturing technology implies the establishment of large production units with a high level of fixed costs, and if marginal production costs are constant or increase only slightly with the level of production, the costs per unit of output will decrease with an increase in production by the individual firm. The investment in transport infrastructure will increase the market area of a firm operating under these production decisions (Hotelling, 1929). The increase of the market area will, in turn, increase the production level of the individual firm and therefore reduce the costs per unit of output.

A further effect on the micro-level concerns the logistics sector (Lakshmanan and Anderson, 2002). The savings arising from reduced freight costs include non-transportation cost items, such as storage, interest and insurance costs. Manufacturing producers must decide on the size of shipments.

Procurement costs will be lower, the larger the order. Core transport costs will also decrease with the size of the shipments on a per unit basis. However, carrying costs, which include interest, insurance and storage costs, will be lower with small batches of goods, as the amounts of goods held in inventory are smaller. Investment in transport infrastructure and the consequent decrease in transport costs, will lead to a re-optimisation of inventory policies, orders for smaller shipments and a resultant higher overall productivity for the production sectors.

The hypothesis that more transport infrastructure - leading to lower transport costs and greater reliability of freight transport - reduces inventory levels has recently been confirmed by Shirley and Winston (2004). An earlier study of the relationship between travel time and logistics found that a 1 per cent reduction in average freight travel time will lead to a 0.5 per cent reduction in logistics costs. The survey, carried out for the medical and surgical instruments industry, also showed that the overall productivity effect was not a strong one: it would require a 20 per cent reduction in freight travel times to achieve savings of 1 per cent of total revenues for that industry (Hickling, Lewis and Brod, 1995).

2.2. Meso-economic effects

Strongly depending on the urbanisation pattern, which might entail hysteresis effects on the interregional development of national economies and the mobility of the work force, investment in transport infrastructure may have strong effects on regional specialisation and the trade gains that result from the reduction of trade costs between regions. The interregional trade gains, due to more or better transport infrastructure facilities, will be greater the less mobile the workforce and the greater the relative differences in resource endowments. The greater the gains from interregional trade, the greater will be the productivity effect.

With a highly mobile workforce and average production costs decreasing with company output, increased infrastructure investment and a resultant reduction of transport costs may have two effects. First, if the goods markets are differentiated markets and the consumers have a preference for the consumption of an ever-greater choice of goods, the infrastructure investment will lead to welfare effects by inducing the production of a greater variety of goods. Such a welfare effect would not be reflected in a productivity study. In many industries, production conditions prevail such that an increase in the spectrum of intermediate goods available leads to an increase in productivity. If intermediate goods are differentiated goods, a reduction of transport costs will induce interregional trade in differentiated intermediate goods, resulting in turn in a productivity increase in the industries which use these inputs (Krugman, 1991; Fujita *et al.,*1999).

If the workforce is highly mobile, a reduction of mobility costs due to an increase in transport infrastructure investment will strengthen agglomerative forces, in addition to the expansion of intra-industry trade. A positive productivity effect then results, not only from the availability of a larger set of specialised inputs but from an increase in the scale of output at the company level.

Investment in urban infrastructure, and a resultant improvement of urban transport, has the potential to improve the working of local labour markets (Arnott, 1998b; Gobillon *et al.*, 2005). The spatial mismatch hypothesis states that involuntary housing segregation and the malfunctioning of urban transport systems discourages the search for an acceptance of jobs at workplaces far from the workers' residences. This has been confirmed in studies for the US (Johnson, 2006) and for European countries (Patacchini and Zenou, 2005). The improvement of employer-employee relationships leads to productivity increases, due to the investment in urban transport infrastructure.

All these effects would ultimately be reflected in productivity changes of the national economy.

2.3. Macroeconomic growth rate effects

Transport infrastructure investment might also have positive effects on the long-run growth of the economy. The determinants of the long-run growth rates of national economies have been studied by the "endogenous" growth theory (Howitt and Aghion, 1998a).

One of the theoretical approaches to the explanation of long-run economic developments is based on the idea that education and the acquisition of organisational and technical knowledge relevant to production are not only a matter of individual education and training decisions but depend on the ease of interaction between those who pursue individual learning processes (Lucas, 1988).

The improvement of national transport systems might contribute to more intensive dealings in "human capital accumulation". To the extent that this is the case, transport infrastructure might not only lead to one-off income increases, due to a rise in productivity, but indirectly to long-run technical change and the dynamics of income growth.

3. THE EMPIRICS OF THE PRODUCTIVITY EFFECTS OF TRANSPORT INFRASTRUCTURE INVESTMENT

The first major empirical works analysing the link between infrastructure investment and macroeconomic productivity were the studies by Aschauer (1989 and 1990), who estimated aggregate production functions for the US that included public capital. The studies supported the claim of strong positive effects: the elasticity of output with respect to public capital ranged from 0.36 to 0.56. According to the calculations of Gramlich (1994), these values of the production elasticity of public capital would translate into annual gross returns of 100% or more, or a payback period of one year or less. Despite the fact that these results appeared to be implausible to many, these studies sparked an enormous literature. Already five years after the appearance of the behaviour studies, a reviewer noted "*…at least forty other econometric studies using different data and techniques*", giving the impression that "…*(a) bubble has happened and may even be beginning to burst* (Gramlich, 1994, p. 1177)."

In fact, the literature continues to expand, even today. It tries to clarify the lack of robustness of the econometric studies with respect to changes in how the production sector is depicted, the econometric techniques used, the geographical object and scope of the study, as well as the data used. While there is no unanimous agreement on the lessons learned from these debates, focal points of discussion have emerged:

- There are many advocates of more flexible functional forms of the estimation equations. More specifically, a flexible cost function approach is considered to be more appropriate than the production function approaches of the early studies.

- Estimation of the relationship between "first differences" in income or productivity, on the one hand, and transport infrastructure stock on the other, led to the estimation of a far weaker effect of public investments on aggregate income, which were sometimes statistically insignificant.

- The use of panel data, i.e. regional cross-sections for a number of time periods, often had similar results.

- There is agreement that the direct estimate of the link between infrastructure and output was subject to the problem of "reverse causality". Higher income levels might have been induced by transport infrastructure investment, but it is also possible that higher volumes of output had allowed for higher levels of investment. To simply assume that the statistical correlation between transport infrastructure and output is caused entirely by infrastructure entails the econometric problem of a simultaneous equation bias. It implies the overstatement of the returns on public infrastructure.

Two of the background papers base attempts to deal with these problems on panel data approaches, with an emphasis on isolating the externality effect of transport infrastructure. A third paper puts forward a co-integration approach, to avoid the pitfalls of the early econometric studies on the relationship between transport infrastructure capital stock and aggregate production levels.

A first approach to address the challenge of capturing the productivity effects of transport infrastructure investment, central to the background papers of Hulten (2007) and Kopp (2007), is the estimation of productivity as an empirical function of infrastructure stock. In Hulten's paper, productivity is estimated as the increase in gross output of manufacturing which cannot be explained by an expansion of capital, labour or intermediate goods used in production.

This measure of "total productivity" is estimated in two steps. First, the growth rate of gross output was estimated by subtracting the rates of growth of labour, private capital and intermediate goods inputs, each weighted by its share in total income, from the growth rate of real gross output. The resulting residual estimate of the growth rate of total productivity was then converted to levels. This yields an estimate of the total productivity variable for each year and region whose relationship to the infrastructure variable is estimated in a second step.

This estimation model has been applied to the manufacturing sector of the Indian economy, the US manufacturing sector and the aggregate economy of Spain (Mas *et al*., 1998). The comparison of the results illustrates the difference made by the development stage and geography to the application of the estimation of the productivity effects of transport infrastructure investment. The study of the Indian manufacturing sector showed a substantial and statistically significant productivity effect. The transport infrastructure productivity effect accounted for about one-quarter of the total productivity observed.

In contrast to the results for the Indian manufacturing sector, the parameter indicating the productivity effect of transport infrastructure was not statistically different from zero. Total industry productivity was almost identical for the sample regions. Given the cross-section nature of the study, there was therefore little opportunity for infrastructure to matter for productivity. The comparison seems to suggest that the effect of transport infrastructure on productivity, the strength of the effects mentioned in section two, depends on the extent of pre-existing networks. Due to the network character of most of the transport infrastructure, one can expect that aggregate transport infrastructure investment has a weaker effect in built-up environments with a high infrastructure density than in regions with significant infrastructure deficits.

The Round Table discussed the applicability of the macro-econometric approach to the jurisdictional level of the nation states. This was done against the backdrop of a background paper which used panel data methods for the analysis of ECMT infrastructure investment data for 13 Western European countries. In this paper, the problem that demand for infrastructure services is not directly observable is addressed by exploiting the fact that the demand for infrastructure services is a derived demand, and the fact that the demand is conditioned by the demand for vehicles. Aggregate production at the national level and the level of the country group as a whole is defined as a function of the private inputs of capital, labour and transport services. The transport services, in turn, depend on the inputs "vehicles" and "road infrastructure services". The growth of output that cannot be traced back to an increased use of private inputs, i.e. labour, private capital and vehicles, is then considered to be determined by the supply of infrastructure services and random influences or shocks.

The supply of infrastructure services is usually approximated by the real value of national road stocks. In the background paper of the Round Table, the infrastructure supply variable takes account of the interdependence of the national transport sectors and different degrees of congestion in the individual countries. The road use of foreign consumers is taken account of by the construction of a combined infrastructure stock index which adds up national road stock values by weighing them by the weights of the bilateral trade between pairs of partner countries. Moreover, the road service indicator tries to capture the development of congestion. While congestion is certainly not evenly spread over road networks, the changes in congestion are assumed to be approximated by the changes in the ratios of the number of national registered vehicles and the real values of capital stock.

Using a panel of road stock data, the endogeneity problem, or the problem of a possible influence from income increases on increase in investment volumes, is dealt with by decomposing the random influences at the national level into an aggregate shock and a country-specific one. The aggregate shock is that part of the income increase of the country group that cannot be explained by the overall changes in private inputs of the country group. The country specific shock is equal to the national deviation from the overall shock and therefore, by definition, orthogonal from the aggregate random influence.

The data showed a declining share of investment in GDP for the Western European economies. Despite the relative decline of road infrastructure investment, the road stocks expanded continuously. The estimation of the influence of road infrastructure investment on productivity development showed that there is a positive influence. The variance of road infrastructure investment explained about ten per cent of the productivity growth in the highly developed economies of Europe. The estimation does not suggest, however, that there is a pronounced underinvestment in road infrastructure. The imputed rate of return for road infrastructure investment is in a range that suggests rates of return which are slightly lower than the rates of return for private capital.

That the rates of return on road investment are on average somewhat lower for road investment than for private investment was confirmed by the background study of Canning and Bennathan (2007). In this paper, a different approach has been taken to evade the endogeneity or reverse causality problems of the macro studies on the productivity effects of transport infrastructure. The translog production functions used differ from the Cobb-Douglas production function of the other studies. This functional form allows to gain important insights into the relationship between the level of economic development of individual countries and the benefits of transport infrastructure invesmtent. In contrast to other studies which are based on the calculation of road infrastructure stock as an input to aggregate production, this background paper used physical figures of paved roads as an indicator of the supply of road transport services.

Canning (1999) had shown that the time series of input and output figures entering the estimation of a production function relationship are non-stationary. The estimation function of the production function therefore forms a “co-integrating” relationship. An investment function, depicting net increases of capital stock as the savings of an economy as a function of income, minus the depreciation of capital stock, also forms a co-integrating relationship. The use of modern time series methods does not therefore solve the reverse causality problem *per se*. To solve the problem, the assumption is made, based on empirical studies of aggregate investment behaviour, that the production function relationship holds across different countries, while the investment function differs between countries, even if they have comparable income levels.

The country-specific error term of the time series of the difference between actual investment behaviour in each country and the world average is then non-stationary, and eventually becomes very large. With these assumptions, the production function relationship can be estimated using a dynamic ordinary least squares estimator (Kao and Chiang, 1999).

The use of the trans-log production function allows for the identification of the interdependence between different inputs employed in the production process. The background paper showed that there was a strong complementarity between physical capital and the educational level of the population – the human capital. Moreover, there was a positive interaction between transport infrastructure and other forms of capital. This suggests that infrastructure investment is not sufficient by itself to induce large changes in output. Infrastructure can, however, be a very productive investment in economies with high levels of physical and human capital. Transport infrastructure investment then raises the profitability of the other types of investment.

Looking at different national income levels also, the study based on co-integration methods found that, on average, rates of return for road investments were at par with or lower than other forms of capital. The study does, however, suggest that the relationship between the rates of return for transport infrastructure and the level of development seem to have the shape of an inverted U. That is, in middle income countries an acute shortage of paved roads was found. The excess returns indicating this shortfall appear to follow from a period of sustained economic growth during which road capacity expansion has lagged behind the build-up of private physical capital and the expansion of the knowledge base of the economies.

CONCLUSION

The Round Table had three objectives. As an overall objective, the examination of planning methods was aimed at improving transport policymaking by facilitating comparisons between competing programmes and projects. Secondly, the Round Table aimed at assessing the state of the art of methods to measure the macroeconomic impact of transport infrastructure investment. Its third objective was to identify critical data needs, with the perspective of providing feedback to data collection activities, not least the collection of transport infrastructure investment data by the ECMT.

With respect to the first objective, the Round Table discussed the relative importance of macroeconomic studies for other planning instruments. Macroeconomic studies help to identify overall funding needs for infrastructure investments, enabling overall rates of return on investment expenditures to be derived. Beyond the direct effects, an increase in transport infrastructure might have negative or positive external effects, i.e. effects that are not felt by those who decide to consume infrastructure services. Environmental costs are among the most important external costs, and increases in competition between the producers of goods and services are the most significant external benefits. While many of the external costs of transport infrastructure are captured in much of standard cost-benefit analysis, this holds to a lesser extent for the external benefits. To the extent that external costs and benefits pertain to household consumption and not to firm production, they are not necessarily captured by macro studies, which focus on production and income effects only. There are, however, a number of "secondary" effects from transport infrastructure investment which go unnoticed in standard CBAs. Several effects of transport infrastructure investment, such as the impact on the efficiency of logistics systems, or the growth effects of induced changes in the pattern of urbanisation, are not or are incompletely captured by other planning instruments. Macroeconomic studies complement these other planning instruments, such as computable general equilibrium models that focus on the interregional or intersectoral effects of transport infrastructure investments, or cost-benefit analysis, which emphasizes the immediate effects on the local level, taking the secondary effects as being fixed.

The attention that macroeconomic studies might command in transport policy discussions was undermined by methodological flaws in early studies on the productivity of public expenditures that reported spectacular results. The Round Table reviewed progress made in solving the endogeneity problem, i.e. the econometric problem of determining causality: did public investment cause income growth or did higher income permit more investment? Solutions to this problem, in terms of time series and panel data analyses, were presented. The history of the empirical studies strongly suggests that the quantitative relationship between transport infrastructure investment and growth depends on the stage of development of the nation or region studied.

The Round Table participants viewed efforts for extension and harmonisation of the collection of transport infrastructure investment data as important. International and interregional comparisons of infrastructure policies suffer as a result of the different methods used to account for wear and tear and to analyse the effects of maintenance expenditures. These differences influence the computation of infrastructure capital stock figures significantly.

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TRANSPORT INFRASTRUCTURE INVESTMENT AND ECONOMIC PRODUCTIVITY

This Round Table is one of a series of research events to discuss tools to improve transport planning. It addressed the macroeconomic effects of transport infrastructure policies, and aimed at identifying analytical and empirical tools that could determine the overall volume of public expenditure for transport infrastructure investment. It also sought to identify state-of-the-art methods for assessing the macroeconomic impact of transport infrastructure investment.

Macroeconomic studies help to identify overall funding needs for infrastructure investment and allow overall rates of return on investment expenditure to be derived. Several effects of transport infrastructure investment, such as the impact on the efficiency of logistics systems, or the growth effects of induced changes in the pattern of urbanisation, are not (or not fully) captured by other planning instruments.

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