No. 2399

TELECOMMUNICATIONS INFRASTRUCTURE AND ECONOMIC DEVELOPMENT: A SIMULTANEOUS APPROACH

Lars-Hendrik Röller and Leonard Waverman

INDUSTRIAL ORGANIZATION

Centre for Economic Policy Research

ISSN 0265-8003

TELECOMMUNICATIONS INFRASTRUCTURE AND ECONOMIC DEVELOPMENT: A SIMULTANEOUS APPROACH

Lars-Hendrik Röller, WZB, Humboldt University, INSEAD and CEPR
Leonard Waverman, London Business School and University of Toronto

Discussion Paper No. 2399
March 2000

Centre for Economic Policy Research
90–98 Goswell Rd, London EC1V 7RR
Tel: (44 20) 7878 2900, Fax: (44 20) 7878 2999
Email: cepr@cepr.org, Website: http://www.cepr.org

CEPR Discussion Paper No. 2399

March 2000

ABSTRACT

Telecommunications Infrastructure And Economic Development: A Simultaneous Approach*

This Paper investigates how telecommunications infrastructure affects economic growth. This issue is important and has received considerable attention in the popular press concerning the creation of the 'information superhighway' and its potential impacts on the economy. We use evidence from 21 OECD countries over a 20-year period to examine the impacts that telecommunications developments may have had. We estimate a structural model, which endogenizes telecommunication investment by specifying a micro-model of supply and demand for telecommunication investments. The micro-model is then jointly estimated with the macro-growth equation. After controlling for country-specific fixed effects, we find evidence of a significant positive causal link, especially when a critical mass of telecommunications infrastructure is present. Interestingly, the critical mass appears to be at a level of telecommunications infrastructure that is near universal service.

JEL Classification: L96, O47, O57
Keywords: economic growth, telecommunications, economic development

Lars-Hendrik Röller
Wissenschaftszentrum Berlin
für Sozialforschung (WZB)
Reichpietschufer 50
D-10785 Berlin
GERMANY
Tel: (49 30) 2549 1440/1
Fax: (49 30) 2549 1442
Email: roeller@medea.wz-berlin.de

Leonard Waverman
London Business School
Sussex Place
Regent's Park
London NW1 4SA
UK
Tel: (44 171) 262 5050
Fax: (44 171) 402 0718
Email: lwaverman@london.edu

* We would like to thank two anonymous referees for their comments and suggestions. This research was produced as part of a CEPR research network on The Evolution of Market Structure in Network Industries, funded by the European Commission under the Training and Mobility of Researchers Program (contract #ERBFMRXCT980203). Röller gratefully acknowledges

financial support from the Deutsche Forschungsgemeinschaft (DFG) for this project. Financial assistance from the OECD and INSEAD during early stages of this research are also gratefully acknowledged. We specifically would like to thank Dimitri Ypsalanti and Paul Wijdicks of the OECD for providing us with much of the Telecommunication data and Andreas Stephan for excellent research assistance. All remaining errors are ours.

Submitted 21 February 2000

NON-TECHNICAL SUMMARY

This Paper investigates how important communications infrastructure is in explaining economic growth. This is an important issue in terms of explaining today's growth of some countries and even as to why some other countries are not growing as fast. In this Paper we find that communications infrastructure is responsible for a large proportion of economic growth throughout many OECD countries. In addition, we find that communication investments are subject to a *critical mass* phenomenon, which implies that much of the growth effects are only realized above a certain *level* of communication infrastructure. Since most non-OECD countries are below this critical level, we find that the growth impact of communication infrastructure investments may be disappointing.

It is a fact that communication infrastructure and economic growth are positively correlated. However, it is unclear which way the causality runs: does communication infrastructure cause higher economic growth, or does higher economic growth create more demand for communication infrastructure. Upon reflection, the answer must surely be a resounding yes to both questions. In other words, both simultaneously determine each other. Disentangling those two effects is the contribution of this Paper. Once this is accomplished, one can answer how much communication infrastructure effects growth, which is the topic of this Paper.

To do this we build an econometric model that takes the two-way causality of communication infrastructure and economic growth into account. One important characteristic of telecommunication technologies which the model allows for are the so-called *network externalities:* the more users are on the network, the more value the network has to each user. An implication of such network externalities is that the impact of telecommunication infrastructure on economic growth might be larger whenever a significant network size is achieved. This would imply that positive growth effects might be subject to having achieved a *critical mass* in a given country's communications infrastructure. The model is then estimated using evidence from 21 OECD countries over a 20-year period. The results are surprising.

The first finding is that investments in communication infrastructure have indeed very strong growth effects. For example, taking the case of Germany, we find that the impact of communications infrastructure on aggregate economic growth to be at a compounded annual effect of 1.2%. The impact for other OECD countries is equally impressive. Given that the OECD has grown at a compounded annual growth rate of some 1.96%, we find that about one-third of growth can be attributed to investments in communications (about 0.59%).

Another important finding is that for high levels of communications infrastructure the impact on economic growth is substantially larger. These results imply increasing returns to communication investments, which is consistent with the presence of network externalities. In particular, we find a ***critical mass*** phenomenon in infrastructure investments, which corresponds to a 40% penetration rate. Interestingly, a 40% penetration rate corresponds to what is coined *universal service* (with approx. 2–2.5 people per household), which means that growth effects are significantly higher for countries whose telecommunication infrastructure has approached universal service. In fact, our analysis implies that the impact is twice as large for those countries that have achieved *universal service*.

Not surprisingly, most OECD countries have nowadays developed their communication infrastructure so that growth effects are above the critical level. However, taking a sample of non-OECD countries we find that those countries are on average far below the critical level of 40%. In fact, the non-OECD countries have a mean penetration rate of only 4%. In this context, our analysis implies that ***marginal*** improvements in communication infrastructure in non-OECD countries will not generate the largest possible growth effects. Therefore, non-OECD countries might only realize significant growth effects, if a relatively large improvement in communications infrastructure is undertaken.

Another implication of the increasing returns to communication infrastructure is that this might explain divergence in economic performance. Those countries that are above the critical mass would have a higher growth rate, while others would grow much slower. Turning the argument, a convergence in communication infrastructure would offset divergence in economic performance.

I. Introduction

Explaining the sources of economic growth has ranked amongst the most significant issues that economists have examined. Romer's 1986 work began a set of theoretical and empirical analyses focusing on the endogeneity of the growth process as compared to Solow (1956) type neoclassical growth models which use an aggregate production function approach and exogenous technical changes. Numerous papers since then have attempted to disentangle those elements of a national economy, which create growth. Many of these papers have examined empirically whether economic growth is converging relative to the USA and what the forces are that may lead to convergence [see for example Barro and Sala-i-Martin (1992); Mankiw, Romer and Weil (1992); De Long and Summers (1991, 1993)]. Grossman and Helpman (1994) survey the recent literature on the determinants of economic growth and divide these works into three types: one set considers the accumulation of 'broad' capital, including human capital and different types of physical capital. A second set of papers utilizes spillovers or external economies, and finally a third set "cast industrial innovation as the engine of growth[2].

This paper investigates how telecommunications infrastructure affects economic growth. This issue is important and has received considerable attention in the popular press concerning the creation of the "information superhighway" and its potential impacts on the economy. We use evidence from 21 OECD countries over twenty years to examine the impacts that telecommunications developments may have had.

Telecommunications infrastructure investment can lead to economic growth in several ways. Most obviously, investing in telecommunications infrastructure does itself lead to growth because its products - cable, switches, etc. - lead to increases in the demand for the goods and services used in their production. In addition, the economic returns to telecommunications infrastructure investment are much greater than the returns just on the telecommunication investment itself. Where the state of the telephone system is rudimentary, communications between firms is limited. The transaction costs of ordering, gathering information, searching for services are high. As the telephone system improves, the costs of doing business fall, and output will increase for individual firms in individual sectors of the economy. "If the telephone does have an impact on a nation's economy, it will be through the improvement of the capabilities of managers to communicate with each other rapidly over increased distances" [Hardy (1980), p. 279]. Thus, telecommunications infrastructure investment and the derived services provide significant benefits; their presence allows productive units to produce better. The ability to communicate at will increases the ability of firms to engage in new productive activities[3]. Moreover, the importance of

---

[2]See also Quah (1993a, 1993b) who criticizes the entire set of empirical studies, which examine whether long term growth is converging for a number of countries.

[3]Leff (1984) argues that telecommunications lowers the fixed and variable costs of information acquisition. An expansion of the telecommunications network generates cost savings externalities to other markets. These

this effect increases as the information intensity of the production process increases. Thus, telecommunication investments might lead to benefits in other sectors. In suggesting that a country's telecommunications infrastructure has strong effects on economic growth, it has been argued that telecommunications investments have important spillovers and create externalities[4].

These arguments are in fact reminiscent of the public infrastructure debate of recent years. Public infrastructure refers to more general "traditional infrastructures" such as transportation, sewer systems, water, electricity etc. Early studies show (see for example Aschauer 1989) tremendous returns to public infrastructure investment[5]. As has been pointed out by a growing number of papers, these results are subject to a severe simultaneity bias and spurious correlation. Once these two problems have been econometrically controlled for, returns to infrastructure are much reduced. Clearly, the same problems of reverse causality and spurious correlation do potentially exist for telecommunication infrastructure.

Reverse causality implies that one needs to distinguish two effects: (i) the increase in economic growth which is attributable to increases in telecommunications infrastructure and services development and (ii) the increase in the demand for telecommunication services which is attributable to increases in economic growth (i.e. the income elasticity of telecommunication demand). The causation is clearly two-way and unless telecommunications infrastructure investment is modeled, the measured effect on telecommunications infrastructure on growth will be biased. In this paper we attempt to estimate a simultaneous model for telecommunication investments and economic growth. We specify a structural model, which endogenizes telecommunication investment by specifying a micro-model of supply and demand for telecommunication investments. The micro-model is then jointly estimated with the macro-production equation. In this way, we endogenize telecommunication investment controlling for the simultaneity discussed above. The second problem of spurious correlation may arise because regional specific infrastructure investments might be correlated with other growth promoting measures like R&D investments, investment in human capital, taxes, etc. In order to control for these correlations we will allow for country-specific fixed effects.

---

externalities involve lower costs of search, an increased ability to arbitrage, and increased information on the distribution of prices and services, all leading to lower transactions costs and more efficient operation of the telecommunications - using markets. Leff shows that firms can have more physically dispersed activities as telecommunications increases, and adds that X-inefficiency will be lower.

[4]It is a common conception that a modern communications system is essential to development. Studies by the United Nations Economic Commission for Europe, 1987, *The Telecommunication Industry: Growth and Structural Change;* by the International Telecommunications Union, Geneva, 1980, *Information, Telecommunications and Development;* and by R.J. Saunders, J.J. Warford and B. Wellenius, 1983, for the World Bank and the Brundland Commission, *Telecommunications and Economic Development* all attest to the need to have a modern efficient telecommunications sector as part of a nation's basic infrastructure and as a precursor to economic growth.

[5] Aschauer found that the return to infrastructure could be as high as 70% per year. This would imply that a $1 million invested over 30 years would result in a return of almost $5 trillion.

This paper concentrates on telecommunication infrastructure and its impact on economic output. Clearly, telecommunication infrastructure is intrinsically different from other types of infrastructure: information highways are different from transportation highways. One seemingly important characteristic of telecommunication technologies, which is not present in other types of infrastructure, are *network externalities:* the more users, the more value is derived by those users[6].

Given that these network externalities are not equally present in public infrastructure in general, one might expect that telecommunication infrastructure investments lead to higher growth effects than what has been found for the other types of infrastructures. Another implication of such network externalities is that the impact of telecommunication infrastructure on growth might not be linear, as the growth impact might be larger whenever a significant network size is achieved. This would imply that positive growth effects might be subject to having achieved a *critical mass* in a given countries communications infrastructure.

A relevant question to ask is then whether such nonlinearities in telecommunications do exist, and if so, what the critical mass is. Our empirical analysis below will attempt to answer such questions. In addition, it will be interesting to compare the public infrastructure results to those obtained for telecommunication infrastructure, especially given the importance for public policy in this area.

The paper is organized as follows. Section II briefly summarizes other related studies. The data and some simple correlations are discussed in Section III, Section IV specifies the econometric model with the results and interpretations in Section V. Section VI concludes.

II. Previous Related Studies

In order to address the impact of infrastructure investments on economic performance it is necessary to differentiate between various types of infrastructure. It is clear that the effect of telecommunication and information technology infrastructure on productivity and economic growth are potentially very different from other types of infrastructures. Given the importance for public policy in this area, it will be interesting to compare the public infrastructure results to those obtained for telecommunication infrastructure. In what follows we first discuss the available evidence for general infrastructure investment and then survey several studies that investigate the impact of telecommunication and information technology on economic performance.

---

[6] For instance, in transportation infrastructures no such (positive) network externality exist. In fact, there might be significant *negative* network externalities present in transportation due to congestion.

There are several studies that address the returns to public infrastructure investments. An influential study by Aschauer (1989), estimates a production function on time series data and finds a very large contribution of infrastructure to output. Aschauer suggested that *the stock of public infrastructure capital is indeed a significant determinant of total factor productivity growth*. He also found a striking relationship between the US productivity growth slowdown and the decline in the rate of growth of the public capital stock. These early estimates did have an bi-important impact on the public policy debate in the U.S., as infrastructure is often cited as an answer to the employment problem.

Unfortunately, these early empirical results appear to collapse once more sophisticated econometric procedures are used[7]. The Aschauer model constitutes a classical production function approach and can be criticized as not accounting for the appropriate causalities and correlations. For example the work by Holtz-Eakin (1993, 1994) and Garcia-Mila and McGuire (1992) demonstrates that the introduction of state-level fixed effects reduces the returns dramatically. Similar results are obtained by Kelejian and Robinson (1994) and Pereira and Frutos (1995) which use other econometric corrections. Using a cost function model, Nadiri and Mamuneas (1996) show that the returns to public infrastructure are comparable to those of private investments. Hulten and Schwab [(1984), see also their (1991) study] estimate a production function for the manufacturing sector on state-level data. They found that most of the cross-state variation in value-added growth was explained by variations in the rate of private and capital accumulation, leading them to suggest that *public infrastructure capital was irrelevant in explaining differences in productivity growth*. Balmaseda (1996) argues that the results found by Aschauer can be explained by simultaneity and aggregation biases. He shows that the large positive effects of public investment on growth can be reduced to zero, if causality and aggregation biases are accounted for. Hulten (1994) offers several explanations for this empirical finding of zero return on public infrastructure. More recently, Fernald (1999) investigates the relationship between infrastructure (as measured by roads) and productivity. He finds that road-building explains much of the productivity slowdown through a one-time unrepeatable productivity boost in the 1950's and 1960's.

Thus, the available evidence regarding the returns from public infrastructure appears to be that the original high returns do not hold up once a number of econometric measures are employed. We now turn to studies that focus directly on the effect of telecommunication infrastructures on economic output (for evidence on the positive growth effects of information technology investments see for example Lichtenberg (1995)).

Despite the obvious policy relevance, there are far fewer studies that concentrate on the specific role of telecommunication investment on economic growth and

---

[7] For a survey of the infrastructure literature see Munell (1992) and Grammlich (1994).

development. As in the research discussed above even fewer studies address the causality between telecommunication investments and growth. As expected, telecommunications infrastructure investments (or stocks) are correlated with economic growth (see also Röller and Waverman (1996)). This evidence, however, does not imply that there is causal relationship. As a consequence, policy suggestions for increased infrastructure investments based on this kind of evidence are without merit.

Hardy (1980) is one of the first studies we are aware of that investigates the potential impact of telecommunication on growth. Using data for over 15 developed and 45 developing nations from 1960 to 1973, Hardy regresses GDP per capita on lagged GDP per capita, lagged telephones per capita and the number of (lagged) radios. He concludes that telephones per capita does have a significant impact on GDP, whereas the spread of radio does not. However, when the regression is attempted for developed and developing economies separately, no significant effects occur. One explanation of this might be that there are important fixed effects. Neither fixed effects nor the problem of reverse causality was addressed by Hardy.

A more complete analysis of the telecommunication economic growth relationship is provided by Norton (1992). Using data from 47 countries for the period of 1957-1977, he estimates the effect of the average stock of telephones between 1957 and 1977 on the mean annual growth rate, controlling for the stock of telephones in 1957 and a number of macroeconomic variables. Norton finds that the telecommunication variable is positive and significant and concludes that the existence of telecommunications infrastructure reduces transactions costs since output rises "when the infrastructure is present." Since the beginning period telephone stock is significantly related to subsequent growth, Norton argues that the relationship "is clearly not due to reverse causality."[8] Norton also estimates the higher growth rates that Burma, Honduras, Sri Lanka and Bolivia would have had given the estimated coefficients and either Mexico's or Canada's telephone penetration rates. He finds extremely high impacts and states it is "implausible that Burma could or would have increased its investment- income rate by 55.5% and its growth rate by roughly the same amount simply by increasing its stock of telephones to a level comparable with Mexico's stock“. One explanation is that many growth effects are being captured by the telecommunication variables, including the growth of all the industries that telecommunications encourages. This is similar to the state-level fixed effects in the public infrastructure literature.

Finally, Greenstein and Spiller (1996) investigate the impact of telecommunication infrastructure (as measured by the amount of fiber-optic cable and ISDN lines) on

---

[8] Norton also estimates a simpler equation for 78 countries for the 1970-80 and 1960-80 periods. Only four right-hand-side variables are included - initial year income per capita, the standard deviation of real output, TELPOP and a dummy variable for centrally planned economies. Again the coefficient on TELPOP is positive and significant. "... consistent with the view that the stock of telecommunications lowers transaction costs and stimulates economic growth."

economic performance in the U.S. They find that infrastructure investment is responsible for a substantial fraction of the recent growth in consumer surplus and business revenue in local telecommunication services.

In sum, the above studies provide some evidence that telecommunications investment has positive effects on output. However, most of these studies use single equation models. In contrast to the above papers, we estimate a more structural model, which endogenizes telecommunication investment by specifying a micro-model of supply and demand for telecommunication investments. The micro-model is then jointly estimated with the macro-production equation. This is important because infrastructure investment affects many other sectors which makes a macro-level growth analysis necessary. Moreover, as has been demonstrated by the studies around the public infrastructure debate, fixed effects might be important. In light of the public infrastructure experience, it would be important for public policy to investigate whether the positive growth effects of telecommunication investments hold up. Our empirical analysis below will attempt to shed some light on this issue.

III. Data and Correlations

In this section we investigate simple correlations between telecommunications infrastructure investment and aggregate output. Similar to other studies, we utilize data for 21 OECD countries over a twenty-year period 1970 to 1990. The 21 OECD countries are listed in Table 2.

The data gathered consist of data on general economic variables and country characteristics - GDP, GDP deflator, capital stock, population, CPI, gross domestic investment, gross domestic savings, government deficit (or surplus), geographic area, population density, labor force, unemployment rate, percentage of school age children in primary, and in secondary school. Most of this data is from the Summers and Heston (1991) data base. Also gathered are data on a number of characteristics of telecommunication developments[9] - mainlines, residential mainlines, waiting list for mainlines, national and international trunk traffic, income from telephone services, national and international telex traffic, income from telex services, the number of data terminals, circuit ends connected to automatic switching exchanges, machines equipped for direct dialing and investment in telecommunication. It should be stated that much of these data (e.g. number of data terminals) are available for only a few years and for only a few countries, typically the OECD countries.

Using the individual country data provided on the investment in telecommunications, we construct the stock of telecommunications capital through

---

[9]We are indebted to Paul Wijdicks (OECD) who was able to acquire much of the data needed in our study.

the perpetual inventory method (PIM) setting the discount rate at 10%. Since we do not know the initial capital stock of telecommunications for the year 1970 we choose the initial stock such that the growth rates of mainlines is consistent with the growth rate in telecommunications capital for the period, 1970-1980[10]. Given the high discount factors usually attributed to telecommunications, the initial stock in 1970 has virtually no effect for the period 1980-1990. Table 1 defines the variables used in this study and presents some summary statistics.

Before turning to our model, we present some broad averages and examine simple correlations. Table 2 provides estimates for OECD countries of the average growth rates of real GDP per capita and main lines per 100 inhabitants, over the 1971–1990 period. The OECD average growth rate for GDP per capita was 1.96% and for mainlines 3.96%. Overall, real GDP is very strongly positively associated with the number of mainlines producing a correlation of .99.[11,12] Given this near total correlation between the number of mainlines and real GDP across the OECD, it is not surprising that regressions of GDP on mainlines finds substantial effects. Figure 1 shows the relationship for the OECD countries for one year, 1990, between mainlines per 100 inhabitants and real GDP per capita. A univariate linear cross-country regression of mainlines explains about 65% of the variance in GDP.

IV. An Econometric Model of Telecommunication Investment and Aggregate Output

In this section we employ a more structural model, a production function framework, which endogenizes telecommunications investment. In order to endogenize the telecommunications sector into the aggregate economy a micro-model of supply and demand is specified and jointly estimated with the macro-production equation. In this way, we endogenize telecommunications investment and control for the causal effects discussed above. In addition we will allow for fixed effects.

We relate national *aggregate* economic activity to the stock of capital *net* of telecommunications capital (K), the stock of human capital (HK), the stock of telecommunications infrastructure (TELECOM), and an exogenous time trend (t). The stock of telecommunications infrastructure is needed (rather than

---

10 More precisely, we have used a country specific regression explaining the growth rate in capital stock of telecom in terms of the growth rate in mainlines and other country-specific variables using the period of 1980-1990, which is where we have data. The estimated country-specific relationship is then applied to the period 1970-1980.

11 There is, however, less of a relationship between real GDP per capita and the number of mainlines (.42). Thus the correlation between GDP and mainlines may partially be an artifact of country size. Another explanation is the different degree of development across the OECD.

12 For more correlations on the same data set, as well as for non-OECD countries, see Röller and Waverman (1996).

telecommunications investment) since consumers demand telecommunications infrastructure not telecommunications investment per se. A measure of telecommunications demand is required in order to model both the demand for and the supply of telecommunications, itself.

Our aggregate production function equation is then as follows:

$$GDP_{it} = f\left(K_{it}, HK_{it}, TELECOM_{it}, t\right) \tag{1}$$

The coefficient on TELECOM in equation (1) estimates the one-way causal relationship flowing from the stock of telecommunications infrastructure to economic output. In order to differentiate between the two effects, i.e. the income elasticity of telecommunications infrastructure as well as the impact of TELECOM on GDP, we specify three other equations, which endogenize the demand and supply of telecommunications infrastructure and its investments.

Demand for Telecommunications Infrastructure:

$$TELECOM_{it} = h\left(GDP_{it} \;/\; POP_{it}, TELP_{it}\right) \tag{2}$$

Supply of Telecommunications Investment:

$$TTI_{it} = g\left(TELP_{it}, Z_{it}\right) \tag{3}$$

Telecommunications infrastructure production function:

$$TELECOM_{it} - TELECOM_{i,t-1} = z\left(TTI_{i,t}, R_{it}\right) \tag{4}$$

Equation (2) states that the demand for the stock of telecommunications infrastructure is a function of the price of telephone service (TELP) and per capita GDP. Equation (3) represents the supply of telecommunications infrastructure. Since the supply is in the form of investment we specify in (3) that telecommunications infrastructure investment (TTI) is a function of the telephone price and a number of exogenous variables effecting supply. Equation (4) provides for the relationship between investment in telecommunications infrastructure and the change in the stock of telecommunications infrastructure.

It is important to note that equations (2), (3), and (4) endogenize telecommunications infrastructure, since these three equations involve the demand for and supply of telecommunication infrastructure. The income elasticity of the demand for telecommunications services is provided for in equation (2).

Empirical Implementation:

The empirical implementation of the above model corresponding to (1)-(4) involves estimation of the following system of four equations.

$$\log(GDP_{it}) = a_{0i} + a_1 \log(K_{it}) + a_2 \log(TLF_{it}) + a_3 \log(PEN_{it}) + a_4 t + \varepsilon_{it}^1 \qquad (1')$$

$$\log(PEN_{it} + WL_{it}) = b_0 + b_1 \log(GDP_{it} / POP_{it}) + b_2 \log(TELP_{it}) + \varepsilon_{it}^2 \qquad (2')$$

$$\begin{aligned}\log(TTI_{it}) = c_0 + c_1 \log(GA_{it}) + c_2 GD_{it} + c_3 (1-USCAN)\cdot WL_{it} \\ + c_4 (1-USCAN)\log(TELP_{it}) + c_5 USCAN \cdot \log(TELP_{it}) + \varepsilon_{it}^3\end{aligned} \qquad (3')$$

$$\log(PEN_{it} / PEN_{i,t-1}) = d_0 + d_1 \log(TTI_{it}) + d_2 \log(GA_{it}) + \varepsilon_{it}^4 \qquad (4')$$

where GDP is the real gross domestic product, K is a measure of the real capital stock (from Summers and Heston 1991) net of telecommunication capital, TLF is the total labor force which is a proxy for the stock of human capital[13], t is a linear time trend, WL is the waiting list per capita, TELP is a measure of the telephone service price, TTI is real investment in telecommunications infrastructure, GD is the real government deficit, GA is the geographic area of the country, and USCAN is a dummy variable for the US and Canada which is set equal to one for the years of 1983 and beyond (see also Table 1 for variable definitions).

The variable PEN is defined as the penetration rate, given by the number of main lines per capita. We use the penetration rate as our measure to proxy the stock of telecommunications infrastructure. Since PEN is bounded between 0 and 1 we have transformed it into a (positive) unbounded variable by redefining it as $PEN = PEN/(a - PEN)$ in (1')-(4'). Given that the maximum penetration rate is .68 (see Table 1) we have chosen $a = .7$.

Note that (1') allows for the intercept to depend on the country. In other words, we control for country fixed effects, which has been of crucial importance for the estimated effect of public infrastructure discussed above. Equation (2') postulates that the *effective* demand for main lines per capita (the number of main lines per capita and the waiting list per capita) is a function of the price of telephone service and real per capita GDP. The waiting list per capita is added to the penetration rate since the number of mainlines in existence at any point in time can not be explained by the telephone price. There would be excess demand in some countries at that price. Unfortunately, there is no measure of the price of telephone service e.g. local service, domestic trunk or international calling available across this broad spectrum of countries. Instead, we use telephone revenue per mainline as a proxy.

---

13 To the extent that changes in the stock of human capital are not correlated with TLF, but correlated with PEN, the estimated in (1') will be inconsistent.

Modeling the supply side of telecommunications across various OECD countries is not straight forward, given that market structure and the role of governments vary a great deal. One possibility would be to specify a political economy model of infrastructure allocations.[14] In the present context this seems rather difficult to imagine, since the political economy is potentially very different across OECD countries. We therefore adopt a more reduced-form approach and assume in equations (3’) that investment in telecommunications infrastructure is generally determined by economic, political, and geographic variables. We operationalize these determinants through variables such as the geographic areas of a country, the government deficit, the waiting list per capita, and the price of telephone service as representative explanatory variables. Furthermore, the US and Canada are “dummied out” in terms of their supply-side response to prices and the waiting line. Given the private market driven telecommunications suppliers in the USA and Canada one would expect a different price elasticity of supply.

The model is estimated by nonlinear general methods of moments (GMM) for the OECD countries. Table 3 reports the parameter estimates for various specifications of model (1’)-(4’).

V. Results and Interpretation

The first estimation of model (1’)-(4’) does not control for fixed country effects, that is the intercept in (1’) is held constant. The results are reported in the first column of Table 3. The estimated parameters for the aggregate production equation indicate that labor and capital are positive and significantly associated with output. The elasticities for labor and capital are roughly .6 and .4 respectively.

Similarly, we find that the coefficient on the penetration rate in the aggregate production equation is positive and significant. This suggests that an increase in the penetration rate generates significant aggregate economic output. The magnitude of this effect can be calculated as follows. The point estimate of the elasticity equals .15, which implies that a one percent increase in the PEN variable increases economic growth by, on average, .15%. In order to get some better idea of the magnitude of this estimate it is instructive to work through an example. Germany has had an increase in the penetration rate from 15.76% in 1971 to 47.41% in 1990 (see Table 2), which amounts to a 5.97% compounded annual growth rate in the penetration rate over 20 years. Using the above estimate of .15 and the definition of PEN, we obtain an compounded annual growth effect of

---

14 For an empirical assessment of a political economy model of road infrastructure allocation, see Cadot, Röller and Stephan (1999).

3.4%[15]. In other words, the above estimate implies that Germany's investment into its telecom infrastructure boosted aggregate economic output by some 3.4% annually. Clearly this estimate is too high. While, for other countries, as well as the OECD average, results are somewhat lower (see Table 2), the results from this specification attribute an unbelievably large impact to telecommunications infrastructure. For example, given that the OECD has grown at a compounded annual growth rate of some 1.96%, while the above estimates imply that some 1.80% of growth are due to telecommunications (see Table 2 again), we obtain that 92% of OECD growth in GDP can be attributed to telecommunications (see Table 2).

These large effects are reminiscent of the early estimates of the impact of public infrastructure on economic growth discussed above. Even though there are reasons to believe that telecommunication infrastructure might be rather important for economic growth, an estimate this large is excessive. One explanation investigated below is that there is spurious correlation, suggesting a fixed effects model. Note that the coefficient on the time trend is negative and statistically significant. This implies that much of the positive growth effects can be explained by telecommunication infrastructure, human and physical capital. This is consistent with spurious correlation, since it appears that telecommunication picks up many other growth promoting factors.

Before turning to the other equations in column (1) let us emphasize that the focus of the empirical analysis is not on the estimation of demand and supply relationships in the telecommunications industry. Nevertheless, we want to control for them as much as possible. Moreover, it is comforting that the most of the remaining parameters are fairly robust across the different specifications below. For the demand equation, the effective demand is significantly inversely related to telephone price. The elasticity of demand is estimated at -1.13 and is significantly larger than one, implying an elastic demand. Regarding the income effect, we find the demand for telecommunications infrastructure is positively related to real GDP, with the income elasticity begin rather large and very significant. This finding is important for our purposes, since we argued above that there is two-way causality between telecom infrastructure and growth because their are likely to be income effects.

For the supply function we find that the geographic area is very significant in explaining telecommunications investments, i.e. larger countries do invest more in telecommunications. The level of government deficit is also significantly related to telecommunications investment across the OECD. One might have felt that

---

15 The compounded annual growth effect can be calculated as $\left[\left(\dfrac{\dfrac{PEN_{90}}{.7-PEN_{90}}-\dfrac{PEN_{70}}{.7-PEN_{70}}}{\dfrac{PEN_{70}}{.7-PEN_{70}}}\right)\cdot\hat{\alpha}_3+1\right]^{1/20}$, where $\hat{\alpha}_3$ is the estimate of .15.

telecommunications infrastructure investment would be positively affected by a government surplus in the OECD since the existence of a surplus would loosen the constraints on investment by the PTT. However, we find a negative relationship, indicating that PTT investment is associated with a deficit. One possible explanation for this is that telecommunications infrastructure investment is associated with other spending programs which jointly cause larger government deficits, i.e., the existence of a deficit is not an impediment to investment in telecommunications infrastructure. The waiting list for mainlines per capita is positively related to the supply of telecommunications infrastructure. This would suggests that those countries with a large waiting list invest less. However, the relationship is not statistically significant, which indicates that supply does not respond to excess demand, possibly due to technical constraints. Finally, the price of telecommunications services is inversely related to supply. This is surprising as it suggests that supply is larger, when prices are lower. This might be due to market structure being rather different across countries. As we will see below, this result will not survive, once we control for country-specific effects.

The last equation reported in column (1) in Table 3 is the production function relating investment to the penetration rate. As expected, its relationship is positive and significant. The elasticity is about .003, indicating that a one time 10% increase in investment would result in a .3% increase in the penetration rate. Again we find that the geographic area is a significant determinant of the penetration rate: the larger the country the more investment is needed to accomplish a given telecommunications infrastructure.

As discussed above in the context of public infrastructure, much of the impact on economic growth disappears once one controls for fixed effects. In order to test whether this is so for telecommunications infrastructure we next re-estimate our model, allowing for a country-specific intercept in equation (1’). The results are reported in column (2) of Table 3.

As can be seen, most of the parameter estimates and the statistical significance change only slightly. We therefore do not discuss all the estimates again. However, the impact of the penetration rate does change substantially by incorporating country-specific factors: the point estimate of the elasticity is now reduced to .045, implying growth effects that are much more reasonable than before. For example, taking the case of Germany again, we now estimate the impact of telecommunications infrastructure on aggregate economic growth to be at a compounded annual effect of 1.2%. Table 2 computes the annual compounded impact of telecommunications infrastructure for various OECD countries. It can be seen that the resulting impact on growth is much lower for the fixed effects model ($\alpha_3 = .045$). For the OECD average the impact of telecommunications is reduced to some .59% of GNP annually. Given that the OECD has grown at a compounded annual growth rate of some 1.96%, our fixed effect estimates imply that about one third of growth can be attributed to telecommunications.

Overall, it can be said that the fixed effects estimates are more reasonable, even though they are still rather large. In sum, these results are indeed very similar to the earlier literature on the returns of public infrastructure capital. It appears that less impact is found, once simultaneities and fixed effects are controlled for.

As we have noted above, there is one important characteristic in telecommunications: network externalities. A priori there is no reason to believe that the growth impact from telecommunications infrastructure should not be substantially larger than other types of infrastructure that are not subject to network externalities. An implication of network externalities is that the impact of telecommunications infrastructure on growth might not be linear, as the growth impact might be larger whenever a significant network size is achieved. This would imply that positive growth effects might be subject to having achieved a *critical mass* in a given countries communications infrastructure.

It is worth emphasizing that our specification of demand (2’) does not test for the existence of network externalities explicitly. The purpose of our study is to analyze the effect of telecommunication infrastructure on output, and to test whether there is a non-linearity in the output equation. One possible explanation of such non-linearities is the existence of network externalities, since telecom is a network commodity per excellence. However, we can not be explicit about the link between network externalities and output, since we do not measure network externalities directly. Consequently, our results concerning network externalities are only suggestive

In order to test whether such non-linearities in telecommunications do exist we re-specify (1’) as,

$$\begin{aligned}\log\left(GDP_{it}\right) &= a_{0i} + a_1 \log\left(K_{it}\right) + a_2 \log\left(TLF_{it}\right) \\ &+ \left(a_3 + \alpha_4 MEDIUM_{it} + \alpha_5 HIGH\right)\cdot PEN_{it} + a_6 t + \varepsilon_{it}^1\end{aligned} \qquad (1'')$$

where the dummy variables *MEDIUM* and *HIGH* correspond to a medium and high penetration rate as defined in Table 1. Roughly about half of our sample falls into the medium range (a penetration rate of telephones per population between 20% and 40%), whereas about 25% of the sample is classified as a high penetration rate (i.e. a penetration rate of over 40% which amounts to at least a phone in every household). The remaining 25% is classified into a low penetration rate (see Table 1 for a precise definition). Note that (1’’) again allows for fixed country effects. What we are interested in is the significance and relative magnitudes of $\left(a_3, \alpha_4 \alpha_5\right)$. For example, whenever a_3 is positive and significant, but a_4 and a_5 are negative then we have support for a "diminishing returns" hypothesis. If, however, the signs are reversed (i.e. $a_4 > 0$ and $a_5 > 0$), then we have evidence in support of a “critical mass“ theory, as the impact might be relatively insignificant for low penetration rates.

The estimation results of the system (1’’), (2’)-(4’) are given in column (3) of Table 3. As expected, most of the parameter estimates change only slightly compared to the previous model. Note that the price of telephone service now has the expected sign in the supply equation, yet it is not statistically significant. Most importantly the parameter estimate corresponding to the growth effects of telecommunication infrastructure for low penetration rates is 0.034, which is below the average effect discussed above. However, it is statistically significant (t-stat of 3.55), which implies that important growth effects from telecommunication infrastructure exist, even for countries with a relatively low penetration rate.

Interestingly, the growth effects achieved at relatively low levels of telecom infrastructure are not any larger for medium levels of infrastructure. The parameter estimate in Table 3 for medium penetration rates is small and not significant (t-stat of .96), indicating that for a large range there are no additional growth gains. However, for high levels of telecommunications infrastructure the impact on aggregate economic growth is substantially larger. In fact, the impact is twice as large for the high end as it is for the low and medium ends. We therefore find a constant effect until a penetration rate of 40%, with stronger growth effects for levels of infrastructure of above 40%. Since a 40% penetration rate approaches universal service (with roughly 2-2.5 people per household) we find that growth effects are significantly higher for countries whose telecommunication infrastructure has approached universal service.[16]

These results suggest that there might be increasing returns to telecommunication investments, which is consistent with the presence of network externalities. In particular, there might be a ***critical mass*** phenomenon in infrastructure investments. In the context of our analysis this critical mass would correspond to a 40% penetration rate, which includes most of the OECD countries today. However, taking a sample of non-OECD countries that we were able to obtain data for[17], we find that those countries are on average far below the critical level of 40%. In fact, the non-OECD countries have a mean penetration rate of only 4%. In this context,

---

[16] Another interesting issue might be to investigate the extent to which the simultaneity effects the results, in particular our estimate of the telecom impact on output. We have therefore re-estimated our model for the production function alone for the three alternative specifications in Table 3. The results are as follows. For the simpler specification (Models 1 and II), the point estimates are not much effected. However, for Model III, results are changed more substantially. For example, the high-penetration impact is increased from .074 to .091 by ignoring the simultaneity, which translates into nontrivial growth effects. In sum, it appears that the impact of simultaneity is not always equally significant, depending on the precise specification. In fact, given that the supply equation is in flows, whereas the production function is in stocks, there is no a priori reason to believe that the simultaneity is enormous. Nevertheless, for the most important specification for our purposes (Model III) it turns out that correcting for simultaneity is crucial.

[17] See Röller and Waverman (1996) for details. The list of non-OECD countries used in this study includes: Algeria, Argentina, Brazil, Chile, Costa Rica, Egypt, India, Indonesia, Korea, Malaysia, Mauritius, Mexico, Morocco, and Tunesia.

our results would imply that ***marginal*** improvements in the telecommunication infrastructure in non-OECD countries might not generate the largest possible aggregate growth effects. Therefore, non-OECD countries might only realize the growth effects through telecommunication investments like their OECD counterparts, if a significant improvement in the telecommunications infrastructure is achieved.

Another implication of the increasing returns to telecommunication infrastructure is that there may be a tendency for divergence in economic performance. Those countries that are above the critical mass would have a higher growth rate, while others would grow much slower. Turning the argument around would imply that a convergence in telecommunication infrastructure would offset divergence in economic performance.

VI. Conclusion

In this paper we have attempted to investigate the relationship between telecommunications infrastructure investments and economic performance. We estimate a model which endogenizes telecommunications investment by specifying a micro-model of supply and demand for telecommunications investments. In order to pick-up economy-wide effects, the micro-model is then jointly estimated with the macro-production equation. After accounting for simultaneity and country-specific fixed effects, we find a causal relationship between telecommunications infrastructure and aggregate output.

One important characteristic of IT technologies, which is not present in other types of infrastructures, are *network externalities*. An implication of network externalities is that the impact of telecommunications infrastructure on growth might not be linear. Allowing for three levels of telecommunication infrastructure we find that a *critical mass* exists, leading to increasing returns on growth at levels approaching universal service. This suggests that increases in telecommunications infrastructure could create higher growth effects in OECD countries than in the less-developed non-OECD countries.

An important question not addressed in this paper, and one that would naturally build on the existence of growth effects, is: what market structure might be suited best to appropriate these returns? This includes the specific role of government, if any, in providing an efficient infrastructure to foster growth and competitiveness. A related issue of considerable interest is the relationship between telecommunications infrastructure investments and job creation.

TABLE 1

Variable Description and Summary Statistics

Variable	Description
K[1]	Non-residential Capital Stock net of Telecommunications Capital in billion 1985 US$
TLF[1]	Total labor force in millions
PEN[2]	Penetration rate, main lines per capita
GDP[1]	GDP in billion 1985 US$
TELP[2]	Price of telephone service, in 1985 US$, measured as total real service revenue per mainline
GA[2]	Geographic area in thousand km^2
GD[3]	Government surplus (deficit) in billion 1985 US$
WL[2]	Waiting list for main lines per capita
TTI[2]	Investment in telecom infrastructure in billion 1985 US$
USCAN	Dummy variable for US and Canada
T	Time trend
LOW	Dummy variable set to one when PEN ≤ 20%
MEDIUM	Dummy variable set to one when 20 < PEN ≤ 40%
HIGH	Dummy variable set to one when PEN > 40%

Variable	Mean	Std Dev	Minimum	Maximum
K	413.91	680.40	10.98	3818.58
TLF	16.70	24.48	1.10	126.42
PEN	0.30	0.14	0.01	0.68
GDP	424.73	770.76	14.79	4524.97
TELP	536.66	158.42	244.62	1000.70
GA	1516.39	3088.25	30.513	9970.61
GD	-15.48	31.37	-214.57	8.93
WL	0.01	0.02	0	0.11
TTI	2.78	4.73	.07	25.83
USCAN	0.03	0.18	0	1
T	11	6.06	1	21
LOW	.27	.45	1	0
MEDIUM	.48	.50	1	0
HIGH	.25	.43	1	0

Sources: [1] Penn World Table 5.6 (Summers and Heston); [2] ITU Yearbook 1993; [3] IMF Yearbook 1992, World Bank 1993

Table 2: Compounded Annual Growth Rates (CAGR) of GDP, Mainlines, and Telecommunication Contribution to GDP for OECD Countries

	GDP per Capita (in US$)		CAGR (percent)	Mainline per 100 Inhabitants		CAGR (percent)	Contribution of Telecommunication CAGR 1971-90 (percent)	
	1971	1990	1971-90	1971	1990	1971-90	$\alpha_3 = .154$	$\alpha_3 = .045$
Australia	9513	12575	1.48	22.08	47.09	4.07	2.16	0.73
Austria	10230	16991	2.71	14.19	41.76	5.85	2.81	0.99
Belgium	10739	16013	2.13	14.83	39.26	5.26	2.31	0.78
Canada	10985	16472	2.16	31.38	57.46	3.24	2.73	0.95
Denmark	14708	20496	1.76	26.50	56.63	4.08	3.31	1.19
Finland	10860	20135	3.30	20.49	53.54	5.18	3.67	1.35
France	11359	17399	2.27	9.02	49.78	9.41	6.32	2.70
Germany	12850	19799	2.30	15.76	47.41	5.97	3.42	1.24
Greece	3750	4896	1.41	11.90	38.94	6.44	2.95	1.04
Iceland	11648	19724	2.81	28.99	51.37	3.06	1.86	0.62
Ireland	5764	9921	2.90	8.23	28.06	6.67	2.44	0.84
Italy	7834	14718	3.37	12.90	38.77	5.96	2.67	0.93
Japan	13383	22443	2.76	15.39	43.47	5.62	2.81	0.99
Luxembourg	11251	18783	2.73	25.36	48.17	3.43	1.85	0.61
The Netherlands	11685	16080	1.69	18.24	46.42	5.04	2.71	0.94
New Zealand	9409	10490	0.57	29.37	43.60	2.10	0.91	0.28
Norway	12767	19962	2.38	19.75	50.28	5.04	3.11	1.11
Portugal	2689	4378	2.60	6.68	24.13	6.99	2.42	0.83
Spain	5390	8713	2.56	9.52	32.35	6.65	2.65	0.92
Sweden	13676	20001	2.02	45.90	68.33	2.12	7.38	3.32
Switzerland	20998	27831	1.49	32.59	58.02	3.08	2.70	0.94
Turkey	723	1201	2.71	1.16	12.38	13.26	5.30	2.15
United Kingdom	8490	12625	2.11	16.51	44.25	5.32	2.70	0.94
United States	14719	18656	1.26	34.06	45.34	1.52	0.68	0.21
OECD Average	11297	16321	1.96	20.38	42.58	3.96	1.80	0.59

Notes: GDP per capita is expressed in US$ at 1987 exchange rates and prices; CAGR stands for Compounded Annual Growth Rate.
Source: OECD Communications Outlook 1993, ITU and own calculations

TABLE 3

Telecommunication and Growth: OECD Countries

(Nonlinear GMM Estimates of Equations (1') - (4'))[1]

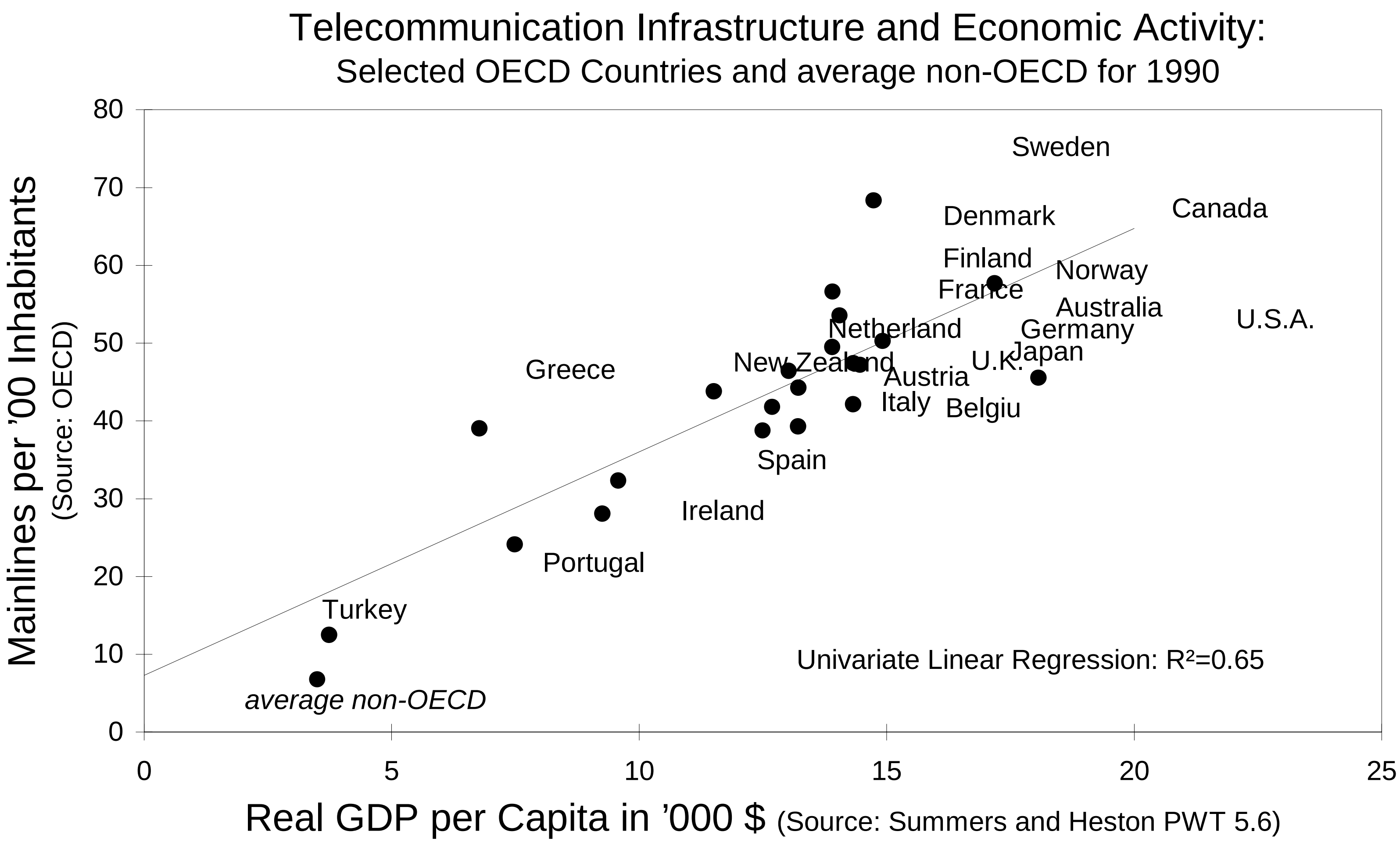
Variable	(1) Estimate	(1) T-Ratio	(2) Estimate	(2) T-Ratio	(3) Estimate	(3) T-Ratio
Growth						
Intercept	-8.367	-23.17	-	-	-	-
K	0.411	11.49	0.556	19.88	0.627	19.01
TLF	0.627	16.44	0.614	7.91	0.529	6.52
PEN	0.154	7.84	0.045	4.87	0.034	3.55
MEDIUM	-	-	-	-	0.010	0.96
HIGH	-	-	-	-	0.040	2.40
t	-0.009	-5.10	-0.005	-2.37	-0.007	-2.80
Demand						
Intercept	2.073	3.90	0.711	2.76	0.718	2.76
GDP/POP	2.382	39.63	2.081	60.42	2.076	59.22
TELP	-1.131	-14.55	-1.130	-36.71	-1.127	-36.05
Supply						
Intercept	-4.267	-1.79	2.257	2.74	2.345	2.80
GA	0.396	14.19	0.322	32.49	0.320	31.49
GD	-0.029	-18.97	-0.024	-32.49	-0.024	-31.70
WL	3.624	1.09	-6.727	-6.07	-6.739	-6.06
(1-USCAN)*TELP	-0.752	-2.60	-0.050	-0.51	-0.041	-0.41
USCAN*TELP	-0.535	-1.79	0.150	1.42	0.163	1.53
Production						
Intercept	0.133	7.85	0.141	17.76	0.141	17.60
TTI	0.003	2.29	0.002	1.80	0.002	1.58
GA	-0.005	-3.22	-0.005	-7.31	-0.005	-7.11

[1] Column (1) refers to standard (no fixed effects) model. Column (2) reports the fixed effects estimates, and Column (3) refers to the dummy variable model of the effects on growth. The mean squared error (MSE) of each equation is as follows:

	Growth	Demand	Supply	Production
Model (1):	0.025	0.171	0.906	0.002
Model (2)	0.003	0.154	0.794	0.002
Model (3)	0.003	0.154	0.794	0.002

Number of Observations: 396

Figure 1


Telecommunication Infrastructure and Economic Activity:
Selected OECD Countries and average non-OECD for 1990
Mainlines per '00 Inhabitants
(Source: OECD)
Real GDP per Capita in '000 $ (Source: Summers and Heston PWT 5.6)
0
10
20
30
40
50
60
70
80
0
5
10
15
20
25
Sweden
Canada
Denmark
Finland
Norway
France
Australia
U.S.A.
Netherland
Germany
Japan
New Zealand
U.K.
Greece
Austria
Italy
Belgiu
Spain
Ireland
Portugal
Turkey
Univariate Linear Regression: R²=0.65
average non-OECD

Bibliography

Aschauer, David Alan, 1989, "Is Public Expenditure Productive?" *Journal of Monetary Economics,* 23: 177-200.

Balmaseda, Manuel, 1996, "Simultaneity Bias and the rate of Return on Public Capital," CEMFI, working paper.

Barro, Robert J. and Xavier Sala-i-Martin, 1992, "Convergence," *Journal of Political Economy,* 100: 223-251.

Cadot, Olivier, Lars-Hendrik Röller and Andreas Stephan, 1999, “A Political Economy Model of Infrastructure Allocation: An Empirical Assessment,” CEPR discussion paper.

De Long, J. Bradford and Lawrence H. Summers, 1991, "Equipment Investments and Economic Growth," *Quarterly Journal of Economics*, 105: 445-502.

De Long, J. Bradford and Lawrence H. Summers, 1993, "How Strongly Do Developing Countries Benefit from Equipment Investment?" *Journal of Monetary Economics,* 32 (3): 395-415.

Fernald, John G., 1999, “Roads to Prosperity? Assessing the Link Between Public Capital and Productivity”, *American Economic Review*, vol. 89, No.3, pp. 619-638, June.

Garcia-Mila, T. and T. J. McGuire, 1992, "The Contribution of Publicly Provided Inputs to States' Economies," *Regional Science and Urban Economics,* 22: 229-241.

Grammlich, Edward M., 1994, “Infrastructure Investment: A Review essay”, *Journal of Economic Literature*, September, 32 (2), pp. 1176-96.

Greenstein, S. and Pablo T. Spiller, 1996, "Estimating the Welfare Effects of Digital Infrastructure," NBER working paper # W5770, September.

Grossman, Gene M. and Elhanan Helpman, 1994 "Endogenous Innovation in the Theory of Growth," *Journal of Economic Perspectives*, vol.8, No.1, pp. 23-44, Winter.

Hardy, A., 1980, "The Role of the Telephone in Economic Development," *Telecommunications Policy,* 4: 278-286.

Holtz-Eakin, Douglas, 1993, "State-specific estimates of state and local government capital," *Regional Science and Urban Economics,* 23: 185-209.

Holtz-Eakin, Douglas, 1994, "Public-Sector Capital and the Productivity Puzzle," *The Review of Economics and Statistics,* 76: 12-21.

Hulten, Charles R., 1994, "Optimal Growth with Infrastructure Capital: Implications for Empirical Modelling," University of Maryland, working paper.

Hulten, Charles R. and Robert M. Schwab, 1984, "Regional Productivity Growth in U.S. Manufacturing, 1951-1978," *American Economic Review,* 74: 152-162.

Hulten, Charles R. and Robert M. Schwab, 1991, "Is There Too Little Public Capital? Infrastructure and Economic Growth," Paper presented at the AEI Conference, February.

Kelejian, Harry H. and Dennis P. Robinson, 1994, "Infrastructure Productivity Estimation and its Underlying Econometric Specifications: A Sensitivity Analysis," University of Maryland, Working paper.

Leff, Nathaniel H., 1984, "Externalities, Information Costs, and Social Benefit-Cost Analysis for Economic Development: An Example from Telecommunications," *Economic Development and Cultural Change,* 32: 255-276.

Lichtenberg, Frank., 1995, "The Output Contributions of Computer Equipment and Personnel: A Firm Level Analysis," *Economics of Innovation and New Technology*, 201-207.

Mankiw, N.G., D. Romer, and D. N. Weil, 1992, "A Contribution to the Empirics of Economic Growth," *Quarterly Journal of Economics,* 107: 407-437.

Munnell, Alicia H., 1992, "Policy Watch: Infrastructure Investment and Economic Growth," *Journal of Economic Perspectives*, 6: 189-198.

Nadiri, M. Ishaq and Theofanis P. Mamuneas, 1996, "Contribution of Highway Capital to Industry and National Productivity Growth," working paper, March.

Norton, S. W., 1992, "Transaction Costs, Telecommunications, and the Microeconomics of Macroeconomic Growth," *Economic Development and Cultural Change,* 40: 175-196.

Pereira, Alfredo M. and Rafael Flores de Frutos, 1995, "Public Capital Accumulation and Private Sector Performance in the U.S.," unpublished working paper, August.

Quah, Danny, 1993a, "Empirical Cross-Section Dynamics in Economic Growth," *European Economic Review,* 37: 426-434.

Quah, Danny, 1993b, "Galton's Fallacy and Tests of the Convergence Hypothesis," *Scandinavian Journal of Economics,* 95: 427-443.

Röller, Lars-Hendrik and Len Waverman, 1996, "The Impact of Telecommunications Infrastructure on Economic Growth and Development: A first Look at the Data," in The Implications of Knowledge-Based Growth for Micro-Economic Policies, The University of Calgory Press.

Solow, Robert M., 1956, “A Contribution to the Theory of Economic Growth”, *Quarterly Journal of Economics*, 70:65-94.

Summers, R. and A. Heston, 1991, "The Penn World Table (Mark 5): An Expanded Set of International Comparisons, 1950-1988," *Quarterly Journal of Economics*, 106: 327-368.