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Estimating the contribution of infrastructure to national productivity in Europe

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Abstract

While there is much interest in understanding the contribution that investment in different types of infrastructure can make to the economic development of cities, regions and nations, such research is constrained by various methodological difficulties. Following the approach of Égert, Kozluk and Sutherland (2009), this paper seeks to identify whether countries might be over- or under-investing in infrastructure relative to other forms of capital investment, from the point of view of raising productivity. While subject to various limitations (and also highlighting the continuing data constraints in this area), such an analysis provides a consistent and comparable basis on which to assess whether countries might benefit from additional infrastructure investment or, conversely, whether they might in fact stand to gain from alternative forms of fixed capital formation.

The article analyses five types of infrastructure in the 27 Member States of the European Union (prior to 2013), Norway and Switzerland. We find some evidence of over-investment in electricity-generation capacity (investment in other forms of capital would likely yield higher productivity returns) and under-investment in roads, motorways and telephone infrastructure (there is potential for greater productivity growth from investing in these infrastructures). The evidence of a relationship between rail investment and productivity is less clear. While the results suggest that countries might stand to improve their national productivity by shifting the balance between infrastructure and other capital, higher productivity is not a country's only objective. Resilient infrastructure provision and/or upgrades with a view to pursuing other objectives such as climate-change mitigation may take precedence, necessitating at least some degree of 'non-optimal' investment.

Keywords: Infrastructure; Investment; Growth; Eurostat

Background

There is much interest by policy makers in understanding how investment in infrastructure can influence economic growth (Aschauer 1989, Esfahani and Ramírez 2003, Calderón and Servén 2004, Canning and Pedroni 2004, Romp and de Haan, 2005, Égert et al. 2009, Sahoo, et al. 2010). In the United Kingdom for example, HM Treasury commented recently that "Infrastructure forms the economic backbone of the UK. It is the fabric that defines us as a modern industrialised nation. The standard and resilience of infrastructure in the UK has a direct relationship to the growth and competitiveness of our economy, our quality of life and our ability to meet our climate change objectives and commitments" (HM Treasury, 2010).

Whilst it is clear that investment in infrastructure (often referred to as public capital) is essential to stimulate economic growth much remains unknown about the size of the contribution it can make and how this varies by type of infrastructure. As Romp and de Haan (2005) remarked in their extensive review article the issue had received 'only scant attention' at that time, although they did present findings from some fifty studies. They also cited Holz-Eakin and Lovely's earlier observation that a somewhat surprising feature of the existing literature was 'the noticeable absence of formal economic models of the productivity effects of infrastructure" (1996, p 106).

The relative paucity of research in this important area must partly reflect the conceptual and measurement

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problems associated with identifying the relationship between economic growth and infrastructure. The problems were extensively reviewed by Romp and de Haan (2005). They suggested that perhaps 'the most important concern is the direction of causality between public capital and aggregate output: while public capital may affect productivity and output, economic growth can also shape the demand and supply of public capital services, which is likely to cause an upward bias in the estimated returns to public capital if endogeneity is not addressed' (p 42). Romp and de Haan (2005) also drew attention to the problems of defining and measuring infrastructure, including the advantages of physical measures.

The econometric issues posed in relation to causality have recently been examined by Pradhan and Bagchi (2013) in their assessment of the effects of transportation infrastructure on economic growth in India. They find evidence using a Vector Error Correction Model for bidirectional causality between road transportation and economic growth and unidirectional causality from rail transportation to economic growth. They highlight the importance of investment in these infrastructures on the growth of the Indian economy.

Other research has also pointed to the problems of establishing what might be considered an *optimal* level of investment expenditure in new infrastructure and how this compares to the actual level. (Romp and de Haan, 2005, Hulten, 1996 and Canning and Pedroni 2004).

There is also an emerging body of research on the relationship between investment in broadband infrastructure and economic growth (Czernich et al., 2011, Koutroumpis, 2009, and Tranos, 2012).

This article investigates the contribution that investment in different types of infrastructure can make to the growth of productivity relative to other forms of gross fixed capital formation (investment) using, where possible, *physical* indicators of the infrastructure stock. In principle the approach outlined can also be used for cities and regions for which the appropriate data exists. To illustrate the basic approach we have used data from Eurostat for the 27 Member States of the European Union (prior to Croatia's accession in 2013), Norway and Switzerland. The analysis follows the time-series approach of Égert et al. (2009), applied in a European, rather than OECD context. The results highlight interesting patterns of European investment in infrastructure across countries relative to some notion of the 'optimal' level of investment vis-à-vis productivity growth. In particular, these results suggest over-investment in electricity and under-investment in roads, motorways and telephones. The application of this approach also reveals the challenges presented by inadequate data, particularly when only short time series exist.

The next section reviews the recent literature and highlights key research challenges.

Past analyses of the economic contribution of infrastructure

Our concern is to investigate the relationship between investment in infrastructure and the growth of productivity. The standard approach is to adopt a standard neoclassical production function augmented by infrastructure as a separate growth factor with additional explanatory variables to either decompose the effects of existing inputs on production (e.g., education rates to proxy human capital) or introduce other, perhaps more institutional, factors (e.g., proxies for political stability, internal market competitiveness or trade openness). The literature is substantial and Levine and Renelt (1992) state that 'over 50 variables have been found to be significantly correlated with growth in at least one regression' (page 942). This was the approach adopted by Égert et al. (2009) in their analysis.. They sought to identify the contribution of infrastructure investment to economic growth *relative* to 'conventional' investment. The key types of infrastructure investigated in their research were roads (with motorways identified separately), rail, electricity and telephones. The research used a theoretical framework based on Mankiw et al. (1992). The growth model was a Cobb-Douglas production function with decreasing returns to capital and the estimation work is based on a heterogeneous, fixed-effects cross-country panel framework that adopted an Engle and Granger (1987) two-step error-correction model approach. The data comprised subsets of OECD countries over the period 1960–2005, although the time span by individual country varied greatly (as few as 16 observations in some cases). The work highlighted the nature of the conceptual and empirical problems that arise.

The measurement of capital is a classic empirical (as well as theoretical) problem in economics, with the Perpetual Inventory Method (PIM) being the most popular estimation method. This method models the capital stock as the accumulation of past investments (added to an assumed initial stock), adjusted for assumed depreciation and/or scrappage. Such estimates are sensitive to the underlying assumptions and, while PIM-derived measures are commonplace, they are hardly ideal as proxies for the capital stock. Nevertheless, such data are often sectorally disaggregated, allowing for the identification of individual asset types. Aschauer (1989), for example, makes use of disaggregated economic data to separate capital into its respective components.

In the case of infrastructure, an alternative indicator is of course a physical indicator such as road length or electricity-generation capacity. Such assets are easilyidentified tangible assets, with the information readily available (although the availability of historical time series varies). However, even so, there is little in the way of information about infrastructure quality or its location. The quality of the infrastructure is clearly a factor in its potential contribution to the economy.

The main contribution of Égert et al. (2009) framework is to identify how the contribution of infrastructure investment compares to other forms of investment i.e., whether there might be evidence of over- or under-investment in infrastructure in some countries. In this context, over-investment suggests that a country is utilising its infrastructure inefficiently and resources may in fact be better spent on other forms of capital that yield greater returns in terms of economic growth. Investment in energy provision was found to have a positive and significant impact for most countries investigated. There were also positive effects for road investment in some countries but not all. Positive effects were also found for rail investment in most countries. There was a rather mixed position in relation to investment in telecommunications.

Canning and Pedroni (2004) assessed the long-run impact of infrastructure provision on per-capita income using the Penn World Tables that provide data for some 189 countries (Summers and Heston, 1991). They used data based on physical measures of infrastructure on an annual basis that included kilometres of paved road, electricity generating capacity and telephones per capita. Panel based estimations suggested that in the majority of cases infrastructure did make a contribution to long-term growth, albeit with considerable variations between countries. A key concern was to understand more about whether the amount of infrastructure provided was such that it was at a growth-maximising level and this was shown to be the case although again with a great deal of country variation. Their work helped to explain why there may appear contradictory results between models using cross-sectional rather than time-series approaches.

More recently, Sahoo et al. (2010) have assessed the effects of infrastructure investment on economic growth in China. Recognising that results have varied depending on whether measures of infrastructure are defined by investment expenditure or physical measures they developed a composite index of infrastructure using principal component analysis based on per-capita energy consumption, per-capita energy use, telephone lines per 1000 population, rail density per 1000 population, air-transport freight tons per kilometre and paved road as a proportion of total roads. Their research found that investment in infrastructure made a significant contribution to economic growth in China and they concluded that 'there is unidirectional causality from infrastructure development to output growth justifying China's high spending on infrastructure development since the early nineties' (Sahoo, et al., 2010).

In their analysis, Levine and Renelt (1992) find investment (a proxy for capital) to be 'robustly' correlated with economic growth in the sense that the associated coefficients do not change sign and they remain statistically significant when the set of conditioning variables change (indicators of political stability/country type etc.). Capital is an important contributor to economic growth.

It seems reasonable to suggest that without some basic level of infrastructure provision economic growth is likely to be constrained. However, beyond that point, whether infrastructure enables further growth or economic growth leads to increased infrastructure is difficult to disentangle in statistical terms. Many of the theoretical frameworks implicitly assume that the effect is in one direction: from investment through to economic growth because they include it as an input to production. This remains the case in the analysis that follows.

Methods

The approach in this article applies a simple exogenous-growth model that incorporates infrastructure as an additional factor of production. In this way, it is possible to identify the contribution of infrastructure investment to national productivity in Europe, on a consistent and comparable basis.

This section first sets out the theoretical model, before describing the estimation approach. It then goes on to discuss the interpretation of the results from such a model.

Theoretical model

The underlying exogenous-growth model is based on that of Mankiw et al. (1992), which explains output as a function of physical capital (K), human capital (H) and labour (L), with technology (A) as the residual.

$$Y_t = F(K_t, H_t, A_t, L_t)$$

From there, Mankiw et al. (1992) go on to derive their final human capital-augmented specification, to explain output per capita (i.e., productivity) as follows:

$$ln(\frac{Y_t}{L_t}) = ln(A_0) + gt + \frac{\alpha}{1-\alpha} ln(s_t^K) - \frac{\alpha}{1-\alpha} ln(n_t + g + \delta) + \frac{\beta}{1-\alpha} ln(h_t)$$

Where:
Y/L denotes GDP per capita
A_0 is the starting level of technology

g is the change in technology
s^K is the share of investment in output
n is the change in labour/population
δ is the rate of depreciation
h is human capital
t is a time index

Égert et al. (2009) derive a similar specification, but with a variable for infrastructure per capita (*inf*) in place of Mankiw et al. (1992) use of human capital:

$$ln(\frac{Y_t}{L_t}) = ln(A_0) + gt + \frac{\alpha}{1-\alpha}ln(s_t^K) - \frac{\alpha}{1-\alpha}ln(n_t + g + \delta) + \frac{\beta}{1-\alpha}ln(inf_t)$$

It is this model that forms the basis of the regression analysis in this article. The subsequent decisions regarding the estimation approach are dictated by the data.

Estimation approach

Owing to the varying data availability across countries over time, as well as the heterogeneity observed in the infrastructure relationships across countries, it was not possible to apply an explicit panel-estimation approach. Instead, the analysis comprises a set of single-equation time-series analyses, one for each country and infrastructure type.

The error-correction model adopted posits a long-run, cointegrating, equilibrium relationship between the variables expressed in levels, but the model also includes a dynamic part to the equation both to account for fluctuations in the short run but also for the adjustment process by which the system tends to 'correct' to the long-run relationship. We adopt the Engle-Granger 'two-step' approach to estimate these equations.

In the first step of the Engle-Granger procedure, we estimated the long-term equilibrium as a cointegrating relationship between GDP per capita and its explanatory variables. This is known as the 'levels' or 'long-run' equation:

$$y_t = \beta_0 + \beta_1 s_t^K + \beta_2 \Delta pop_t + \beta_3 time + \beta_4 inf_t$$

where:
y denotes (the natural logarithm of) GDP per capita
s^K is the share of investment in output (in natural logarithms)
Δpop is the first difference of (the natural logarithm) of population
time is a time trend (centred on 2005)
inf it is the natural logarithm of infrastructure per capita indicator
β_0, β_1, β_2, β_3 and β_4 are coefficients to be estimated, with the parameter on infrastructure, β_4, of primary interest

An important specification test of the above equation is of stationarity in the resulting residuals, indicating the presence of a cointegrating relationship between the dependent and independent variables. This test consists of a unit-root (Augmented Dickey-Fuller) test on the residuals, under the null hypothesis that there is a unit root in the residuals (i.e., no cointegration). The absence of cointegration would mean that the equation is mis-specified and risks yielding a spurious regression with apparently (but not actually) statistically-significant results.

The second step of the procedure estimated a dynamic equation, using one-period differences of the variables, to give the 'differences' or 'short-run' equation. This second equation included the lagged residuals from the long-run equation (which represented the deviations from the long-run equilibrium in each year), in order to model the adjustment mechanism by which deviations in per-capita output from that implied by the long-run relationships were corrected for (provided there was such a mechanism):

$$\Delta y_t = \beta_5 + \beta_6 \Delta s_t^K + \beta_7 \Delta\Delta pop_t + \beta_8 \Delta inf_t + \beta_9 ECM_{t-1} + \Sigma_{j=1}^{J} \beta_{10(t-j)} \Delta y_{t-j}$$

where:
y denotes (the natural logarithm of) GDP per capita
s^K is the share of investment in output (in natural logarithms)
Δpop is the first difference of (the natural logarithm) of population
inf it is the natural logarithm of infrastructure per capita indicator
ECM is the one-period lag on the difference between the actual level of GDP per capita and that implied by the long-run equilibrium relationship above, in natural logarithms
Δ is the difference operator
β_5, β_6, β_7, β_8, β_9 and $\beta_{10\ (t-j)}$ are coefficients to be estimated, with the parameter on the long-run deviation, β_9, of primary interest, to test for stability

The value of the lag length J was chosen to include as many lags of the dependent variable as were required to remove serial correlation from the short-run residuals (as judged by a Breusch-Godfrey test at the 5 % level). In the vast majority of cases, one lag was sufficient, with two lags included in some cases. A minority of equations required more lags than that and, typically, could not be estimated at any reasonable lag length that eliminated serial correlation. These results were ignored.

For the purposes of identifying the contribution of infrastructure to productivity growth, the parameters in the short-run equation were of relatively less interest as they did not account for the longer-term trends we were interested in. The coefficients from the long-run equation were the focus of the analysis. The short-run equation was of interest, principally, to indicate whether an individual country's per capita GDP growth did indeed revert to the long-run relationship identified. This was the case if the parameter on the error-correction term (*ECM*) was negative: other things being equal, above-equilibrium output is met by lower growth in the following period and, conversely, below-equilibrium output was met by higher growth in the following period. The equations are estimated by Ordinary Least Squares (OLS) in lieu of others that may have better finite-sample properties, but at the cost of reducing degrees of freedom; a concern owing to short time series in some cases.

In addition to the 'basic' regression of the form set out above, we also carried out a series of tests of robustness as discussed in Levine and Renelt (1992). These tests involved extensions to the basic specification with the addition of other explanatory variables, to assess the sensitivity of the results to alternative specifications. For comparability with the previous research we used the Eurostat equivalents of the following variables, which are among those thought to contribute to long-term productivity growth:

- *h*, a measure of human capital proxied by the proportion of adults who have completed an upper-secondary or tertiary education
- *tax*, the ratio of government tax receipts to GDP
- *trade*, trade openness, proxied by the ratio of the sum of imports and exports to GDP

The sensitivity of the econometric results of the contribution of infrastructure to productivity growth can be gauged by the stability of the coefficient values following the addition of the above variables (one at a time, rather than *en masse*). We interpreted long-run coefficients on infrastructure that differed little as the equation specification changed as providing evidence of robustness.

In summary, the key criteria we adopted as indicative of a meaningful relationship between infrastructure and a country's productivity were:

- A statistically-significant parameter estimate for infrastructure (β_4) in the long-run (first-step) equation
- The presence of a cointegrating relationship in the long-run equation, as evidence of a well-specified equation
- Evidence of stability (robustness) in the estimated relationship, as judged by similar coefficient values in the additional equations

Interpreting the equation results

The parameter of interest in the analysis was that on infrastructure (β_4). It is this parameter that provided an indication of the contribution (or otherwise) of a particular infrastructure to a country's productivity.

A key distinction between the original Mankiw et al. (1992) specification and the approach in this article is that the infrastructure investment in inf_t is double-counted in the total investment term s_t^K. This arises from the difference in measurement techniques: total investment is an economic volume while the infrastructure variable is in physical units. The conceptual problem was that corresponding physical data are not available for all other forms of capital, precluding a disaggregation such as that applied by Aschauer (1989).

The advantage of using a physical indicator of infrastructure is that it provides a more accurate measure of that fixed capital compared to an economic-volume measure (as might be estimated by PIM, for example). A physical measure also overcomes problems of combining/reconciling public and private investment measures (as private financing has become increasingly relevant in many countries over time).

Because disaggregation is not straightforward, we included both the total investment indicator and the infrastructure indicator in each regression. With the infrastructure indicator already included in economic terms in the investment indicator, the effect identified in such regressions should be interpreted as the contribution to productivity growth of infrastructure investment *relative* to investment in other forms of capital.

A positive sign on the estimated coefficient indicated that investment in infrastructure was more efficient relative to other forms of investment. In that sense, a country may well be under-investing in its infrastructure for the purposes of raising productivity. Conversely, where the sign on an infrastructure coefficient was negative, this was interpreted as evidence of relative inefficiency in infrastructure investment, as such investment has relatively less effect in improving productivity. It is possible that such countries are over-investing in such infrastructure, from the point of view of raising productivity.

The assessment of the efficiency of infrastructure investment was considered in the light of the objective of raising productivity. It should be recognised that countries may have other objectives for wanting to increase their levels of investment in infrastructure and thus they may opt for non-optimal levels of infrastructure to balance their efforts with these other objectives.

Data

The focus of this article is on the contribution of infrastructure investment, relative to investment in fixed capital more generally, to productivity growth in Europe. The dataset for this analysis, sourced entirely from Eurostat, covers the 27 EU Member States (prior to Croatia's accession in 2013), Norway and Switzerland. Table 1 summarises the variables used in the regressions (see Appendix Table A for further information).

The first four variables were included in all the regressions, along with one of the final five (the infrastructure variables, measured in physical units). These variables comprised the 'core' equation specification. The analysis considered each of the infrastructure types in isolation i.e., there was one set of country-level equations for electricity, another set for rail etc. The analysis did not go on to model the combined contribution of these infrastructure types to productivity growth.

As mentioned in the previous section, the analysis also considered the robustness of the estimates in the core equations by including additional control variables (numbered 5–7 in Table 1). These variables were included one at a time alongside the main five to test the sensitivity of the estimated contribution of infrastructure to productivity.

The span of the data varies by country and infrastructure type, with the largest available samples (for which there are data for GDP per capita, investment, population and an infrastructure variable) covering 1970–2011, such that the dataset does include some periods from the recent recession. In the interests of maximising the length of the series, these years were preserved in the dataset.

Where breaks were found within a series, the data points in the intervening years were linearly interpolated. The series that required most filling were the road-transport variables: motorways and roads. For these variables, there were a number of missing periods between data points, generally before 1990. While a number of series are filled extensively before 1980 (usually over 1971–1978), data limitations elsewhere actually meant that Denmark was the only country to make use of filled pre-1980 data (1975 onwards). Moreover, the results for this country did not yield a statistically-significant relationship from a well-specified cointegrating equation.

A complete listing of filled data points can be found in Appendix Table B. Other than the aforementioned data-filling procedure, the only additional processing required was to aggregate series such as electricity capacity (which had to be aggregated up from the individual plant types) and telephones (the sum of fixed lines and mobile subscriptions) and derive per-capita series and ratios to GDP.

The treatment of telephone lines attempted to account for the switch away from fixed lines towards mobile telephones, thus reflecting growth in connectivity (although, arguably, increases may represent the utilisation of the network, rather than increases in capacity). In this sense, of the five infrastructure types considered, telephones were perhaps the most at risk of actually signifying demand, rather than supply. The data on subscriptions was used in lieu of the availability of a more appropriate indicator (e.g., on the physical infrastructure, data for which tends to be proprietary, limiting its availability).

Table 1 Regression variables

		Description	Units
1	*Y/L*	GDP per capita	Millions of euros, 2005 chain-linked volumes per capita
2	s^K	Investment share	%
3	*N*	Population growth	%
4	*T*	Time trend	2005 = 0
5	*H*	Human capital	% of adults achieving an upper-secondary or tertiary education
6	*Tax*	Ratio of tax receipts to GDP	%
7	*Trade*	Ratio of (exports + imports) to GDP	%
8	*Elec*	Electricity capacity per capita	MW per capita
9	*Mway*	Motorway length per capita	km per capita
10	*Rail*	Length of rail tracks per capita	km per capita
11	*Road*	Non-motorway length per capita	km per capita
12	*Tel*	Number of fixed-line and mobile telephone subscriptions per capita	# lines/subscriptions per capita

Some of the time series in the dataset were relatively short, with as few as 15 observations in some cases. The availability of data before then depended on the data-transmission procedures of the relevant national statistics office. By running single-country time-series regressions, we sought to use as much of the data as possible in each equation.

Results and discussion

This section presents the results from the analysis. It begins with a brief description of the preliminary analysis before providing an overview of the regression results. The remainder of this section goes on to discuss the results by individual infrastructure type, with a focus on their relative contribution to national productivity and whether there might be any evidence of over- or under-investment with respect to the objective of raising productivity.

Preliminary analysis

The starting point was to consider the correlation matrix for the variables included in the long-run equation and examine the pair-wise relationships between the (natural logarithms of the) variables i.e., the variables as they appeared in the long-run equation (see Table A3 of the Appendix). With the exception of rail, the correlation between infrastructure and GDP was positive, with somewhat stronger positive correlation observed with electricity, motorway length and telephones. The correlation with road length was weaker while the correlation with rail was, negative, albeit weakly. Interestingly, the correlation between GDP per capita and the investment share was also mildly negative, as was the relationship between GDP per capita and education. The latter case may well be a result of a relatively short time series for education from the Eurostat database. The trade openness indicator exhibited a slightly negative correlation with GDP per capita while the relationship between the tax ratio and GDP per capita was quite strong.

Unit root tests tended to fail to reject the null hypothesis of a unit root in the levels series (see Tables A4 and A5 of the Appendix for the results for GDP per capita and the investment share). There were higher rates of rejection in the first differences of the series although these results (particularly for GDP per capita) did not show strong evidence that the differenced data were stationary in all countries in the dataset. In the case of the infrastructure variables, null-hypothesis rejection rates on the differenced data were relatively low for telephones, electricity and rail (fewer than ten countries) but somewhat higher for roads and motorways (15 and 11 countries, respectively).

This contrast with theory and other, previous empirical analyses may arise, at least in part, from the relatively short length of some of the time series and the low power of the Augmented Dickey-Fuller test. As an exploratory piece of analysis (and with further discussion of the merits of the approach in Section 6), the analysis in this article proceeded despite some series failing the unit-root tests, appealing to both theory and the aforementioned low power of the test.

Overview of regression results

Running the main regression model revealed that the mean long-run investment coefficients were in the range 0.27–0.34 and broadly similar in size to those reported by Égert et al. (2009) of 0.39–0.53. The coefficients on investment after including human capital were, in contrast to previous findings from the literature, higher than in the core regression, although many of the education indicators in our dataset have quite short time spans. Within the constraints of an analysis that draws on purely Eurostat data, this is a weakness of this particular equation. The investment coefficients were significant. The coefficients on population growth were not significant while the significance of the time trend varied across infrastructure types (it is significant for all but telephones) but was, in any case, small in size.

The following sections consider the coefficients on the per-capita infrastructure variables, as it is these which indicate the contribution of each infrastructure type to productivity in each country (over and above the contribution of gross fixed capital formation, regardless of the type of capital). As discussed in the methodology, the main criteria by which we judged a relationship to be 'meaningful' or 'valid' from a statistical point of view were the statistical significance of the estimated coefficient (to distinguish, statistically, from a coefficient of zero, indicating no difference, in productivity terms, between additional infrastructure and additional 'conventional' capital) and the presence of a cointegrating relationship between the variables in the long-run equation, guarding against the possibility of a so-called 'spurious' regression from a mis-specified relationship. The additional equations tested the robustness of these relationships in terms of their stability on adding further variables to the specification.

The tables on the following pages report the results from the econometric analysis. There is one table for each of the five infrastructure types considered (electricity, rail, road, motorways and telephones).

In each table, there are four columns, one for each of the equations estimated:

- 'Main': the core equation specification, as set out in the methodology section

- 'Human capital': the core equation, with an additional variable to proxy human capital; in this case, the proportion of adults who have completed either an upper-secondary or tertiary education
- 'Tax': the core equation, with an additional variable indicating the size of government tax receipts as a ratio to GDP (to proxy the size of the government sector)
- 'Trade': the core equation, with an additional variable to capture a country's openness to trade (calculated as the ratio of the sum of exports and imports to GDP)

Each column of each table reports:

- the mean coefficient on investment (investment as a share of output) from the long-run equation
- the mean coefficient on population growth from the long-run equation
- the mean coefficient on human capital (where applicable) from the long-run equation
- the mean coefficient on the time trend from the long-run equation
- the country-specific coefficients on the infrastructure variables (with indications as to whether the relationship is statistically significant, whether the long-run equation does in fact exhibit cointegration and the number of observations in the equation)
- the mean coefficient on the error-correction terms in the short-run equation
- the mean adjusted R^2 values of the long- and short-run equations
- the mean F-statistics of the long- and short-run equations

Where we conclude that the results from the analysis suggest evidence of over- or under-investment, this is noted alongside the name of the country.

Electricity

For electricity, the longest time series available contained 22 observations, and the equations that yielded significant results generally had around 20 observations or more. The time series for other countries was shorter (closer to 15 observations) which may be a contributing factor in the lack of significance in these results. There are a number of positive coefficients on the electricity-capacity per capita term, but few of them satisfy the requirements of both statistical significance and cointegration in the long-run equation. In fact, of the basic equation specifications, only the relationship for Denmark satisfied the two criteria, suggesting that Denmark may benefit from further investment in electricity infrastructure (and is thus under-investing from the point of view of raising productivity). Even so, this result was not robust to the inclusion of human capital or the tax variable (becoming statistically insignificant), though it was robust in the trade variant of the equation. No other relationships in the basic specification were found to be positive *and* valid, although there are instances of such relationships in the variants to test for robustness. The results are summarised in Table 2.

Evidence for over-investment in European electricity-generation capacity (as judged by negative coefficient values) was somewhat stronger, particularly in Austria, Spain, Italy and the Netherlands. The results for Spain, Italy and the Netherlands were robust in at least two of the three alternative specifications (the result for Austria was only robust in the tax variant).

Elsewhere, there were some valid negative relationships in the equations to test for robustness, but not the main equation. This included Belgium (tax and trade), Switzerland (trade only), France (trade only) Latvia (human capital only). Norway (human capital and tax) and Slovakia (human capital only). The evidence for over-investment in these countries was too weak to say that further investment is inefficient from a productivity point of view. However, in Germany, we found a valid *positive* relationship in the trade variant but a valid *negative* relationship in the tax variant: the results for this country were not robust.

On balance, we found mild evidence of over-investment in electricity capacity in Europe and little evidence of under-investment. From these results, there was no particular reason to think that diverting investment towards electricity generation would contribute relatively more to productivity growth than investment in other assets.

The objectives of a country are perhaps more complicated than the above analysis of this particular infrastructure from the point of view of productivity growth might suggest. This is because systemic electricity-supply under-provision has the potential to completely halt the economy in a way that a failure of, say, road infrastructure may not. In contrast to electricity infrastructure, a failure in road infrastructure would manifest itself as reduced service (congestion etc.). Hence, it will tend to be in a country's interest to invest in redundancy to ensure there is always adequate electricity provision. It is thus not necessarily the case that over-investment in capacity, as is indicated in some Member States in the analysis above, is inefficient in a broader context, because there may be relatively less interest in optimal investment for productivity growth and relatively more interest in investment to promote resilience within the electricity system. Limited evidence of under-investment may support this idea of there being the need for a basic requirement of electricity provision in these economies.

Table 2 Electricity

	Main	Human capital	Tax	Trade
Investment	0.3392	0.4152	0.3561	0.2686
Population growth	0.1109	0.5085	0.2856	0.9598
Human capital	-	0.2853	-	-
Trend	0.0284	0.0234	0.0271	0.0200
AT (Over-investing)	−0.4328*** ++ (22)	−0.6970** (17)	−0.4473** ++ (22)	−0.1706 ++ (22)
BE (Possibly over-investing)	−0.2648 + (17)	−0.6036** (17)	−0.3891** ++ (17)	−0.2461** + (17)
BG	0.0492* (17)	0.0240 +++ (12)	0.0535* (17)	0.0498* (17)
CH (Possibly over-investing)	0.0150 +++ (21)	0.1841 ++ (15)	0.2593 +++ (21)	−0.2627* +++ (21)
CY	0.1271 ++ (13)	0.1155 ++ (13)	0.0914 ++ (13)	0.0950 ++ (13)
CZ	0.1991 ++ (19)	0.0428 +++ (14)	−0.1192 ++ (17)	0.2123 ++ (19)
DE	−0.0189 ++ (21)	−0.0658 ++ (20)	−0.0910* ++ (21)	0.0979* +++ (21)
DK (Under-investing)	0.3547*** ++ (22)	−0.0671 +++ (20)	0.0063 ++ (17)	0.4363*** ++ (22)
EE	0.0034 ++ (19)	0.0060 (14)	0.0029 + (17)	0.0031 ++ (19)
EL	0.5576 (12)	0.0724 + (12)	0.7893* +++ (12)	0.5820 + (12)
ES (Over-investing)	−0.3771*** + (22)	−0.4035*** + (20)	−0.4412*** + (17)	−0.2692** (22)
FI	0.4834 (22)	0.2412 (17)	0.4703 (22)	−0.1029 (22)
FR (Possibly over-investing)	0.2874 (20)	0.1876 (19)	−0.0257 +++ (20)	−0.1218** ++ (20)
HU	−0.0667 (17)	−0.2047 (15)	−0.2207 (17)	−0.0564 (17)
IE	−0.8061* (17)	−0.2775 +++ (17)	−0.3691 ++ (17)	0.0724 (17)
IT (Over-investing)	−0.7730** +++ (22)	−0.4547** +++ (20)	−0.8499*** ++ (22)	−0.5951*** ++ (22)
LT	0.0099 (17)	0.0909 ++ (14)	0.0100 (17)	0.0251 (17)
LU	0.0203 (17)	0.1790 + (17)	−0.0995 (17)	0.1468 (17)
LV (Possibly over-investing)	−2.0138*** (17)	−1.2021*** +++ (14)	−1.8608*** (17)	−2.0194*** (17)
MT	2.2990 (6)	-	-	-
NL (Over-investing)	−0.1947*** +++ (22)	−0.1428 ++ (16)	−0.4024*** +++ (17)	−0.1131* + (22)
NO (Possibly over-investing)	−0.5140 (21)	−1.1028** ++ (15)	−1.3513*** +++ (16)	−0.3742 ++ (21)
PL	−0.0392 (17)	−0.0742 + (15)	−0.0054 +++ (17)	−0.1328 + (17)
PT	−0.1152 ++ (17)	−0.1250 ++ (17)	0.0267 (17)	−0.0996 ++ (17)
RO	−0.6245** (14)	−0.5610* (14)	−0.4950* (14)	−0.8396** (14)
SE	−0.4355 (22)	−0.1630 (17)	−0.5213 (19)	−0.4000 (22)
SI	0.2329 (20)	0.2686 + (16)	0.1134 + (20)	0.2233** +++ (20)
SK (Possibly over-investing)	−0.4774*** (17)	−0.3500** + (14)	−0.4485** (17)	−0.5094*** (17)
UK	−0.1372 ++ (22)	−0.2653 ++ (20)	−0.1280 ++ (22)	−0.1067 (22)
Error-correction term	−0.6520	−1.0092	−0.7981	−0.7784
Adjusted R^2 (long-run)	0.956	0.961	0.965	0.973
Adjusted R^2 (short-run)	0.637	0.682	0.687	0.756
F-statistic (long-run)	369.4	220.8	324.1	436.1
F-statistic (short-run)	12.5	13.1	13.1	18.5

For country-specific coefficients:
Number of observations in the long-run equation given in brackets
***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively
+++, ++ and + indicate equations where the null hypothesis of a unit root in the long-run residuals is rejected at the 1 %, 5 % and 10 % levels, respectively (i.e., a test for cointegration)

Moreover, because the power sector in Europe is a major emitter of greenhouse gases, one further goal of power-sector investment may be to reduce emissions, in line with legislated European targets for emissions reductions. In some countries, this would necessitate further investment, above that which might be considered optimal in productivity-growth terms. As an argument this appears reasonably intuitive: Member States must internalise (incur) the costs of emissions reduction in order to achieve their climate change mitigation targets. In this case, the Member States incur a cost in productivity-growth terms.

Rail

As with electricity the time series can be quite short for rail, with a number of equations having fewer than ten observations (in those cases, there is little point in reading much into the results). The results are summarised in Table 3.

There are two countries that show positive relationships between infrastructure and output. The results for Norway are significant and satisfy our specification test of cointegration in all three robustness variants, but not the main specification (this requirement is met at the 15 % level, only). We also find a positive effect for Sweden, in the main equation and in the tax and trade variants (the coefficient from the human capital-augmented equation was neither statistically significant nor indicative of a well-specified equation in terms of cointegration). The results suggest that productivity growth might be promoted through additional infrastructure investment.

There are also positive relationships for Ireland and Latvia, although the former does not show statistically-significant results in the human capital or tax equations. The latter yields four significant results but three fail the cointegration test, leading to possibly spurious regressions. This is perhaps supported by the fact that the results for those three equations exceed 2.0 in value while the coefficient in the one equation that also satisfies the cointegration requirement is closer to 1.2 in value.

The regression for France provides some evidence of a negative relationship, i.e., over-investment, in rail infrastructure. This result is robust to all but the trade variant of the specification. There is weaker evidence of over-investment for Austria, Italy and Poland, with the results only being significant and coming from a well-specified equation in the robustness variants. Overall, the relationship between rail investment and productivity growth appears quite weak but this is likely to be related to the relatively short time series available from Eurostat.

Road

For road, there were positive relationships and thus evidence of possible under-investment for roads (excluding motorways) in Belgium, Ireland, the Netherlands and Slovenia. The results are summarised in Table 4.

Of these, the results for Belgium and Ireland were significant and were part of cointegrating relationships in all four equations estimated. The remaining two were only robust to one variant: tax (for the Netherlands) and trade (Slovenia). We found weaker evidence for a positive relationship, albeit only in selected equation variants in Switzerland, Cyprus, the Czech Republic, Estonia, Spain, France, Norway and Portugal.

Our analysis suggests that there are a small number of countries that may be over-investing in roads, as indicated by a negative coefficient on the infrastructure indicator. The strongest evidence of this is Austria, with more limited evidence for Latvia. Interestingly, we find two equations, for Lithuania, that satisfy our two criteria for a potentially-valid relationship, but for which the signs differ. Inspection of the other two equations in this set (the main equation and the trade alternative) support the negative relationship more than the positive but it is difficult to draw much from this because we are unable to establish the presence of cointegration in the long-run equation.

Of the variables in our dataset, the series for roads and motorways were the ones subject to the most data filling. This was mostly to complete the series before 1980 although the limited availability of other data was a constraint in these regressions: only the equation for Denmark made use of the pre-1980 data, although after then there were some countries (notably the Netherlands), for which one or two data points at a time had to be filled. Overall, relatively few of the series actually made use of the filled data.

Motorways

As with roads, we found stronger evidence of positive relationships between motorways investment and productivity growth (suggestive of under-investment in these infrastructure assets). The results are summarised in Table 5. The evidence of positive relationships was particularly strong for Belgium, Cyprus, France and Italy. The results for Denmark were also positive, although the presence of cointegration could not always be established. Our results were not statistically significant for Austria, Spain and the Netherlands.

Evidence of a negative relationship and potential under-investment was quite weak, with only Norway exhibiting more than one valid relationship across the four variants. Highly-significant results were evident in the equations with the longest time series (42 years of data). In the case of Belgium, our results suggested that

Table 3 Rail

	Main	Human capital	Tax	Trade
Investment	0.2778	0.3799	0.33	0.1859
Population growth	−1.264	−0.817	−0.2645	0.5313
Human capital	-	0.2451	-	-
Trend	0.0286	0.0248	0.0266	0.0214
AT (Possibly over-investing)	−0.0371 ++ (19)	−0.1783* ++ (13)	−0.0446 ++ (19)	−0.0950* ++ (19)
BE	−0.4400 (15)	−0.4742 (15)	−0.7023** (15)	−0.1781 + (15)
BG	−0.1561 (17)	0.3305 ++ (12)	−0.1735 (17)	−0.1543 (17)
CH	1.9715 + (8)	-	0.9680** (7)	3.0551** (8)
CY	-	-	-	-
CZ	0.1838 + (18)	0.9754 (13)	−0.2515 ++ (16)	0.0968 + (18)
DE	0.0081 ++ (21)	0.0044 ++ (20)	0.0220 (21)	−0.0244 +++ (21)
DK	0.0706 + (7)	0.0564 (7)	-	−0.0009 (7)
EE	0.0550 ++ (19)	0.0837 + (14)	0.0887 + (17)	0.0621 +++ (19)
EL	0.4771 (9)	0.2664 (9)	0.2576 (9)	0.4051 (9)
ES	-	-	-	-
FI	0.1868 (23)	1.9804* (17)	−0.1481 (23)	−0.2717 (23)
FR (Over-investing)	−0.7484*** ++ (17)	−0.7686*** ++ (17)	−0.5812** ++ (17)	−0.1676 ++ (17)
HU	0.1132 (15)	0.0473 (13)	0.0064 (15)	0.4343 (15)
IE (Possibly under-investing)	2.9662*** (14)	1.4312 ++ (14)	1.3474 + (14)	1.3969** +++ (14)
IT (Possibly over-investing)	−0.5229 +++ (17)	−0.5323 +++ (17)	−0.7696* +++ (17)	−0.4848* +++ (17)
LT	−0.2960 (17)	−0.0382 ++ (14)	0.2244 + (17)	−0.2952 (17)
LU	-	-	-	-
LV (Possibly under-investing)	2.2416*** (17)	1.2130*** + (14)	2.0308*** (17)	2.2929*** (17)
MT	-	-	-	-
NL	−0.4506 ++ (12)	−3.3452 (8)	−0.9267 + (9)	0.3556 +++ (12)
NO (Under-investing)	0.7826** (22)	0.5875*** ++ (16)	0.6417*** ++ (17)	0.3892* +++ (22)
PL (Possibly over-investing)	0.0113 + (17)	−0.0532 (15)	−0.1785* +++ (17)	0.0568 + (17)
PT	−0.0632 ++ (17)	−0.0599 +++ (17)	−0.0506 + (17)	−0.0718 + (17)
RO	−2.0451 (16)	−0.0047 (15)	−0.3388 (16)	−2.3211 (16)
SE (Under-investing)	0.1100** ++ (21)	0.1280 (16)	0.1997** ++ (18)	0.1720*** ++ (21)
SI	1.5843 + (20)	1.2281 ++ (16)	0.9800 ++ (20)	0.8841 +++ (20)
SK	−2.7676 ++ (20)	−2.9167 +++ (14)	−2.1368 ++ (19)	−2.6066 ++ (20)
UK	−0.0851 (19)	−0.2981 + (19)	−0.1417 (19)	−0.3252 (19)
Error-correction term	−0.7258	−0.8426	−0.7985	−0.8053
Adjusted R^2 (long-run)	0.955	0.968	0.977	0.977
Adjusted R^2 (short-run)	0.654	0.723	0.722	0.739
F-statistic (long-run)	333.9	208.9	578.1	458.1
F-statistic (short-run)	12.1	13.5	14.7	19.8

For country-specific coefficients:
Number of observations in the long-run equation given in brackets
***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively
+++, ++ and + indicate equations where the null hypothesis of a unit root in the long-run residuals is rejected at the 1 %, 5 % and 10 % levels, respectively (i.e., a test for cointegration)

Table 4 Road

	Main	Human capital	Tax	Trade
Investment	0.3160	0.3922	0.3234	0.2288
Population growth	0.3269	−0.0013	−1.4200	0.6536
Human capital	-	0.4231	-	-
Trend	0.0266	0.0194	0.0258	0.0198
AT (Over-investing)	−0.5343*** + (19)	−0.5049** ++ (17)	−0.5268*** ++ (19)	−0.1069 + (19)
BE (Under-investing)	3.1721*** + (16)	3.0996*** ++ (16)	3.1329*** ++ (16)	2.0762*** ++ (16)
BG	−0.0732 (17)	−0.0322 ++ (12)	−0.0735 (17)	−0.0698 (17)
CH	0.6240 +++ (24)	0.4826 + (16)	0.6897* +++ (22)	−0.0807 +++ (24)
CY	0.7480* (17)	0.6332** +++ (13)	0.4452* (17)	0.4204 + (17)
CZ	0.6683 + (18)	3.4612*** + (13)	0.3250 ++ (16)	0.6061 + (18)
DE	-	-	-	-
DK	1.0698*** (34)	−0.9564 +++ (17)	−0.5914 + (14)	0.8371*** + (34)
EE	0.2351 ++ (19)	1.2578* ++ (14)	0.2701 + (17)	0.2248 ++ (19)
EL	-	-	-	-
ES (Under-investing)	0.4069*** (32)	0.8856*** (20)	1.0523*** +++ (17)	−0.0186 +++ (32)
FI	0.0241 (22)	−0.2659 + (17)	0.0446 (22)	−0.0474 (22)
FR (Under-investing)	1.0486*** (20)	0.8554*** + (19)	0.5674** ++ (20)	0.0738 (20)
HU	0.0474* (15)	0.0433 (13)	0.0381 (15)	0.0757** (15)
IE (Under-investing)	3.0781*** ++ (15)	2.1653*** ++ (15)	2.1079** +++ (15)	1.5051** ++ (15)
IT	0.0011 (21)	−0.0226 ++ (19)	−0.0015 (21)	−0.0200 (21)
LT	−0.6858** (17)	2.5951* +++ (14)	−0.5701** ++ (17)	−0.7075** (17)
LU	−0.1117 + (15)	−0.0396 + (15)	−0.2573** + (15)	−0.0180 + (15)
LV (Over-investing)	−1.7923* + (17)	−0.9026 ++ (14)	−0.9356 ++ (17)	−1.9140* ++ (17)
MT	0.8976 (10)	0.9448* (10)	1.0045 (10)	0.6373 (10)
NL (Under-investing)	0.4599*** ++ (33)	0.4268 ++ (16)	0.6915*** +++ (17)	0.1033 ++ (33)
NO	3.6333*** (24)	2.6966** (16)	2.3772* ++ (17)	2.4351*** + (24)
PL	−0.0091 (17)	−0.0493 ++ (15)	0.0094 +++ (17)	0.0121 (17)
PT (Under-investing)	0.0167 +++ (17)	0.0160 +++ (17)	0.0427** ++ (17)	0.0518** ++ (17)
RO	0.1555 (16)	−0.2571 (15)	0.0044 (16)	0.2410 (16)
SE	0.0044 ++ (40)	−1.2814 (15)	−1.0097 (17)	−0.0431 ++ (40)
SI (Under-investing)	3.0219*** ++ (22)	0.1755 + (16)	0.7040 + (20)	0.7926** +++ (22)
SK	0.0410 +++ (20)	−0.0404 +++ (14)	0.0666* +++ (19)	0.0420 +++ (20)
UK	0.2532 +++ (37)	−2.0241*** + (20)	−0.4538 + (22)	0.2381 ++ (37)
Error-correction term	−0.6143	−1.0933	−0.8539	−0.6569
Adjusted R^2 (long-run)	0.956	0.960	0.955	0.968
Adjusted R^2 (short-run)	0.575	0.721	0.671	0.722
F-statistic (long-run)	466.6	236.7	346.6	582.8
F-statistic (short-run)	9.9	14.1	12.5	18.7

For country-specific coefficients:
Number of observations in the long-run equation given in brackets
***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively
+++, ++ and + indicate equations where the null hypothesis of a unit root in the long-run residuals is rejected at the 1 %, 5 % and 10 % levels, respectively (i.e., a test for cointegration)

Table 5 Motorways

	Main	Human capital	Tax	Trade
Investment	0.3179	0.4000	0.3442	0.2383
Population growth	−1.5365	0.2732	−2.2123	−0.7293
Human capital	-	0.2784	-	-
Trend	0.0268	0.0199	0.0257	0.0197
AT	0.1022 (23)	1.1235 ++ (17)	0.1230 (23)	0.3309 ++ (23)
BE (Under-investing)	1.7039*** ++ (16)	1.7725*** +++ (16)	1.4843*** +++ (16)	0.9934*** +++ (16)
BG	0.4821** (17)	0.4588* ++ (12)	0.4803** (17)	0.5260** (17)
CH	−0.0501 +++ (24)	−0.0454 (16)	−0.0934** +++ (22)	−0.0455 +++ (24)
CY (Under-investing)	0.2331*** +++ (17)	0.1675*** +++ (13)	0.1588*** + (17)	0.1943*** +++ (17)
CZ	−0.1631 ++ (18)	−0.0684 ++ (13)	0.2138 ++ (16)	−0.1636 ++ (18)
DE	0.2269 ++ (21)	0.0839 + (20)	−0.4857 (21)	0.1879 +++ (21)
DK (Possibly under-investing)	0.3339*** (34)	0.3682*** +++ (17)	0.3977** (14)	0.2815*** ++ (34)
EE	0.0293 ++ (19)	0.1039 + (14)	−0.0824 (17)	−0.0154 ++ (19)
EL	-	-	-	-
ES	0.0813*** (32)	0.4340** (20)	0.8150** (17)	0.0257* +++ (32)
FI	−0.0902* (37)	0.4692 ++ (17)	−0.1010 (36)	−0.3092*** (37)
FR (Under-investing)	0.4195*** ++ (20)	0.4196*** ++ (19)	0.3342*** +++ (20)	0.1622** (20)
HU	−0.1845** (15)	−0.1728 (13)	−0.1529 (15)	−0.2009** (15)
IE	−0.4413*** (15)	−0.1998 +++ (15)	−0.2787*** +++ (15)	−0.1227 (15)
IT (Under-investing)	2.1896*** +++ (21)	1.9721*** +++ (19)	2.1933*** +++ (21)	1.5180*** ++ (21)
LT	−0.0920 (17)	0.1139 +++ (14)	−0.1220 ++ (17)	−0.0910 (17)
LU	−0.2165 (15)	−0.1421 (15)	−0.6055*** (15)	−0.0979 + (15)
LV	-	-	-	-
MT	-	-	-	-
NL	−0.1691 (35)	−0.0791 ++ (14)	−0.0259 (15)	0.0894 +++ (35)
NO (Over-investing)	−0.1641*** ++ (42)	−0.0948 (16)	−0.1246* ++ (17)	−0.1596*** +++ (42)
PL	0.0382 + (17)	0.0233 + (15)	0.0283 +++ (17)	0.0461* (17)
PT	0.0576 +++ (17)	0.0659 ++ (17)	0.0337 + (17)	0.0468 ++ (17)
RO	0.1545** (16)	0.0964* (15)	0.0871 (16)	0.1593* (16)
SE	0.0583 ++ (40)	0.0186 (15)	−0.2783 (17)	0.0575 ++ (40)
SI	0.0081 + (22)	−0.2068* + (16)	−0.1706 ++ (20)	−0.0239 ++ (22)
SK	−0.1688 +++ (20)	0.2350 +++ (14)	−0.1612 ++ (19)	−0.1597 +++ (20)
UK	0.0794 ++ (37)	−1.1118 ++ (20)	−0.1116 + (22)	0.1367** ++ (37)
Error-correction term	−0.5672	−0.9821	−0.9200	−0.6773
Adjusted R^2 (long-run)	0.975	0.967	0.977	0.983
Adjusted R^2 (short-run)	0.623	0.695	0.709	0.756
F-statistic (long-run)	620.6	234.8	406.4	814.5
F-statistic (short-run)	10.3	12.1	14.0	19.8

For country-specific coefficients:
Number of observations in the long-run equation given in brackets
***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively
+++, ++ and + indicate equations where the null hypothesis of a unit root in the long-run residuals is rejected at the 1 %, 5 % and 10 % levels, respectively (i.e., a test for cointegration)

Table 6 Telephones

	Main	Human capital	Tax	Trade
Investment	0.2733	0.3411	0.2615	0.1939
Population growth	−0.5522	−0.8906	0.1483	−0.8947
Human capital	-	0.1377	-	-
Trend	0.016	0.0176	0.0166	0.0129
AT (Under-investing)	0.0625*** +++ (30)	0.1243*** ++ (15)	0.0703*** +++ (30)	0.0406** +++ (30)
BE (Under-investing)	0.1941*** ++ (15)	0.1899*** ++ (15)	0.1700** ++ (15)	0.0278 ++ (15)
BG	0.3333*** (15)	0.1581 + (10)	0.3355*** (15)	0.3344*** (15)
CH (Under-investing)	0.0607** +++ (30)	0.0570** ++ (14)	0.0675** ++ (20)	−0.0024 +++ (30)
CY	0.2161* ++ (15)	0.1616 +++ (11)	0.0770 + (15)	0.1061 +++ (15)
CZ	−0.0172 (17)	0.0748 ++ (12)	−0.0544 + (15)	−0.0203 (17)
DE (Under-investing)	0.0631** +++ (19)	0.0585** +++ (18)	0.0640*** +++ (19)	0.0347 +++ (19)
DK	0.0260 (30)	0.0794 ++ (18)	0.0678* ++ (15)	0.0806* (30)
EE	0.0153* (17)	0.1570 (12)	−0.0196 (15)	0.0194** ++ (17)
EL	−0.0696 (10)	0.1138 (10)	0.0110 (10)	−0.0981 (10)
ES (Under-investing)	0.1211*** (30)	0.0911*** ++ (18)	0.1009*** +++ (15)	0.0599*** +++ (30)
FI	−0.0688 + (30)	−0.3648* + (15)	−0.1013 ++ (30)	−0.1912*** + (30)
FR	0.1646*** (18)	0.1333** (17)	0.0747** +++ (18)	−0.0007 ++ (18)
HU	0.1931* (15)	0.2255* (13)	0.1569 (15)	0.2048* (15)
IE (Under-investing)	0.3916*** ++ (15)	0.3870*** ++ (15)	0.3664*** +++ (15)	0.4643*** ++ (15)
IT	0.1643*** (20)	0.1164** + (18)	0.1687*** (20)	0.1068*** (20)
LT	0.1889** + (15)	0.0684 +++ (12)	0.0423 (15)	0.1794* ++ (15)
LU	0.1741** + (15)	0.2179* + (15)	0.2050*** (15)	0.0743 + (15)
LV	0.2664 ++ (15)	−0.2863 +++ (12)	0.4673** +++ (15)	0.3615* ++ (15)
MT	−0.2222* + (10)	−0.2293* + (10)	−0.2523 + (10)	−0.1609 (10)
NL (Under-investing)	0.0833*** +++ (30)	0.0608** + (14)	0.0859*** ++ (15)	−0.0340 +++ (30)
NO (Under-investing)	0.2177*** +++ (30)	0.1399** +++ (14)	0.1428*** +++ (15)	0.1916*** +++ (30)
PL	−0.0093 ++ (15)	0.0076 +++ (13)	0.0041 +++ (15)	−0.0295* ++ (15)
PT	0.0711 ++ (15)	0.0763 ++ (15)	0.1001* ++ (15)	0.1062** ++ (15)
RO	0.1691 (14)	0.0505 + (13)	0.0911 (14)	0.5165** (14)
SE	0.2097*** + (30)	0.1695 (15)	0.2414* (17)	0.2128*** + (30)
SI	−0.0376*** + (20)	−0.0288 + (14)	−0.0062 ++ (18)	0.0056 ++ (20)
SK	0.0004 ++ (18)	−0.0593 +++ (12)	−0.0061 ++ (17)	−0.0000 ++ (18)
UK	0.0080 + (30)	0.2146** (18)	0.1363** (20)	−0.0232 + (30)
Error-correction term	−0.7577	−1.3025	−1.1068	−0.9670
Adjusted R^2 (long-run)	0.966	0.964	0.966	0.972
Adjusted R^2 (short-run)	0.665	0.767	0.723	0.755
F-statistic (long-run)	460.9	200.7	339.5	629.2
F-statistic (short-run)	13.3	17.6	14.9	22.7

For country-specific coefficients:
Number of observations in the long-run equation given in brackets
***, ** and * indicate significance at the 1 %, 5 % and 10 % levels, respectively
+++, ++ and + indicate equations where the null hypothesis of a unit root in the long-run residuals is rejected at the 1 %, 5 % and 10 % levels, respectively (i.e., a test for cointegration)

investment in both roads and motorways would be beneficial for productivity growth. One could draw a similar, albeit weaker, conclusion for France, although the contribution of road was not quite as strong.

Telephones

For telephones (which we define as fixed-line and mobile subscriptions), we found a relatively large number of estimated relationships to be positive in nature for Austria, Belgium, Switzerland, Germany, Spain and Ireland, the Netherlands and Norway. Table 6 shows the results.

Somewhat weaker evidence of a positive relationship was apparent in Lithuania, Luxembourg, Latvia, Portugal and Sweden. However, in some cases the span of the data was generally quite limited (15 years or less). As such, we did not read too much into these outcomes. Similarly, for the one country for which there might arguably be a negative relationship between telephone uptake and productivity growth, Malta, there were only ten observations and this hardly provided strong evidence of the estimated negative relationship. Moreover, only two of the four equations satisfied our criteria for a valid statistical relationship between productivity growth and infrastructure.

The analysis presented in this article has applied a simple exogenous-growth model to analyse the contribution of infrastructure investment to the growth of productivity, over and above that of other non-infrastructure investment. In doing so, the approach allows for a comparable and consistent assessment of the contribution of infrastructure to a number of different European countries. Based as it is on an established theoretical and empirical framework, the analysis can be related to previous work both in the area of infrastructure economics but also the more-general field of economic growth.

However, the analysis also carries some methodological limitations that relate to the specificities of infrastructure and the assumptions that underpin the chosen model. Investigating these limitations would be fruitful areas for future research and are discussed below.

Infrastructure projects are typically large and costly. As such, and given that they often possess the characteristics of public goods, there has traditionally been an important role for the state in financing or guaranteeing such projects. This may in turn prompt questions as to the potential for state intervention (for example, if a country were to decide to pursue a renewed programme of investment to improve productivity) to ‘crowd out’ private-sector investment. The source of finance is not considered in the analysis and the implicit assumption is that improvements in productivity from infrastructure investment are independent of the source of funding.

Infrastructure is also distinct from many other forms of capital because of the manner in which it raises productive potential, by providing connectivity to other goods and services e.g., roads linking cities, enabling passenger and freight transport around a region. In many cases, infrastructure permits activity elsewhere whereas, for other forms of fixed capital, the asset permits a particular form of activity on-site. In that sense, location is important and, by extension, so is the likely differing ‘quality’ of a particular infrastructure asset. As a result, aggregate, non-spatial measures of infrastructure may be misleading, by equating, say, the effect of one additional kilometre of road in one country with one additional kilometre in another. Moreover, such a treatment may, perhaps incorrectly, equate one additional kilometre with another in the same country (also raising the issue of economies of scale, discussed below). We have no explicit treatment of location or quality in this analysis and these limitations could be potentially addressed in future work. Such work might, for example, consider a set of infrastructure indicators (or even a composite one) that accounted for spatiality (e.g., proximity to areas of higher/lower output or population density); technology (e.g., electrified or non-electrified rail) or utilisation/congestion (e.g., in the case of roads or rail).

A further assumption is that the infrastructure in place in a country only contributes to that particular country’s productivity growth. In some countries, and for some infrastructure types, this may be true e.g., in the case of roads in island nations, where the connection boundary coincides with the national border. However, in other cases, this assumption is less tenable e.g., where there are electricity interconnectors between countries or, in mainland Europe, where roads and rail networks span multiple countries. The nature of infrastructure in such cases is that investment is mutually beneficial (and may be mutually financed), facilitating trade and other spillover effects. In an increasingly-connected region such as Europe, developments in one country must take more account of impacts in other countries. Failing to account for this represents a potential source of bias in the results that would merit further investigation in the future.

The equation specification, based as it is on per-capita measures, is also limited in its ability to deal with issues relating to economies of scale and the concentration/density of production and population. Disaggregation or quality adjustment may well help in this area, too, as might other features of the countries’ geographical and economic structure (including with reference to adjacent countries).

Finally, as Salimans (2012) points out, the application of a linear regression model derived from the framework of Mankiw et al. (1992) may be overly restrictive. This is because it restricts attention to models that comply with the classical Solow model. New growth theory puts forward an alternative class of models in which economic growth is a nonlinear function of its determinants. Moreover, Salimans (2012) emphasises the importance of joint analysis of variable selection and functional form (to test for such non-linearities). The analysis presented in this article addresses variable selection in the form of the robustness analysis of Levine and Renelt (1992) but not the functional-form issue, which may be highly relevant to infrastructure, which has a number of properties that distinguish it from many other forms of capital, such as its network/connective features. While the current analysis permits comparisons to earlier work that adopts the neo-classical framework, comparisons against more-sophisticated analysis by Salimans (2012) and others would be an important area for investigation.

The discussion above highlights various specificities relating to infrastructure that can complicate an analysis such as this one. However, these features also point to a number of interesting areas for future research. Some of these issues would require a more-extensive dataset and further work to develop an augmented version of the Eurostat-derived data would yield a number of advantages in the analysis of European economic growth. This is particularly because of the level of harmonisation required by Eurostat in the compilation of European statistics.

Conclusions

This article has identified the contribution infrastructure investment makes to productivity growth over and above that of investment in other, non-infrastructure forms of capital. We have followed an annual time-series regressions approach albeit with somewhat limited data in some cases but, where possible, using physical indicators of the size of infrastructure rather than the mainly expenditure-based measures used previously. We recognise that there is substantial heterogeneity in infrastructure effects across countries. In our analysis we found some evidence of over-investment in electricity generation capacity in Europe. We do, however, note that in the case of this infrastructure asset, resilient provision of infrastructure and/or transition to a low-carbon economy may take precedence. Productivity growth is but one objective in Europe, alongside considerations such as climate-change mitigation.

Our analysis of rail found limited evidence of over or under-investment in this infrastructure type across countries while our results for roads and motorways provided stronger evidence that further investment in road-transport links might be beneficial for productivity growth. Similarly, we identified a number of countries for which the relationship between telephone connectivity and productivity growth was positive.

There is no clear evidence in our results of differing effects between so-called Old and New Member States although in some cases the length of the time series can be quite short, making any kind of inference difficult. This is a limitation of our analysis and one of a number of areas that we would like to improve on in future research, in order to better identify the connective and spatial effects of infrastructure (e.g., at the city and region level).

Endnotes

[1]The consequent problem of not accounting for the public-private financing split is discussed later on in this article.

[2]Égert, Kozluk and Sutherland (2009) note the difficulties in interpreting the coefficient on the infrastructure indicator as a result of the units by which it is measured (in physical terms) differing from the units by which capital accumulation is measured (in economic volumes). As such, it is the sign and the significance of the coefficients that is of primary interest

[3]According to classical, rather than robust, standard errors.

Appendix

Table A1 lists the variables in the dataset used to carry out the regressions. All data are from Eurostat.

An aggregate electricity capacity figure is not available in the Eurostat database and has instead been constructed as the following series (both main activity producers and auto producers) from the energy infrastructure database:

- Combustible fuels
- Nuclear
- Hydro
- Geothermal
- Wind
- Other sources
- Solar
- Tide, waves and ocean

The final figures closely match the figures reported in Table 2.5.1 of Eurostat (2012), which shows total installed capacity by broad technology. Note that these figures are total capacity, rather than net maximum capacity.

Table A1 Data

	Description	Units	Database	Comment
GDP	Real GDP	Millions of euros, 2005 chain-linked volumes	nama_gdp_k	Divided by population to derive GDP per capita
Population	Population, total	#	demo_pjanbroad	Denominator in per-capita variables
Investment	Real Gross Fixed Capital Formation	Millions of euros, 2005 chain-linked volumes	nama_gdp_k	Divided by GDP to derive the investment share
Human capital (education)	Proportion of adults attaining an upper-secondary or tertiary education	%	edat_lfse_08	
Tax	Government tax receipts (excluding EU institutions) as share of GDP	%	gov_a_tax_ag	Divided by GDP to derive tax revenue as a ratio to GDP
Trade	Real exports and imports	Millions of euros, 2005 chain-linked volumes	nama_gdp_k	Summed and then divided by GDP to derive the ratio of trade to GDP
Electricity	Electricity generation capacity	MW	nrg_113a	Divided by population to derive per-capita figures
				See overleaf for constituent plant types
Motorways	Length of motorways	km	road_if_motorwa	Divided by population to derive per-capita figures
Rail	Length of rail track	km	rail_if_tracks	Divided by population to derive per-capita figures
Road	Length of non-motorway roads	km	road_if_roads	Divided by population to derive per-capita figures
Telephones	Fixed line and mobile telephone subscriptions	#	isoc_tc_ac1	Summed and then divided by population to derive per-capita figures

Table A2 lists the series for which missing data points were filled by linear interpolation. Table A2 Series filled

	Countries and years filled
Human capital	DE, IE, LU, UK: 1998
Motorways	BE, DE, DK, EL, ES, FI, FR, IT, LU, NL, NO, PT, UK: 1971-1978
	BG: 1991–1995
	DK: 2003–2005
	FI: 1979
	IE: 2006
	LU: 1995–1997
	NL: 1991, 1993–1994, 1996
	NO: 1979, 1981–1989, 1991–1993, 2003
	PT: 2003-2005
Rail	AT: 2003, 2004, 2005, 2006
	DE: 1994, 2003, 2004
	DK: 1995, 1996
	FR: 2008
	IE: 2002, 2003, 2004, 2006
	LV: 1991, 1992
	NL: 1995
	PL: 2003
	PT: 2003, 2004, 2005, 2006, 2007
	UK: 2007
Road	BE, DE, DK, EL, ES, FR, IT, LU, PT: 1971–1978
	BG: 1981–1989
	CH: 2001–2003
	CY: 1981–1989
	CZ: 1981–1989
	DK: 1989, 2003–2005
	ES: 1979, 1981
	FR: 2005
	HU: 2004–2007
	IE: 2006
	IT: 1998–1999
	LT: 1992
	LU: 1995–1997
	MT: 1991, 1993–1996, 2003-2008
	NL: 1980–1981, 1983, 1985–1987, 1991, 1993–1994, 1996, 1998–2000
	NO: 2001–2003
	PT: 1991, 1995–2005
	SI: 1991–1997
Telephones (mobile)	RO: 1995

Table A3 below shows the correlation matrix for the variables in the long-run part of the cointegrating equations. All variables in the matrix are natural logarithms.

	Population growth	Education	Electricity capacity per capita	GDP per capita	Investment share	Motorway length per capita	Road length per capita	Rail track length per capita	Tax ratio	Telephones per capita	Trade openness
Population growth	1.000										
Education	−0.185	1.000									
Electricity capacity per capita	0.273	0.188	1.000								
GDP per capita	0.393	−0.041	0.522	1.000							
Investment share	−0.008	0.041	−0.043	−0.178	1.000						
Motorway length per capita	0.143	−0.137	0.277	0.450	−0.051	1.000					
Road length per capita	−0.057	0.463	0.057	0.155	−0.063	0.305	1.000				
Rail track length per capita	−0.102	0.637	0.025	−0.187	0.016	−0.213	0.401	1.000			
Tax ratio	0.117	0.056	0.305	0.514	−0.236	0.306	0.160	0.112	1.000		
Telephones per capita	0.130	0.242	0.398	0.342	0.111	0.370	0.174	−0.141	−0.023	1.000	
Trade openness	−0.031	0.247	−0.020	−0.064	0.269	0.237	0.225	0.053	−0.222	0.228	1.000

Table A3 Correlation matrix Tables A4 and A5 report the results from Augmented Dickey-Fuller tests for (the natural logarithms of) GDP per capita and the share of investment in GDP respectively.

	Levels (constant only)				Levels (constant and time trend)				First differences (constant only)			
	Statistic	p-value		# obs	Statistic	p-value		# obs	Statistic	p-value		# obs
AT	−1.6992	0.4231		37	−1.4231	0.8368		37	−3.6880	0.0087	***	36
BE	−1.2610	0.6352		33	−0.8091	0.9542		33	−2.9610	0.0499	**	32
BG	−1.6042	0.4589		18	−0.8989	0.9323		18	−1.5512	0.4831		17
CH	−1.3445	0.5965		33	−2.7744	0.2163		33	−3.4795	0.0155	**	32
CY	−2.1988	0.2135		18	1.3522	0.9999		18	0.4682	0.9794		17
CZ	−0.7986	0.7966		20	−1.5210	0.7853		20	−1.6878	0.4202		19
DE	−0.2514	0.9170		22	−3.3462	0.0862	*	22	−3.8213	0.0097	***	21
DK	−1.8932	0.3318		38	−0.4385	0.9822		38	−2.7693	0.0728	*	37
EE	−1.8225	0.3590		20	−0.5633	0.9694		20	−1.9730	0.2948		19
EL	−2.1112	0.2429		18	−1.2182	0.8729		18	−0.1245	0.9307		17
ES	−1.8913	0.3320		33	−0.0717	0.9932		33	−1.5320	0.5044		32
FI	−1.4461	0.5492		38	−2.3135	0.4167		38	−2.9936	0.0450	**	37
FR	−2.3679	0.1620		22	−0.2418	0.9869		22	−1.6817	0.4248		21
HU	−2.1806	0.2194		18	−0.6337	0.9620		18	−0.9829	0.7326		17
IE	−2.2331	0.2027		18	−1.1509	0.8882		18	−1.2020	0.6462		17
IT	−1.7199	0.4080		23	0.7165	0.9992		23	−1.3685	0.5775		22
LT	−1.1697	0.6618		18	−0.8470	0.9393		18	−2.0198	0.2762		17
LU	−2.5322	0.1257		18	−0.2949	0.9831		18	−1.1455	0.6701		17
LV	−0.7414	0.8158		23	−1.6476	0.7398		23	−2.3211	0.1749		22
MT	−0.1868	0.9165		13	−2.1626	0.4653		13	−1.6372	0.4326		12
NL	−0.9765	0.7515		38	−1.3123	0.8692		38	−2.6527	0.0922	*	37
NO	−2.5937	0.1022		43	−0.4290	0.9831		43	−2.5568	0.1101		42
PL	−0.6212	0.8411		18	−2.1198	0.4995		18	−1.5960	0.4616		17
PT	−3.1275	0.0435	**	18	−2.0782	0.5204		18	−1.3129	0.5967		17
RO	−1.5353	0.4907		17	−1.8963	0.6097		17	−1.9165	0.3165		16
SE	−1.6926	0.4290		53	−3.0227	0.1361		53	−3.7430	0.0061	***	52
SI	−2.3886	0.1561		23	−0.2204	0.9879		23	−2.1094	0.2431		22
SK	−0.8974	0.7674		21	−2.3298	0.4008		21	−2.1565	0.2269		20
UK	−1.6854	0.4326		53	−1.3361	0.8676		53	−3.1220	0.0311	**	52

*, ** and *** indicate rejection of the null hypothesis of a unit root at the 90 %, 95 % and 99 % levels, respectively

Table A4 Augmented Dickey-Fuller tests for log (GDP per capita)

	Levels (constant only)				Levels (constant and time trend)				First differences (constant only)			
	Statistic	p-value		# obs	Statistic	p-value		# obs	Statistic	p-value		# obs
AT	−1.1381	0.6899		37	−1.5301	0.8002		37	−3.1714	0.0304	**	36
BE	−1.737	0.3964		18	−1.6883	0.7116		18	−1.6159	0.4521		17
BG	−2.9934	0.0557	*	18	−0.1189	0.9892		18	−1.2559	0.6225		17
CH	−3.3185	0.0223	**	33	−2.9475	0.162		33	−3.37	0.02	**	32
CY	−2.6482	0.1032		18	−1.0954	0.8995		18	0.1661	0.9607		17
CZ	−2.1016	0.2461		20	−3.1347	0.1268		20	−4.5755	0.0023	***	19
DE	−0.9776	0.7415		22	−2.8923	0.1842		22	−3.2911	0.0293	**	21
DK	−1.8417	0.3552		38	−4.2771	0.0088	***	38	−3.4591	0.0152	**	37
EE	−2.3285	0.1738		20	−2.0885	0.5191		20	−3.4093	0.0245	**	19
EL	0.4271	0.9746		13	0.2276	0.9941		13	−0.77	0.7872		12
ES	−1.9112	0.3232		33	−1.2002	0.8935		33	−1.7746	0.3855		32
FI	−2.4152	0.1446		38	−3.3239	0.0781	*	38	−4.042	0.0034	***	37
FR	−2.5858	0.1012		64	−2.3709	0.3908		64	−3.7609	0.0053	***	63
HU	−1.3951	0.5598		18	−0.616	0.9635		18	−1.3914	0.5599		17
IE	−1.6239	0.4495		18	−1.6635	0.7225		18	−2.5049	0.1326		17
IT	−1.2253	0.6443		23	−0.9208	0.9352		23	−2.2607	0.1927		22
LT	−1.7492	0.3907		18	−0.9008	0.932		18	−2.4236	0.1512		17
LU	−0.9728	0.7379		18	−5.0282	0.0048	***	18	−4.808	0.0018	***	17
LV	−2.7923	0.0802	*	18	−2.1198	0.4995		18	−3.0708	0.0495	**	17
MT	−0.4339	0.8733		13	−2.7876	0.2276		13	−1.3957	0.5452		12
NL	−2.6211	0.0979	*	38	−2.9123	0.1704		38	−3.0358	0.041	**	37
NO	−1.6315	0.458		43	−1.562	0.791		43	−4.0788	0.0028	***	42
PL	−2.597	0.1127		18	−3.4785	0.0742	*	18	−2.8156	0.0782	*	17
PT	1.2755	0.9971		18	0.0724	0.9936		18	−0.8181	0.7863		17
RO	−0.9362	0.7488		17	−1.928	0.594		17	−2.2709	0.1925		16
SE	−2.7565	0.0706	*	63	−2.9477	0.1553		63	−5.1226	0.0001	***	62
SI	−2.864	0.0659	*	23	−0.4879	0.976		23	−1.923	0.3161		22
SK	−1.0956	0.6963		21	−2.9233	0.1764		21	−4.0077	0.0069	***	20
UK	−2.2085	0.2068		38	−2.9835	0.1502		38	−3.8158	0.0062	***	37

*, ** and *** indicate rejection of the null hypothesis of a unit root at the 90 %, 95 % and 99 % levels, respectively

Table A4 Augmented Dickey-Fuller tests for log (GDP per capita)

Table A5 Augmented Dickey-Fuller tests for log (investment share)

Country list

Eurostat Country codes			
Code	Name	Code	Country
AT	Austria	IT	Italy
BE	Belgium	LT	Lithuania
BG	Bulgaria	LU	Luxembourg
CH	Switzerland	LV	Latvia
CY	Cyprus	MT	Malta
CZ	Czech Republic	NL	Netherlands
DE	Germany (until 1990 former territory of the FRG)	NO	Norway
DK	Denmark	PL	Poland
EE	Estonia	PT	Portugal
EL	Greece	RO	Romania
ES	Spain	SE	Sweden
FI	Finland	SI	Slovenia
FR	France	SK	Slovakia
HU	Hungary	UK	United Kingdom
IE	Ireland		

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
CT undertook the modelling work and wrote up the first draft of the article. PT edited the article and refined the literature review, aims and results. RB helped with econometrics. All authors read and approved the final manuscript.

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