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## Catching Up or Falling Behind? The Effect of Infrastructure Capital on Technology Adoption in Transition Economies

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# Catching up or falling behind? The effect of infrastructure capital on technology adoption in transition economies


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**Abstract**

This paper demonstrates that a link between infrastructure capital and productivity growth can lead to multiple balanced growth equilibria if one accounts for the endogenous provision of infrastructure. Starting with the contribution of Barro (1990), the literature on infrastructure and growth mainly focuses on the relation between private and public capital investments. In contrast, we focus on the relationship between the provision of infrastructure capital and a country's innovative capacity. This is consistent with recent empirical evidence that reports a positive link between the two variables. The framework leads to bivariate causality between the rate of technical change and the provision of infrastructure services and generates scope for multiple strictly positive balanced growth equilibria.


## 1 Introduction

Physical infrastructure capital deviates from other types of capital in two important ways: it is (partly) non-excludable and (partly) non-rival. The former raises the question of an appropriate financing since a partly excludability allows for a private provision. The latter has important implications for economic growth and development. That is, an increase in the infrastructure capital stock exerts an externality on all private producers if infrastructure capital is partly non-rival. In this regard, the provision of productive infrastructure capital can potentially affect long-run growth comparable to the functioning of non-rival knowledge in the endogenous growth theory.

In this paper, we account for both particular features of infrastructure capital to analyze the interdependence between economic growth and the provision of infrastructure capital in a transition economy that is initially constraint by a scarce infrastructure capital stock. We demonstrate in the framework of an endogenous growth model that there exists a two-way causality between the long-run balanced growth path and the provision of infrastructure capital in the economy. This bivariate causality leads to multiple strictly positive balanced growth equilibria.

The theoretical literature on infrastructure and growth literature is substantially influenced by the work of Barro (1990). This approach lumps together private and infrastructure capital with intellectual capital that is accumulated by technological progress. Thus, it is implicitly assumed that (broader) capital accumulation, which is studied by neoclassical theory, and technological knowledge are one and the same. In particular, Barro (1990) assumes a Cobb-Douglas production function that features constant returns to scale for the accumulation of private and infrastructure capital because part of this broader capital accumulation is supposed to reflect technological progress needed to counteract diminishing returns. It follows that infrastructure or private capital investments feature not only level but also growth effects in the long-run. In this model infrastructure investments are financed by means of distortionary taxes. These limit the long-run growth effects. The analysis results in an optimal level of infrastructure capital. Below, infrastructure investments are growth enhancing while beyond they trigger negative growth effects due to the distortionary financing. In the literature this finding is referred to as the *Barro Curve*. This approach has been generalized in several ways, i.e. Turnovsky (1997) accounts for infrastructure capital which is subject to congestion, Kosempel (2004) for the case of finitely lived households, Turnovsky (2000) for an elastic labor supply and Ghosh and Mourmouras (2002) for an open-economy framework. An alternative approach is followed by Bougheas et al. (2000) who show that infrastructure investments increase an economy's degree of specialization. Finally, Ott and Turnovsky (2006) account for a partly excludability of infrastructure capital which enables the provider to charge the users of infrastructure services. This more realistic approach justifies a private provision of infrastructure services.

The main empirical challenge in the literature on infrastructure and growth is the identification of *cause and effects*. That is, a positive correlation between the two variables might be due to the effect that governments spend more on infrastructure in countries or periods that feature high growth since financing constraints are less binding in this case. Several empirical contributions report a positive relation between infrastructure and GDP-growth for different regions and time periods.[1] Yet, most of these earlier studies do not address the potential endogeneity of infrastructure investments. Roeller and Waverman (2001) formulate a structural model for the supply and demand of telecommunication infrastructure to separate cause and effects on aggregate production.[2] They find large positive effects of telecommunication investments on economic growth in a panel of 21 OECD countries from 1970-90. Moreover, they show that higher GDP-growth triggers infrastructure investments due to an increasing demand for infrastructure services. Belaid (2004) confirms the results with an analog methodology for a panel of 37 developing countries from 1985-2000. Fernald (1999) shows that the rise in road services substantially increased the productivity (TFP) across industry in the U.S. from 1953 to 1973.[3] The author employs an implicit test for endogeneity by showing that productivity growth is above average in vehicle intensive industries. Calderón and Servén (2005) apply an instrumental variables approach to estimate a positive causal effect of different infrastructure measures on GDP-growth in a panel of 121 countries from 1960-2000. Finally, Bougheas et al. (2000) and Hulten et al. (2003) detect a positive impact of infrastructure on the degree of product specialization and productivity in the U.S. and India, respectively.

The empirical results suggest a bivariate relation between the provision of infrastructure capital and economic growth. Against this background, the World Bank emphasizes in a recent report (World Bank (2008)) that infrastructure capital is an important determinant of the innovative capacity of developing countries. The report refers to basic infrastructure, i.e. roads, electricity, and telephony, as "enabling technologies" that spur the spread of other technologies by improving the capacity of firms to interact. World Bank (2008) concludes (page 153): "The government can also have an important impact on economic progress by integrating new technology into its own operations, including in the provision of education, health, and publicly-provided infrastructure."

In this paper, we explicitly account for a reversed causality between infrastructure and

[1] Gramlich (1994) or Holtz-Eakin and Schwartz (1994) survey the earlier empirical literature on infrastructure and growth.

[2] The identification of cause and effects crucially hinges on the specification of demand and supply functions and the conformance of price elasticities across the OECD countries.

[3] He measures a rate of return of 100% before 1973 and a negative rate from 1973-89. To put it in the words of Fernald (1999): "the interstate highway system was very productive, but a second one would not be".

growth in transition countries that are initially constraint by a low provision of infrastructure capital. We deviate from the existing literature in two ways. First, we endogenize the provision of partly excludable infrastructure capital. In particular, we suppose that the provider of infrastructure capital dynamically optimizes her expected future profits from current investments.[4] In contrast, the existing literature, which is based on the Barro (1990) approach, implicitly assumes that public infrastructure investments follow an automatic rule governed by the static government's balanced budget constraint. That is, the amount of infrastructure investments is determined as a residual from a balanced budget constraint defined by the equilibrium level of GDP and the tax rate in an economy.[5] Second, we suppose that the distribution of specialized intermediate goods in a transition economy is costly due to transportation or information costs. Furthermore, we assume that these costs are decreasing in the economy's infrastructure capital stock. It follows that the return on investments in specialized intermediate goods, i.e. a country's innovative capacity, is affected by the equilibrium provision of infrastructure capital in the economy. Hence, in contrast to earlier studies, we explicitly allow for an impact of infrastructure capital on the innovative capacity of a country.[6] This is consistent with recent anecdotal and empirical evidence, compare, e.g. Chandra (2006), World Bank (2008), Fernald (1999), Bougheas et al. (2000), and Hulten et al. (2003).

We generalize previous findings by demonstrating that the allowance for a dynamically optimizing provider of partly excludable infrastructure capital can lead to the existence of multiple strictly positive balanced growth equilibria in economies that are initially constraint by scarce infrastructure capital. In a high-growth scenario, the high balanced growth rate encourages investments in infrastructure by increasing the expected future profits from these investments. It follows that the economy is characterized by a high infrastructure capital stock and fast technological change. In the low-growth scenario, the rate of technological change is constraint by the low provision of infrastructure capital which lowers the incentive to invest in the adoption of new technologies and hence the rate of long-run growth. The low equilibrium growth rate, in turn, limits investments in infrastructure by

[4]It does not matter if the infrastructure provider is private or public as long as she dynamically optimizes the investments.

[5]Note that earlier approaches, which are based on a static government budget constraint, incorporate a feedback effect from the level of GDP to infrastructure investments. In contrast, the explicit modelling of the incentives of a dynamically optimizing infrastructure provider involves a direct effect of the growth rate on expected future profits from infrastructure investments.

[6]In particular, our approach differs from the previous literature, which is based on Barro (1990), in that we account for a general equilibrium effect of the stock of infrastructure capital on the incentives to invest in R&D instead of private capital accumulation.

reducing the expected future profits from infrastructure investments. In principle, a *sizable* exogenous financing source, e.g. a government subsidy, can induce a shift from the low to the high equilibrium balanced growth path.

Section 2 outlines a standard endogenous growth model that accounts for the impact of infrastructure capital a country's innovative capacity. In section 3, we illustrate the conditions that ensure the existence of multiple strictly positive balanced growth equilibria for a given endogenous provision of infrastructure capital. The final section concludes.

## 2 The partial model

In the this section, we present a growth model of endogenous technological change à la Romer (1990). The basic model is extended in two ways. First, it accounts for transportation and information costs that distort the distribution of specialized intermediate goods to final output producers. Second, it includes an infrastructure capital sector that provides infrastructure services to the economy. The endogenous provision of infrastructure capital is analyzed in section 3.

The model consists of a competitive final output sector, a intermediate goods sector which is characterized by monopolistic competition, an infrastructure capital goods sector, and a law of motion for the stock of technologies.

**Final output sector ($Y$)**

Competitive firms employ manufacturing labor ($L_y$), a (symmetric) combination of all varieties of specialized intermediate goods ($x_j$) and an aggregate of all varieties of infrastructure services ($G$) to produce a final output good ($Y$). Each specialized intermediate good corresponds to a new technology, whereas $A_t$ denotes the stock of existing technologies. Hence final output is manufactured according to the production function $Y = L_{y,t}^{\chi} G_t^{\beta} \int_0^{A_t} x_{j,t}^{\alpha} dj$, $\alpha, \beta, \chi > 0$.

The Romer (1990) model involves several assumptions underlying the functional form of the production function that are worth discussing. As in the basic model of growth results from an increasing specialization of the intermediate goods sector, whereas each new innovation ($A_t$) involves a new intermediate good. The specific form of the production function supposes that the elasticity of substitution between different intermediate goods or between intermediates and infrastructure capital is equal to one (Cobb-Douglas).[7]

For convenience, we normalize the price of the final output good to one ($p_y = 1$). The final producers buy the intermediate products, pay a wage ($w_y$) for manufacturing labor, and a price ($p_G$) for the usage of infrastructure services in the production process. Hence, infrastructure capital is a productive input in the final output sector which allows for the analysis of a private provision of infrastructure capital (see section 3).[8] The representative firm in the competitive final output sector takes prices as given and chooses its inputs to maximize instantaneous profits in $t$ ($\pi_{y,t}$):

$$\pi_{y,t} = L_{y,t}^{\chi} G_t^{\beta} \int_0^{A_t} x_{j,t}^{\alpha} dj - \int_0^{A_t} p_{I,j,t} x_{j,t} dj - w_{y,t} L_{y,t} - p_{G,t} G_t \tag{1}$$

where ($p_{I,j}$) is the price of of an intermediate product $j$.

The final producer determines its use of $x_{j,t}$, $L_{y,t}$ and $G_t$ to maximize its profit resulting in the first-order conditions:[9]

$$p_{I,j,t} = L_{y,t}^{\chi} G_t^{\beta} \alpha x_{j,t}^{\alpha-1} \tag{2}$$

$$w_y = \chi L_Y^{\chi-1} G_t^{\beta} A x_j^{\alpha} \tag{3}$$

$$p_{G,t} = L_Y^{\chi} \beta G_t^{\beta-1} A x_j^{\alpha} \tag{4}$$

**Intermediate capital goods sector ($x$):**

We assume that each intermediate good $j$ is provided by a monopolist since the innovation of a specialized intermediate good creates market power. An intermediate producer requires $\eta$ units of $K$ to produce one unit of an intermediate $j$, i.e. $K = \eta \int_0^A x_j dj$.[10] In addition to the basic Romer (1990) model, we impose the following assumptions.

**Assumption 1:** *The provision of an intermediate good for final producers is costly. It involves transportation and information costs which increase the effective costs of an inter-*

[7]Alternatively, we could have employed a constant elasticity of substitution (CES) production function as in Young (1993). This does not change the functioning of the model. In this more general case, the equilibrium growth rate simply depends on an additional parameter measuring the degree of substitutability in the economy.

[8]Note that we do not impose the special case of constant returns to scale in private and infrastructure capital ($\beta + \alpha < 1$) as in Barro (1990). As a consequence, including $G$ in the production function of final producers exclusively has level but not growth effects in the long-run.

[9]Note that final output firms demand the same amount of each intermediate so that $x_j = x$, $p_j = p$, $\pi_j = \pi$ and $Ax_j^{\alpha} = \int_0^{A_t} x_j^{\alpha} dj$ hold because of symmetry.

[10]We abstract from further constraints in the provision of private capital.

*mediate good by* $1+\phi$*. These costs are decreasing in the provision of infrastructure services in the economy, i.e.* $\phi = \phi(G)$, $\phi'(G) < 0$.

Thus, $\phi$ acts like a costly exogenous distortion of the interactions between intermediate and final producers. In this regard, its functioning is equivalent to the one of exogenous iceberg costs in trade models. Assumption 1 is justified by the empirical evidence of Holtz-Eakin and Schwartz (1994). He detects a negative relationship between intermediate business costs and the provision of infrastructure capital in the economy. Moreover, Bougheas et al. (2000) detect a positive relationship between infrastructure capital and the degree of specialization in the intermediate sector for the U.S. economy.[11]

**Assumption 2:** *$\phi$ is a negative, continuous, monotonic function of the infrastructure capital stock with the following properties:* $\phi(G)$, $\phi' < 0$, $\phi'' > 0$, $\lim_{G\to\infty} \to 1$, $\lim_{G\to 0} \to \infty$*. Thus, $\phi$ is convex, approaches a lower bound if $G$ approaches infinity and approaches infinity if $G$ approaches 0.*

Assumption 2 involves the constraint that the price premium can not become negative. Moreover, it defines that intermediate specialization is not feasible as costs approach infinity in the absence of infrastructure capital.

Each monopolist chooses $x_j$ to maximize his profits ($\pi_{I,j}$) given the perceived inverse demand function for each intermediate ($p_{I,j,t}$), the interest rate ($r$) payments per unit of capital, and the costs of providing the intermediate good to the final producer ($\phi$). Because of symmetry the former is the same for all intermediates ($p_{I,j} = p_I$). Note that a successful research project in the Romer (1990) results in the entry of a new intermediate producer. Therefore, $\phi(G)$ is taken as given by potential new market entrants that base their entry decision on the net present value of the return of potential research investments.[12] In other words, we separate the infrastructure service in the production of final output from its impact on potential business costs of new intermediate producers.[13] Hence, we obtain the

[11]For example, $\phi$ captures fixed entry costs which are necessary to set up a new business. In addition it appears reasonable to assume that such entry costs are decreasing in the provision of infrastructure capital - e.g. the appearance of high-speed telecommunication networks potentiates the firm's ability to sell/transmit specialized goods via internet without the need to establish a widespread distribution system (Fernald and Ramnath, 2004). There are various additional plausible empirical anecdotes in favor of this assumption, e.g. the construction of the interstate highway system in the U.S. (Fernald, 1999), the disposability of electricity in the beginning of the last century (Jovanovic and Rousseau, 2004).

[12]At this stage, a new intermediate firm has not entered the market so that the aggregate infrastructure capital stock is exogenous for the potential intermediate producer. Our qualitative results would not change if $\phi$ could be (partly) internalized by intermediate producers as long as infrastructure capital is (partly) non-rival. The reason is that intermediate producers do not internalize the externality of their own demand for infrastructure capital on the costs of entry of other potential producers. The provision of infrastructure in a decentralized equilibrium would be inefficient.

[13]Note that infrastructure capital is partly excludable. On the one hand, the provider can exclude final

following profit function:[14]

$$\pi_I = \frac{p_{I,j}x_j}{1+\phi(G)} - r\eta x_j = \frac{L_y^{\chi}G^{\beta}\alpha x_{j,t}^{\alpha}}{1+\phi(G)} - r\eta x_{j,t} \tag{5}$$

Computing the first-order condition and substituting for $r\eta$, we obtain:

$$\pi_I = \frac{(1-\alpha)p_I x}{1+\phi(G)} \tag{6}$$

**R&D sector** ($A$)

We suppose, in accordance with the literature on technology adoption (e.g. Barro and Sala-i-Martin (1997) or Howitt (2000)), that the adoption of new technologies requires investments in research activities. Hence, the rate of technological change ($\dot{A}$) is a positive function of research labor ($L_R$), a productivity parameter ($\lambda$) and its stock of knowledge ($A$):

$$\dot{A}_t = \lambda L_{R,t} A_t \tag{7}$$

It is implicitly assumed that all researchers have free access to the entire stock of knowledge, so that each new innovation/imitation induces a positive externality on future research. This specification is due to Romer (1990). An increase in population raises the rate of technological change, hence it entails scale effects. We abstract from such scale effects by setting population growth to zero (normalize $L = 1$).

**Households**

Identical, infinitely lived households maximize their utility from consumption ($C$) subject to a resource constraint and *No-Ponzi* game conditions. The utility function supposes a constant relative risk aversion: $u(c_i) = \frac{c_i^{(1-\sigma)}-1}{1-\sigma}$, where $\sigma$ is the degree of risk-aversion. We implicitly assume an inelastic labor supply. Thus, the consumption plan satisfies the standard Euler equation:

$$\dot{C}_t = \frac{r_t - \rho}{\sigma} C_t \tag{8}$$

output firms from infrastructure services so that they can be charged for their direct use. On the other hand, the provider can not control that the existence of an infrastructure network causes a positive externality on the costs of the provision of new intermediate goods.

[14] In the following, we concentrate on symmetric balanced growth equilibria, so that we can omit time subscripts to simplify the notation.

where $r_t$ is the real interest rate, $\rho$ a time-preference rate and $\sigma$ the degree of risk-aversion.

**Solution for a balanced growth equilibrium**

So far we have not characterized the financing structure of infrastructure capital (the market structure in the sector). Yet, we will solve the (partial) model for a balanced growth equilibrium, in which $A$, $G$, $C$ and $Y$ all grow at the same constant exponential rate, to illustrate the mechanism of the model for a given financing structure.

The key mechanism involving technological progress is a free-entry condition into the research sector. It is the basic assumption underlying the market structure of monopolistic competition and translates expected future profits in the intermediate sectors into investments in innovation activities.[15] In particular, the free entry condition into research ensures that the present discounted value of expected future profits from a new innovation equals the costs for the production of a new design. If we assume that monopoly profits last forever the present discounted value equals $\frac{\pi}{r}$, where $r$ is the real interest rate. The costs of a new design are productivity adjusted wages paid to research labor ($\frac{w_R}{\lambda A}$). Thus, the free entry condition amounts to:

$$\frac{\pi}{r} = \frac{w_R}{\lambda A} \tag{9}$$

The labor force is free to work in the manufacturing or research sector so that in equilibrium wages in both sectors must be equal ($w_y = w_R$).[16] Given the wage in manufacturing (3) and the profit function (6) the free-entry condition is solved for the equilibrium demand for manufacturing labor:

$$\Rightarrow L_Y = \frac{\chi r(1 + \phi(G))}{\lambda\alpha(1 - \alpha)} \tag{10}$$

It follows from (7) that the equilibrium growth rate of the technology stock amounts to $\gamma = \frac{\dot{A}}{A} = \lambda L_R = \lambda(1 - L_Y)$. We know from the production function that final output grows in a balanced growth equilibrium at the same rate as $A$. Hence, $\frac{\dot{C}}{C}$ also grows at the rate $\gamma$. If we substitute for $L_Y$ from (10) and $r = \gamma\sigma + \rho$ from (8) we obtain the following growth

[15] Hellwig and Irmen (2001) show that expected future rents due to imperfect competition are not in general necessary to ensure investments in R&D since intentional actions of entrepreneurs looking for profits can trigger such investments even in perfectly competitive markets.

[16] We abstract from any labor market constraints ($L = L_R + L_Y$).

rate for the stock of technologies:

$$\gamma = \frac{\dot{A}}{A} = \frac{\alpha(1-\alpha)\lambda - \chi\rho(1+\phi(G))}{\alpha(1-\alpha) + \chi\sigma(1+\phi(G))} \tag{11}$$

We can infer from (11) that the growth rate of the stock of technologies is an increasing function of the stock of infrastructure capital ($\frac{\partial\gamma}{\partial G} > 0$, $\frac{\partial^2\gamma}{\partial^2 G} > 0$). Since (endogenous) technological change is the only source of GDP-growth in a balanced growth equilibrium, GDP also grows at that rate.[17]

**Proposition I**: *Given the assumptions underlying the models of endogenous technical change à la Romer (1990) and Assumptions 1-2, it follows that the rate of technical change (and hence output growth) is an increasing function of the stock of infrastructure capital* ($\frac{\partial\gamma}{\partial G} > 0$)*.*

Intuitively, a higher provision of infrastructure reduces the business costs in the intermediate sector ($\phi(G)$). This cost-reducing feature of infrastructure capital augments the demand for specialized intermediate goods and hence increases the net present value of the returns of investments in new technologies. Due to the research arbitrage (free-entry) condition this leads to a shift of resources from the manufacturing sector ($L_y$) to innovation activities ($L_R$). Consequently, a low provision of infrastructure capital represents an impediment for economic growth because investments in new technologies are relatively unprofitable.
Besides, $\gamma$ is a positive function of the exogenous productivity parameter in the research sector ($\lambda$). This relationship is quite crucial since the effectiveness of domestic innovation activities measured by $\lambda$ determines the potential scale of the positive infrastructure externality on the incentive to invest in research ($\frac{\partial^2\gamma}{\partial G\partial\lambda} > 0$). If $\lambda$ is high, the impact of the infrastructure externality is large. Hence, there exists a complementarity between the effect of infrastructure investments and the effectiveness of the research sector. Since $\lambda$ is exogenous it represents all country-specific factors that are neglected in this model and that influence the effectiveness of the research sector, e.g. intellectual property rights, tertiary education, or corruption. It is important to note that the equilibrium growth rate is not necessarily strictly positive. If we set (11) equal to 0 we can compute the threshold level for

[17] The equilibrium growth rate suggests a minor technical restriction: In order to ensure that consumer's preferences are finite we need to impose that the growth of current utility $(1-\sigma)\gamma$ is less than the discount rate $\rho$.

the productivity of the research sector ($\lambda^*$) such that $\gamma$ is positive: $\lambda^* > \frac{\chi\rho}{\alpha(1-\alpha)}(1+\phi(G))$.

# 3 Endogenous provision of infrastructure capital

In this section, we endogenize the infrastructure capital stock ($G$). Ex ante, the interaction between an endogenous infrastructure supply and economic growth is not clear. On the one hand, infrastructure investments are costly or dissipate scarce resources. On the other hand, higher growth facilitates the financing of infrastructure investments due to higher expected future profits from infrastructure investments. In this regard, our results are based on two additional assumptions.

**Assumption 3:** *Investments in infrastructure require different scarce resources than investments in research.*

Assumption 3 reflects that infrastructure investments are intensive in unskilled labor while research is human capital intensive.

**Assumption 4:** *Infrastructure capital is partly excludable and provided by a dynamically optimizing supplier facing potentially increasing marginal investment costs $\mathcal{C}(I_t, t)$. $\mathcal{C}(I_t, t)$ is an increasing continuous, monotonic function with $\mathcal{C}_1 = \frac{\partial \mathcal{C}}{\partial I_t} > 0$, $\mathcal{C}_2 = \frac{\partial \mathcal{C}}{\partial t} \geq 0$ and $\mathcal{C}_{I_t,t} = \frac{\partial^2 \mathcal{C}}{\partial I_t \partial t} \geq 0$.*

Assumption 4 requires that the infrastructure provider optimizes her expected future profits from infrastructure investments. Note that it does not matter if the provider is private or public as long as she dynamically optimizes her profits. Moreover, the costs of supplying infrastructure are potentially increasing over time since the costs of infrastructure resources, e.g. unskilled labor, are increasing with the income level in the economy. Both assumptions appear to be empirically plausible.

In the following, we show that this framework leads to a reversed causality between the provision of infrastructure and GDP-growth implying the existence of multiple balanced growth-equilibria in the presence of increasing marginal infrastructure investment costs over time.

### Infrastructure capital goods sector ($G$)

Conceptually, we suppose that the infrastructure sector consists of competitive firms supplying infrastructure services and a monopolistic network provider.[18] The competitive service

[18] Due to fix costs (see below) the sector displays a natural monopoly. It does not matter if the network

firms take the perceived inverse demand function for infrastructure services ($p_{G,t}$) as given and pay a proportional rental price ($r_{G,t}$) for the access to operate the infrastructure network. Thus, as long as the infrastructure service sector is perfectly competitive, we have $p_{G,t} = r_{G,t}$. In this case, it makes no difference if the network provider supplies infrastructure services himself or sells the rights to do so to competitive firms. The network provider invests $I_t$ in infrastructure capital ($G_t$) incurring variable ($\mathcal{C}(I_t, t)$) and fixed ($F$) investment costs. Note that time enters as an explicit argument in the costs function since we do not exclude that the cost function depends on additional time-dependent (endogenous) variables (e.g. $A_t$ or $Y_t$). Thus, marginal costs increase over time if $\mathcal{C}_2 = \frac{\partial \mathcal{C}}{\partial t} > 0$ (e.g. strictly convex investment costs). Increasing marginal costs might be a more realistic assumption for an economy that grows according to a balanced growth rate.[19]

**Monopolistic provider of infrastructure capital**

The instantaneous profit function of the monopolist is given by the perceived inverse demand function ($p_{G,t}$), the investment, and the fix costs: $\pi_{G,t} = p_{G,t}G_t - \mathcal{C}(I_t, t) - F$. It follows that the monopolist faces a dynamic optimization problem. The depreciation rate of the infrastructure capital stock amounts to $\delta$, so that $\dot{G}_t = I_t - \delta G_t$. Hence, the private monopolist chooses $I_t$ to maximize the (discounted) current value of its expected future profits subject to $\dot{G}_t = I_t - \delta G_t$ and $\int_t^\infty \pi_{G,s} ds \geq \hat{F}$.[20] If the latter condition is satisfied the monopolist faces the following maximization problem:[21]

$$\max_{I_t, G_t} \int_0^\infty e^{-\rho t}[p_{G,t}G_t - \mathcal{C}(I_t, t) - F]dt, \qquad \dot{G}_t = I_t - \delta G_t \tag{12}$$

To solve the dynamic optimization problem we define the current value Hamiltonian:

$$H(I_t, G_t, \lambda_t, t) = e^{-\rho t}[p_{G,t}G_t - \mathcal{C}(I_t, t) - F]dt + \lambda_t[I_t - \delta G_t] \tag{13}$$

provider is private or public as long as she dynamically optimizes its investments.

[19]For example, we might assume that the marginal costs increase in the stock of knowledge or GDP to take into account that investment costs are higher if more advanced technologies are applied or if the size of the economy increases.

[20]If the fix costs arise every period we have $[\hat{F} = \int_t^\infty (F) ds]$. If they arise only in the first period we have $[\hat{F} = F]$.

[21]Note that we assume for simplicity that the infrastructure monopolist discounts future profits with $\rho$ and not $r$. In the latter case $G = G(\gamma)$ would be a higher-order non-linear function of $\gamma$. Given $\mathcal{C}(I_t, t) = \mu Y_t I_t$ this results in three balanced growth rates whereas only two are strictly positive. Finally, recall that we abstract from additional private capital constraints in our economy.

Combining the first-order conditions we get the following optimality conditions:

$$\begin{aligned} [p'_{G,t}G_t + p_{G,t}] &= \mathcal{C}_{I_t}\left(\rho + \delta - \frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}}\right) && (14) \\ \dot{G}_t &= I_t - \delta G_t && (15) \\ \lim_{t\to\infty}[\lambda_t I_t] &= 0 && (16) \end{aligned}$$

In the case of constant marginal investment costs ($\dot{\mathcal{C}}_{I_t} = \frac{\partial \mathcal{C}_{I_t}}{\partial t} = 0$), the first condition states that instantaneous marginal revenue must equal marginal costs. Otherwise, the right hand side is adjusted to incorporate the dynamic effects of infrastructure investments on future profits stemming from an increase in the shadow price of infrastructure capital over time. The monopolist extends the provision of $G$ in this case. Intuitively, she anticipates that the shadow price of infrastructure capital increases in the presence of positive balanced growth due to two reasons: (i) future investments are more costly relative to current investments, (ii) the demand for infrastructure capital increases. Hence, she is better off producing more infrastructure capital today since its future value increases for him. The second condition gives the law of motion for infrastructure capital and the third is a transversality condition. If we substitute in (14) for $p_{G,t}$ from (4), and solve for $G_t$, we obtain:

$$G_t = \frac{\beta^2 Y_t}{\mathcal{C}_{I_t}(\rho + \delta - M(\gamma))} \qquad (17)$$

The infrastructure capital stock is increasing in the level of GDP. In addition, it is an increasing function of the elasticity of final output with respect to infrastructure capital as a rise in $\beta$ implies a higher demand for $G$. In contrast, it is decreasing in the depreciation rate ($\delta$) and the inter-temporal elasticity of substitution ($\rho$). However, we know from (11) that $G$ must be constant in a balanced growth path. It then follows from (17) that marginal investment costs ($\mathcal{C}_{I_t}$) must grow proportional to GDP in order to sustain balanced growth. Hence, the monopolist faces increasing marginal investment costs. In this case, the growth rate of marginal investment costs is a positive function of the balanced growth rate of the economy: $\frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}} = M(\gamma)$, $M' > 0$, $M'' = 0$. Thus, the infrastructure capital stock is an increasing function of the equilibrium growth rate of the economy ($\frac{\partial G}{\partial \gamma} > 0$).[22]
Moreover, we show in Appendix A that $\frac{\partial^2 G}{\partial^2 \gamma} > 0$ holds for reasonable parameter values.

[22]The exact derivative is given in Appendix A. Besides, we show that a technical sufficient condition for $\frac{\partial^2 G}{\partial^2 \gamma} > 0$ is $\delta + \rho > \gamma$.

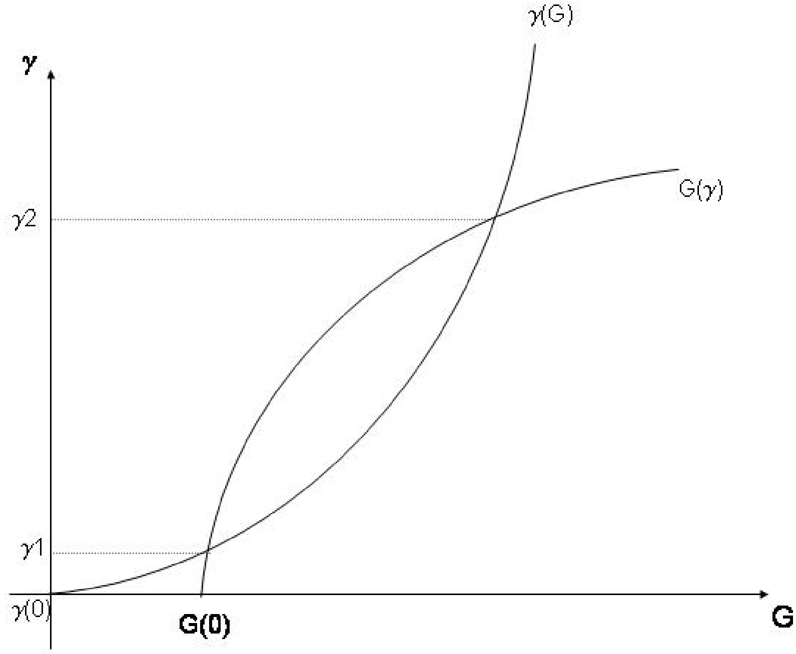


Figure 1: Multiple equilibrium growth rates

Thus, the infrastructure capital stock is an increasing, convex function of the balanced growth rate ($G = G(\gamma)$, where $G' > 0$, $G'' > 0$). We also know from section 2 that the balanced growth rate is in turn an increasing, convex function of the stock of infrastructure capital ($\gamma = \gamma(G)$, where $\gamma' > 0$, $\gamma'' > 0$). In addition, both functions are monotonic and continuous. Consequently, we potentially obtain two different equilibrium growth rates (fixed points) if we combine (11) and (17) to solve for a general equilibrium balanced growth path. Moreover, we assume that $\gamma(G_0) < \gamma(G_{max})$, where $G_{max}$ is defined as the level of $G$ such that $\gamma(G) \to \infty$. Since $\gamma$ is bounded by zero, $\gamma(0) = 0$ (due to the property that $\lim_{G \to 0} \phi(G) \to \infty$) and $G(0) = G_0 > 0$ holds in equilibrium, it follows from the intermediate value theorem and the properties of the two functions $\gamma(G)$ and $G(\gamma)$ that two strictly positive balanced growth equilibria exist. The result is illustrated in *Figure* 1. Thus, the reversed causality between the provision of infrastructure capital and economic growth potentially results in two equilibrium balanced growth rates. In the high-growth scenario, the economy is characterized by a high infrastructure capital stock and fast technological change. In the low-growth scenario, the rate of technological change is constraint by the low provision of infrastructure capital which lowers the incentive to invest in research and hence the rate of GDP-growth. This in turn limits the demand for infrastructure investments (financing constraint). Hence, if the initial stock of infrastructure capital (relative to

GDP) is too low, the growth rate of the economy is constrained. This, in turn, constraints the supply of infrastructure services so that the economy is trapped in a low-growth equilibrium. It follows from (11) that the crucial initial infrastructure level, that needs to be exceeded in order to result in the high-growth equilibrium, is declining in the quality of (research-) institutions ($\lambda$). Thus, the growth effect of infrastructure investments in transition countries depends crucially on complementary structural factors that improve the innovative capacity to adopt new technologies, e.g. an adequate quality of schooling.

In principle, sufficient public subsidies for infrastructure investments, which represent an external financing source in the model, can install the high-growth scenario. Note that public subsidies do not in general induce economic growth, but might trigger the transition to the higher balanced growth path (depending on the financing source).[23] The results of the general equilibrium model with an endogenous supply of infrastructure capital are summarized in Proposition II.

**Proposition II**: *Given the assumptions underlying the models of endogenous technical change à la Romer (1990), Assumptions 1-4, and* $0 < G_0 < G_{max}$*, there exist two strictly positive balanced growth rates with* $\gamma_1 > \gamma_2 > 0$ *if the costs of infrastructure investments are increasing over time (with the size of the economy). The high-growth economy is characterized by fast technological change and a high stock of infrastructure capital, while the low-growth economy by a low provision of infrastructure capital due to reduces expected future profits from infrastructure investments.*

The proof is given in Appendix A.

In the following, we present an explicit example. In particular, we suppose that investment costs are increasing in the size of the economy measured by GDP ($\frac{\partial^2 \mathcal{C}_{I_t,t}}{\partial I_t \partial t} > 0$).

**Increasing marginal costs**

In the following, we assume that the marginal costs of infrastructure investments are increasing in the level of GDP: $\mathcal{C}(I_t) = \mu Y_t I_t$.[24] This relationship is intuitively appealing since the production costs of infrastructure services are expected to depend on the wage level of

[23]We do not analyze the transition path belonging to both balanced growth path, but the growth rate during the transition from $\gamma_2$ to $\gamma_1$ may in principle exceed $\gamma_1$. If so, it suggests that the extraordinary growth performance of some recent economies (*growth miracles*) can be explained by one-time growth effects (and its transition path) due to the accumulation of infrastructure capital.

[24]We et $c = 0$ because this cost function already captures congestion effects.

an economy just like the production costs of final output or research. This cost function can be derived endogenously by assuming that the monopolist needs to hire unskilled labor ($U$) in order to produce infrastructure capital. If the wage of unskilled labor is proportional to the wage of skilled labor ($L$) the costs of infrastructure investments are increasing in the level of GDP. The costs function satisfies the sufficient conditions for multiple balanced growth equilibria outlined above. Substituting $\mathcal{C}(I_t, t)$, $\phi(G_t)$ and (17) into (9), we get:[25]

$$\gamma_1^{im} = \frac{\alpha(1-\alpha)\mu(\lambda+\delta+\rho) + \beta^2\chi\sigma + \chi\mu(\sigma(\delta+\rho)-\rho) + Z^{1/2}}{2\mu(\alpha(1-\alpha)+\chi\sigma)} \tag{18}$$

$$\gamma_2^{im} = \frac{\alpha(1-\alpha)\mu(\lambda+\delta+\rho) + \beta^2\chi\sigma + \chi\mu(\sigma(\delta+\rho)-\rho) - Z^{1/2}}{2\mu(\alpha(1-\alpha)+\chi\sigma)} \tag{19}$$

where $Z = [\alpha(1-\alpha)\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)]^2 - 4\mu[\alpha(1-\alpha)+\chi\sigma][\alpha(1-\alpha)\lambda\mu(\delta+\rho)-\rho(\beta^2+\chi\mu(\delta+\rho))] > 0$. As long as $\lambda > \lambda^{**} = \frac{\rho\beta^2+\rho\chi\mu(\rho+\delta)}{\alpha(1-\alpha)\mu(\delta+\rho)}$ both growth rates are strictly positive. This conditions relates the exogenous productivity of the research sector to the weighted cost of infrastructure investment/capital and ensures that expected future profits from investments in innovations are positive. Moreover, the first regime strictly dominates the second in terms of economic growth ($\gamma_1 > \gamma_2$).

Both equilibrium growth rates are strictly increasing in $\lambda$ (given $\lambda > \lambda^{**}$).[26] In addition, an increase in the exogenous (institutional) productivity parameter has a larger impact on the growth rate in the high-growth regime ($\frac{\partial\gamma_1}{\partial\lambda} > \frac{\partial\gamma_2}{\partial\lambda} > 0$). This result follows directly from the fact that the return of investments in new technologies is constrained by high intermediate business costs (low infrastructure capital) in the low-growth equilibrium. Besides, $\gamma_1$ is increasing in the share of infrastructure capital in the final output sector ($\beta$). Hence, $\gamma_1$ can potentially still be raised to a higher balanced growth path by an additional external financing source.[27] In contrast, the impact of $\beta$ on $\gamma_2$ is indeterminate and depends on the realizations of the parameter values.[28] Finally, an increase in the constant factor of the marginal investment costs ($\mu$) causes a decline in $\gamma_1$. Again, the impact on $\gamma_2$ is indeterminate. Thus, under certain parameter realization the positive effect of $\mu$ on the level of the shadow price of infrastructure capital may outweigh its direct negative effects on the

[25]Note that the infrastructure provider does not internalize the static effect of an increase in $G_t$ on the output level in a decentralized equilibrium.

[26]The exact derivatives are reported in Appendix A.

[27]Thus, the infrastructure externality outweighs the inefficiencies from the monopolies for the infrastructure capital stock belonging to $\gamma_1$. We discuss this result separately in the next section.

[28]Interestingly, the negative effect of $\beta$ on the level of the shadow price of infrastructure capital may outweigh the positive direct effect on the instantaneous profit function of the infrastructure monopolist under certain parameter realizations.

instantaneous profit function of the infrastructure monopolist.

## 4 Conclusion

This paper analyzes the interdependence between infrastructure and growth in a transition economy that is initially constrained by a scarce infrastructure capital stock. Our theoretical approach deviates from the previous literature is two ways. First, we explicitly model the effect of infrastructure capital in an economy where growth stems from investments in innovative intermediate goods. In particular, we assume that infrastructure reduces the distribution costs of specialized intermediate products. Second, we account for an infrastructure provider that dynamically optimizes her expected future profits from current investments instead of implicitly assuming that infrastructure investments follow an automatic rule governed by the static government's budget constraint. We show that these assumptions lead to a bivariate causality between infrastructure and growth. Moreover, we demonstrate that this framework leads to multiple strictly positive balanced growth equilibria if (i) infrastructure investments require different resources than research, e.g. unskilled labor, and (ii) if the costs of providing infrastructure, e.g. wages for unskilled labor, are increasing with the income level of the economy. That is, an economy that is characterized by low initial infrastructure investments may suffer from positive but reduced long-run economic growth as compared to an economy that experiences sufficient initial infrastructure investments to converge to a higher long-run equilibrium balanced growth path. In the former scenario, economies are trapped in a low growth equilibria since a low balanced growth rate reduces the expected future profits from current infrastructure investments. External financing sources, e.g. public subsidies, can potentially trigger the convergence to a high balanced growth equilibrium. Moreover, a structural change in complementary factors that influence the efficiency of technology adoptions, e.g. better schooling or the removal of external trade barriers, may trigger the convergence to a higher long-run balanced growth path. In particular, these complementary factors raise the expected profits from infrastructure investments.

The model illustrates that the relationship between infrastructure and growth is potentially non-linear. Thus, infrastructure investment might induce tremendous growth effects in transition countries if they trigger the convergence of the economy to a higher balanced growth path. This scenario is more likely if complementary structural factors are growth-promoting, e.g. an adequate quality of schooling. On the other hand, the impact of infrastructure investments (subsidies) on growth might be very low or even insignificant if they are not sufficiently large in the low growth scenario. Thus, future empirical work should account for potential non-linearities in the infrastructure growth nexus due to the existence of a bivariate causality. The importance of a non-linear empirical relationship can be examined with cross-country as well as firm-level data if regional infrastructure measures are available.

# A Appendix

## A.1 Proof of Proposition II

Given the assumptions underlying Proposition I, we know that the balanced growth rate is a continuous, monotonic, increasing function of the stock of infrastructure capital (assuming $\lambda > \lambda^{**} = \frac{\rho\beta^2+\rho\chi\mu(\rho+\delta)}{\alpha(1-\alpha)\mu(\delta+\rho)}$). Since we assume $\phi'(G) < 0$, $\phi''(G) > 0$ and $\lambda > \lambda^{**}$, we can infer from (11):

$$
\begin{aligned}
\frac{\partial\gamma}{\partial G} &= \frac{\partial\gamma}{\partial\phi(G)}\frac{\partial\phi(G)}{\partial G} = \left(\frac{-\chi\rho[a+\chi\sigma\phi(G)]-\chi\sigma\hat{\lambda}}{[a+\chi\sigma\phi(G)]^2}\right)\phi'(G) > 0 \\
\frac{\partial^2\gamma}{\partial^2 G} &= \frac{\partial^2\gamma}{\partial^2\phi(G)}\frac{\partial^2\phi(G)}{\partial^2 G} = \left(\frac{\chi^2\rho\sigma[a+\chi\sigma\phi(G)]^2+2\chi^2\sigma^2[a+\chi\sigma\phi(G)]\hat{\lambda}}{[a+\chi\sigma\phi(G)]^3}\right)\phi''(G) > 0
\end{aligned}
$$

where $\hat{\lambda} = a\lambda - \chi\sigma\phi(G) > 0$ and $a = \alpha(1-\alpha) > 0$.
Hence, the balanced growth rate is a strictly convex function of the stock of infrastructure capital: $\gamma = \gamma(G)$, $\gamma'(G) > 0$, $\gamma''(G) > 0$.
The equilibrium provision of infrastructure capital is given in (17). The marginal variable investment costs are a continuous, monotonic, increasing function of time ($\frac{\partial\mathcal{C}_{I_t}}{\partial t}$>0). In order to sustain (positive) balanced growth, we assume that marginal infrastructure investment costs increase proportional to the GDP-level in the economy ($I_t = \delta G_t$), but can not exceed it.[29] It follows from (14) that infrastructure capital is a continuous, monotonic function of the balanced growth rate in equilibrium. This allows us to define $N(t) = \frac{Y_t}{\mathcal{C}_{I_t}}$, where $N'(t) \geq 0$, $N''(t) \geq 0$. We also defined $\frac{\dot{\mathcal{C}}_{I_t}}{\mathcal{C}_{I_t}t} = M(t)$, where $M'(t) > 0$ and $M''(t) = 0$ in a balanced growth equilibrium. Thus, we can infer from (17):

$$
\begin{aligned}
\frac{\partial G}{\partial\gamma} &= \frac{\beta^2N'[\delta+\rho-M(\gamma)]+\beta^2N(\gamma)M'}{[\delta+\rho-M(\gamma)]^2} > 0 \\
\frac{\partial^2 G}{\partial^2\gamma} &= \frac{[\beta^2N''[\delta+\rho-M(\gamma)]-\beta^2N'M'][\delta+\rho-M(\gamma)]+[\beta^2N'[\delta+\rho-M(\gamma)]M']}{[\delta+\rho-M(\gamma)]^3} \\
&+ \frac{[\beta^2N'F'+\beta^2N(\gamma)M''][\delta+\rho-M(\gamma)]+\beta^2N(\gamma)M'M'}{[\delta+\rho-M(\gamma)]^3} > 0
\end{aligned}
$$

[29] Note that this is a necessary but not a sufficient condition for the existence of a balanced growth equilibrium. In order to obtain a sufficient condition, we would need to impose quantitative assumptions on $\phi(G_t)$ and $\mathcal{C}(I_t, t)$ relative to $Y_t$.

The first derivative is always positive. A sufficient condition for the second derivative to be positive is $\delta+\rho-M(\gamma)>0$, which we assume. Hence, we do not allow that the growth rate of the marginal (variable) infrastructure investment costs exceeds the summation of the depreciation rate for infrastructure capital and the intertemporal elasticity of substitution. A violation of this condition is empirically irrelevant so that the restriction is rather technical. Hence, the infrastructure capital stock is a strictly convex function of the balanced growth rate: $G=G(\gamma)$, $G'(\gamma)>0$, $G''(\gamma)>0$.

In addition, we know that $\gamma=\gamma(0)=0$ since $\lim_{G\to 0}\phi(G)\to\infty$ and $G=G(0)=G_0>0$ holds by assumption. Consequently, given a balanced growth path exists, it features two strictly positive balanced growth rates $\gamma_1$ and $\gamma 2$ with $\gamma_1>\gamma 2$.

## A.2 Marginal investment costs increase in $Y_t$:

In the following, we report the partial derivatives of $\gamma_1$ and $\gamma_2$ (from (18) and (19)) with respect to $\lambda$, $\beta$ and $\mu$:

$$
\begin{aligned}
\frac{\partial\gamma_1}{\partial\lambda} &= a\mu\left(1+\frac{a\mu(\delta+\rho-\lambda)+\chi(\mu(\rho+\sigma(\delta+\rho))-\beta\sigma)}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_2}{\partial\lambda} &= a\mu\left(1-\frac{a\mu(\delta+\rho-\lambda)+\chi(\mu(\rho+\sigma(\delta+\rho))-\beta\sigma)}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_1}{\partial\beta} &= 2\beta\chi\left(\sigma+\frac{a\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho))}{Z^{1/2}}\right)>0\\
\frac{\partial\gamma_2}{\partial\beta} &= 2\beta\chi\left(\sigma-\frac{a\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho))}{Z^{1/2}}\right)<>0\\
\frac{\partial\gamma_1}{\partial\mu} &= -\frac{\beta^2\chi(\alpha\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma(\beta^2\sigma\chi+\chi\mu(\rho+\sigma(\delta+\rho))-\sigma Z^{1/2}))}{2\mu^2(a+\sigma\rho)Z^{1/2}}<0\\
\frac{\partial\gamma_2}{\partial\mu} &= \frac{\beta^2\chi(\alpha\mu(2\rho+\sigma(\delta+\lambda+\rho))+\sigma\chi(\beta^2\sigma+\mu(\rho+\sigma(\delta+\rho)))+Z^{1/2})}{2\mu^2(a+\sigma\rho)Z^{1/2}}<>0
\end{aligned}
$$

where $Z=[a\mu(\lambda+\delta+\rho)+\beta^2\chi\sigma+\chi\mu(\sigma(\delta+\rho)-\rho)]^2-4\mu[a+\chi\sigma][a\lambda\mu(\delta+\rho)-\rho(\beta^2+\chi\mu(\delta+\rho))]>0$ and $a=\alpha(1-\alpha)$.

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