PUBLIC INVESTMENT RULES AND ENDOGENOUS GROWTH
WITH EMPIRICAL EVIDENCE FROM CANADA

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Forthcoming in the Scottish Journal of Political Economy

June 2002

Abstract: This paper examines theoretically and empirically the effects of public investment rules on output growth in an economy with private and public capital. It is shown that the decisions on public capital formation are closely associated with the growth rate of output and generate endogenous growth. A permanent change in the policy rule implies a new long-run growth rate of output, but the economy will only gradually approach the new steady-state due to adjustment costs in private capital accumulation. The model predictions are tested using data from Canada for the period 1955-1999. The data support the endogenous growth hypothesis and the two central assumptions of the model: (i) the growth rate of output follows closely the rate of infrastructure formation and (ii) private capital formation also follows the rate of infrastructure formation but adjusts with a delay.

JEL Classification Number: H54; O41
Keywords: endogenous growth, public and private capital, adjustment costs, Canada.

Acknowledgements: Partial financial support from the Secretariat of Research and Development in Greece is gratefully acknowledged. I have benefited from extensive discussions with G. Alogoskoufis and from comments and suggestions by an anonymous referee, P. Kalaitzidakis, A. Philippopoulos, and by seminar participants at the Athens Institute of Economic Policy Studies. Parts of sections 2 and 3 of the paper were circulated in the CEPR Discussion Paper No. 1479 (joint with G. Alogoskoufis) under the title ‘Public Investment and Endogenous Growth in a Small Open Economy’. The usual proviso applies.

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1. Introduction

One of the central aspects of the revival of endogenous growth theory is the focus on the impact of capital accumulation. Generally, ‘capital fundamentalism’ (surveyed by King and Levine, 1994) claims that national policies on capital formation can be viewed as the primary determinant of growth. Empirical studies show that investment rates are significantly related to economic growth when cross-section estimates are considered (Levine and Renelt, 1992) and that differences in growth across countries can, to a large extent, be explained by differences in the capital accumulation process. In the context of endogenous growth theory, Barro (1990) and Barro and Sala-i-Martin (1992) have developed models in which government productive activities affect output through the production function as a factor along with private capital and labour. They have studied how growth rates are affected by the supply of government productive activities and find that output growth can be positively related to the share of these activities in output and examine various policy implications.

This paper examines the impact of public investment rules on growth in an open economy with private and public capital. It is shown that when the authorities pursue a target for public investment formation the rate of public capital formation becomes the sole determinant of the growth rate in the steady state. Also, under the presence of adjustment costs in private investment, the rate of private capital formation adjusts gradually towards the steady state. The model is able to explain persistent differences in growth rates (following, among others, Barro, 1990, and Barro and Sala-I-Martin, 1992) by extending the basic framework to a more general formulation with the inclusion of public capital, which plays a significant role for the performance of the economy.

The approach adopted here differs from those of Barro (1990) and Barro and Sala-I-Martin (1992) in that the public capital accumulation rule is modelled explicitly and in that the economy does not achieve the new steady state growth rate immediately due to adjustment costs in private capital formation. In a similar vein, Turnovsky (1997) has considered an open economy model with the stocks of public and private capital as productive inputs, and adjustment costs in both types of capital. The author has examined the implications for the growth dynamics when public investment enhances private investment and growth, but is also

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1 Levine and Renelt (1992), Mankiw et al. (1992) and De Long and Summers (1993) have used the investment to GDP ratio as an explanatory variable in cross-country regressions and find statistically significant coefficients. Easterly and Rebelo (1993) also report a robust statistical correlation of infrastructure (transport and communication) with growth.

2 For a theoretical analysis of a two-sector model with private and public capital stock and the effects of taxation see Futagami et al. (1993).
subject to congestion. The model of Turnovsky (1997) is suitable for a general equilibrium analysis of public investment effects in the context of endogenous growth, and for the evaluation of fiscal and welfare effects in an economy with enough resources available for financing public capital accumulation.

In the current analysis the weight is placed on the benefits arising from public capital formation on private investment and growth by concentrating entirely on the supply-side impact stemming from increased productivity. Thus, the fiscal stance of the country or welfare issues are not examined. Instead, the model presented here provides a theoretical framework for analysing the long-run impact of these flows on growth and for examining the transitional paths of key variables. It should be emphasized that since the paper focuses on the effects of infrastructure on growth, the issue of financing is sidestepped and, consequently, as in Rebelo (1991) it is not examined whether the policy rules considered are optimally chosen. The rules for infrastructure formation highlight the production-enhancing role of public capital and it is shown that differences in growth rates across countries can be explained by differences in public investment policies.

The theoretical analysis provides a rationale for empirical studies that establish a strong positive link between public investment and output growth. In particular, the model yields two testable predictions. First, the accumulation rate of infrastructure should equal the growth rate of the economy in the long run. Second, the growth rate of private capital should also equal the growth rate of infrastructure in the long run, but should adjust with a delay. These two basic propositions are tested using data from Canada for the period 1955-1999, with infrastructure defined as the capital stock in the transportation, communications, government, education and health sectors. The data provide strong support for the two central hypotheses of the model. The growth rate of infrastructural capital is found to be an important determinant of the growth rate of output and private capital in the long run, with private capital adjusting gradually to equilibrium.

The remainder of the paper is organized as follows. Section 2 sets up the representative firm model and derives the conditions for the decentralized equilibrium. Section 3 examines the implications of public investment rules. Section 4 outlines the empirical methodology and Section 5 presents the empirical evidence from Canada. Section 6 concludes the paper.

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3 Spurred by the work of Aschauer (1989), a series of empirical studies have attempted to measure the effect of public infrastructure on growth and private sector productivity; however, the question on the magnitude of this effect is still open.
2. The core model

Assume a small open economy, consisting of a large number of competitive firms. The production function of firm \( i \) has the following form:

\[
Y_i = AK_i^\alpha (hL_i)^{1-\alpha}
\]  

(1)

where \( Y_i, K_i, \) and \( L_i \) denote output, private capital, and labour of the firm \( i \), respectively, \( A \) is a constant technology parameter with \( A>0 \), and \( \alpha \) and \( (1-\alpha) \) are the relative shares of private capital and labour respectively. Following Alogoskoufis (1995), parameter \( h \) stands for human capital per worker which is a function of the existing total private and public capital stock per worker -denoted by \( K \) and \( A \) respectively- so that:

\[
h = \psi \frac{K^{\beta} A^{1-\beta}}{L}
\]  

(2)

where \( \psi>0 \) is an efficiency parameter that measures the degree of efficient use of total capital (see Holtz-Eakin and Schwartz, 1995). According to (1) and (2) the firm’s output is a function of its private capital and of the total capital which is available for the economy. The return on private capital from (1) is clearly diminishing since \( \alpha<1 \) given the total capital stock. Equation (2) is in the spirit of Romer’s (1986) approach where learning-by-doing and knowledge spillovers arise from total human capital to all producers. Each firm separately neglects its own contribution thus taking the amount of total human capital as given. Barro (1990) has also examined this type of models where public capital (or the flow of aggregate public services) is a non-rival, non-excludable good, which can be used by all firms.

In the presence of adjustment costs in the formation of private capital, the investment cost is assumed to be given by:

\[
\text{cost of investment} = I[1 + \frac{\phi}{2} \left( \frac{I}{K} \right)]
\]  

(3)

where \( I \) denotes private investment and \( \phi>0 \). Now, the infinite horizon problem of the representative firm \( i \) is to maximize the present discounted value of net output, i.e. output

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For an extensive survey see Pfæchler et al. (1996).

*In the subsequent analysis the terms ‘public capital’ and ‘infrastructure’ shall be interchangeably used.*
minus the cost of labour and investment taking \( h \) as given:\(^5\)

\[
\max \int_0^\infty e^{-rt} \left[ Y_i - w_i L_i - \left[ 1 + \frac{\phi}{2} \left( \frac{I_i}{K_i} \right) \right] I_i \right] dt
\]

s.t. to (1) and \( \dot{K} = I_i - \delta K_i \) given (2), where \( r \) is the international real interest rate (assuming uncovered interest rate parity), \( w_i \) is the real wage rate of firm \( i \), and \( \delta \) is the depreciation rate while a dot denotes a derivative with respect to time. The first-order conditions, after aggregating across firms, are given by:

\[
w = A(1 - \alpha) q^{1-\alpha} \left[ \frac{K}{\Lambda} \right]^{\alpha + \beta (1-\alpha)} \frac{\Lambda}{\Lambda}
\]

(5)

\[
\left( \frac{I}{K} \right) = \frac{q - 1}{\phi}
\]

(6)

\[
\dot{q} = (r + \delta) q - A \alpha q^{1-\alpha} \left( \frac{K}{\Lambda} \right)^{\alpha - (1-\beta)} \left( \frac{q - 1}{2\phi} \right)^2
\]

(7)

\[
\lim_{t \to \infty} (qe^{-rt} K) = 0
\]

(8)

Equation (5) is the usual condition that the real wage rate equals the marginal product of labour. Equation (6) states that private investment is an increasing function of the shadow price of private capital \( q \) and a negative function of the adjustment cost parameter \( \phi \). For investment to be positive the shadow price of price of capital has to be larger than unity due to the presence of adjustment costs. Equation (7) gives the change in the shadow price of capital as a positive function of sum of the market rate of return and the depreciation rate of private capital times its shadow price, minus the return on private capital and the marginal reduction

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\(^5\) In the current approach, public capital takes the form of infrastructure which impacts on the production of firms and leaves household utility unaffected. Turnovsky and Fisher (1995) examine the effects of the composition of government intervention between consumption (which provides direct utility to households) and infrastructure (which is highly productive) in an intertemporal optimizing framework. They find that infrastructure investment leads to a rise of the long-run capital stock and (as would be expected) induces a long-run rise of consumption and output. These effects are outweighed by the short-run reduction of welfare brought about by the accumulation of capital and the depression of consumption.
of adjustment costs as private capital increases.\textsuperscript{6} Obviously, under no adjustment costs the shadow price of capital equals unity and the market rate of return would be given by the difference between the rate of return on private capital and the depreciation rate.\textsuperscript{7} Finally, equation (8) gives the usual transversality condition.

3. Effects of public investment rules on growth

In this section the effects of public investment rules on the growth dynamics of the economy are investigated. From (1) and (2) the aggregate production function is given by:

\[ Y = A\psi^{1-\alpha} \left( \frac{K}{A} \right)^{\beta(1-\alpha)} K^\alpha A^{1-\alpha} \]  

(9)

By the aggregate production function the public investment to GDP ratio is given by:

\[ \frac{\dot{A}}{Y} = A^{-1} \psi^{\alpha-1} \left( \frac{K}{A} \right)^{\beta(1-\alpha)} - \theta \]

(10)

where \( \frac{\dot{A}}{A} = \theta \) is the growth rate of public capital accumulation.\textsuperscript{8} Therefore, any decision to target the public investment to output ratio implicitly sets a target on for the public capital accumulation rate. The effects of these two targets on the dynamic behaviour of the economy will be examined in Sections 3.1 and 3.2.\textsuperscript{9}

3.1. Public capital accumulation rate target

The first rule that is examined involves the public capital accumulation rate \( \theta \). By defining the ratio of private to public capital \( \frac{K}{A} = k \), the first-order condition (7) and the equations of motion for \( k \) are given by:

\textsuperscript{6} Competitive equilibrium allocation does not attain of course the social optimum as the marginal product of private capital in (7) falls short of the social rate of return (the term \( \alpha \) in equation (7) should be replaced by \( \alpha + (1-\alpha) \beta \) in the case of a benevolent social planner). Glomm and Ravikumar (1994) examine the correspondence of private optimization and social planning in a growth model with public investment in infrastructure.

\textsuperscript{7} For a detailed discussion of these conditions and the relationship with Tobin’s \( q \), see Hayashi (1982) and Barro and Xala-I-Martin (1995) chapter 3.5.1.

\textsuperscript{8} Note that we abstract from public capital depreciation and assume that all policies are concerned with gross public investment.

\textsuperscript{9} Alogoskoufis (1995) examines the case where the government targets the capital stock to output ratio.
\[ q = (r + \delta)q - \alpha \psi^{1-\alpha} k^{(\alpha-1)/(1-\beta)} - \frac{(q - 1)^2}{2\phi} \]  \hspace{1cm} (11)

\[ \frac{\dot{k}}{k} = \frac{q}{\phi} - \frac{1 + \phi(\delta + \theta)}{\phi} \]  \hspace{1cm} (12)

while the transversality condition can be expressed in terms of the state variable \( k \) by:

\[ \lim_{t \to \infty} (qe^{-(r-\theta)t} k) = 0 \]  \hspace{1cm} (13)

This condition implies that if \( q \) and \( k \) are constant in the steady state, then for the transversality condition to hold the steady-state real interest rate must exceed the rate of public capital accumulation. In any other case, the cost for firms measured by the world real interest rate would be smaller than expected benefits from increased production resulting in an indeterminacy of equilibrium. Hence, although the determination of \( \theta \) is not restricted in the current setting, the transversality condition sets an upper bound on \( \theta \) by imposing \( r > \theta \), i.e. the growth rate of public capital accumulation must not exceed the world real interest rate (see also Turnovsky, 1997).

Balanced growth is defined as the state where \( Y, K, \) and \( \Lambda \) grow at the same rate. In the balanced growth path \( \dot{k} = 0 \) because \( \frac{\dot{\Lambda}}{\Lambda} = \theta \) and \( \frac{\dot{K}}{K} = \theta \), and the steady state growth rate of output equals \( g^*_y = \theta \). Under this rule the growth rate of output in the steady state is solely determined by the growth rate of public capital.

By setting \( \dot{k} = 0 \) in (12) the steady-state value \( q^* \) in terms of the policy parameter \( \theta \) is obtained:

\[ q^* = 1 + \phi(\delta + \theta) \]  \hspace{1cm} (14)

By (11) and (14) the steady-state value of \( k \) is given by:\(^{10}\)

\[^{10}\] For \( k^* \) to be positive the following condition must hold: \((r + \delta)[1 + \phi(\delta + \theta)] > \frac{q}{2}(\delta + \theta)^2 \). The inequality holds and \( k^* \) is positive if: \( \theta < \delta + 2r \) which is always satisfied by the transversality condition.
The transitional dynamics can be analyzed using a phase diagram in terms of $q$ and $k$. Figure 1 shows the dynamics of the system of equations (11) and (12). The arrows indicate that there exists a unique saddle path (see Appendix A1) leading to steady-state convergence. Notice that from (12) the $q = 0$ locus has a positive slope for $q > 1 + \varphi (r + \delta) > q^*$. The last inequality holds because of the steady-state value $q^*$ and equation (13). For a low private to public capital ratio ratio the initial value of $q$ is higher than its steady-state value and the associated private investment is given by (6). Private capital accumulates over time and output increases as well reaching its steady-state growth rate $\theta$.

A permanent rise in $\theta$ moves the $k = 0$ locus upwards, as a higher value of $q$ is required to maintain $k$ steady due to the associated higher adjustment cost. As Figure 1 shows, the rise in $\theta$ is associated with a jump in $q$ along the new saddle path as agents foresee that the marginal product of private capital will increase. This generates an increase of private investment with private capital accumulation gradually approaching its steady state value $\theta$, though with a decreasing rate as adjustment costs start to operate. The economy ends with a lower private to public capital ratio$^{11}$ and a higher shadow price of private capital.

From equation (9) the transitional behaviour of output growth can be derived:

$$g_Y = \beta (1-\alpha) \frac{\dot{k}}{k} + \alpha \frac{\dot{K}}{K} + (1-\alpha) \frac{\dot{A}}{A}$$

(16)

Following the rise of public capital growth output growth rises during the transition period, but at a smaller rate as private capital accumulation is relatively slower initially and approaches only gradually its steady state value $\theta$ when the two growth rates coincide. The dynamic paths of the private to public capital ratio, the growth rate of private capital and

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$^{11}$ Differentiating $k^*$ with respect to $\theta$ one gets:

$$\frac{\partial k^*}{\partial \theta} = \left[ \frac{1}{(1-\alpha)(1-\beta)} \right] \left[ (r+\delta)\varphi \right] \left[ \frac{1+(1-\alpha)(1-\beta)}{(1-\alpha)(1-\beta)} \right] < 0$$, so $k^*$ is lower if $\theta$ increases.
output are depicted in Figures 2A and 2B.

According to this analysis, an economy that experiences a low rate of growth and a relatively low public to private capital ratio can generate higher growth by raising the long-run rate of public capital formation. Increased infrastructure raises the marginal product of private capital and induces private investment. Thus the country can attain a higher long-run growth rate of output (equal to the rate of growth of public capital) accompanied by a lower steady-state ratio of private to public capital.

### 3.2. Public capital formation to output target

Alternatively, the dynamics of private investment and growth can be investigated in the case where the government targets the ratio of gross public capital formation to output as implied by (10). From a practical viewpoint this rule may be more operational since most policy variables are usually linked to the scale of the economy. Let us denote this target by $\gamma$:

$$\frac{\Lambda}{Y} = \gamma \quad (10b)$$

By (6), (10b), and the definition of private capital formation the law of motion for $k$ is now:

$$\dot{k} = \frac{q - 1 - \delta \phi}{\phi} k - A \psi^{1-\alpha} \phi^{(1+\alpha) + \beta(1-\alpha)} \quad (17)$$

Again at equilibrium $\dot{k} = 0 \Rightarrow \dot{K} = \gamma \dot{Y}$ and the private and public capital accumulation rates are

$$\frac{\dot{K}}{K} = \frac{\Lambda}{\Lambda} = A \psi^{1-\alpha} \phi^{(1+\alpha) + \beta(1-\alpha)} \Rightarrow g_Y^* = A \psi^{1-\alpha} \phi^{(1+\alpha) + \beta(1-\alpha)}.$$ Growth is endogenous and depends positively on policy parameter $\gamma$, the constant $A$ (technology), the public to private capital ratio $k$, and the efficiency parameter $\psi$.

The graphical solution of the system of equations (11) and (17) is depicted in Figure 4 and the system is saddle path stable (see Appendix A2). A permanent rise in $\gamma$ moves the $\dot{k} = 0$ locus upwards (Figure 3) implying a higher steady-state value of $g_Y^*$ (see Appendices A3 and A4) while the dynamics are the same as in the case of the public capital accumulation rule developed earlier.
4. Data and empirical methodology

The model and the rules on infrastructure formation presented in the previous sections yield two central predictions about the effects of public capital:

- First, both rules (public capital accumulation rate and gross public capital formation as a share of output) result in an equilibrium path for the economy where the public capital accumulation rate equals the growth rate of the economy.
- Second, under both rules the private capital accumulation also adjusts fully, but with a delay due to adjustment costs in private investment.

These two rules could be tested in developed economies, where the reported stocks of infrastructural capital are not subject to the large measurement errors frequently encountered in capital stock estimates for less developed economies. In the current paper, these predictions are tested empirically using data from Canada on output and capital stocks for three reasons. First, the Canadian economy is relatively open and takes world interest rates as exogenously given. Second, Canada’s economy possesses a variety of natural resources whose exploitation relies heavily on infrastructural capital. Third, the Statistics Canada department provides via the CANSIM database a detailed system for national accounts with stocks of sectoral capital starting from 1955.

The dataset utilized here covers the period 1955-1999 and consists of output growth and accumulation rates for capital. Output growth per capita is given by the GDP growth rate minus the population growth rate. Given the importance of public (infrastructural) capital in the current approach, a definition was adopted that includes the capital stock in the transportation, communication, government, education, health and social service, and other utility industries. This definition takes into account all pure public sector services and, additionally, the human capital formation process. It should be emphasized that although the capital stock in these categories is not entirely of public ownership, the adopted measure broadly constitutes the infrastructural capital of the economy with the largest share involving public sector activities. In turn, the private capital stock is defined as the total capital stock minus infrastructure.12 (The analytical description of the components for each definition of infrastructural capital is given in the Data Appendix.)

Previous studies on the growth determinants in Canada have placed emphasis on the

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12 Alternatively, one could discriminate between ‘productive’ and ‘unproductive’ capital formation, as done by Kneller et al. (1999) for the various forms of government expenditures. ‘Productive’ capital formation would then not differ from infrastructural capital formation, as long as the government can set a target similar to those developed earlier.
export-led character of the economy. This strand of the literature, however, has paid less attention to domestic factors considered to be the driving forces of growth in standard growth models, like private and public investment expenditures. Following the work of Aschauer (1989), some authors have attempted to investigate the effects of private and public investment on output in Canada. Serletis (1994, 1996) reports that the investment to output ratio is found to be non-stationary, even when government investment expenditures are included in the relevant empirical specification; this contrasts with the prediction of the standard stochastic neoclassical growth model with exogenous technological change. Bodman (1998) estimates an extended production function and finds that infrastructural capital has a significant impact on growth. Along the same line, Wylie (1995, 1996) has found that infrastructure plays an important in enhancing productivity in Canada with an elasticity comparable to the one reported for the U.S. by Aschauer (1989). The author stresses that due to the specific characteristics of the Canadian economy (lower population density, harsher physical climate) it is not surprising that infrastructure is found to be crucial in fostering productivity growth.

There is by now a large literature on the empirical impact of public policies on growth (surveyed by, among others, Pfaehler et al., 1996, Poot, 2000, Brons et al., 2000). These studies can be broadly classified into three categories depending on the adopted econometric approach: cross section, time-series, and pooled cross section regressions. All studies emphasize the potential importance of governmental actions on the growth pattern of the economy, which may take various forms. For instance, the government may affect growth through the various forms of public infrastructure and their positive externalities, but also through policies such as taxation, public consumption, defense spending etc.

To isolate the effect of public infrastructure on growth and private capital it is essential to take into account all these factors that are likely to be of importance. Therefore, given (i) the theoretical predictions of the model, (ii) the consideration of the existing empirical literature, and (iii) the dataset consisting of a single country time-series, the testing strategy involves two steps. First, the GDP growth rate is regressed on the public capital growth rate to test the first prediction of the model. Second, the private capital growth rate is regressed on its own lag and the public capital growth rate to test the second prediction. To account for the potential endogeneity between output growth and capital accumulation, all estimates are
obtained by Instrumental Variables with one lag as an instrument. In addition, to examine the robustness of the results the set of conditioning variables is extended to include other potentially relevant variables, such as fiscal components of GDP and a measure of competitiveness in world markets. Their selection is based on previous empirical studies on the impact of various economic variables on growth and on the specific characteristics of the Canadian economy.

5. Empirical results

In this section the two central hypotheses put forward by the theoretical analysis regarding the impact of infrastructure formation on growth and private capital in Canada are tested. The first column of Table 1 gives the empirical results from the regression of output growth on the infrastructure accumulation rate. The estimated coefficient on public infrastructure for this specification is statistically significant and the hypothesis that it equals unity cannot be rejected. For comparison purposes, the estimated equations with an intercept term included are also reported (second column of Table 1). The estimate of the coefficient on infrastructure is now lower, but nevertheless the hypothesis that it equals unity cannot be rejected at the 1% significance level.

Next, the set of variables is extended to examine the robustness of these results to alternative specifications (see the Data Appendix for an analytical description of the conditioning variables). The first version for each model does not include a constant term in the estimated equation (as predicted by the theoretical results). In particular, the third and fourth columns of Table 1 include public consumption (as % of GDP). The latter constitutes the largest part of total public expenditures and, in conjunction with public capital formation, gives a measure of the size of the public sector according to the Barro (1990) model. The coefficient on public infrastructure is again significant, but the null hypothesis that it equals unity is now rejected at the 5% significance level (but not at the 1% level). Public consumption enters with a statistically significant positive coefficient in both specifications,

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13 Standard stationarity tests (Dickey-Fuller and Phillips-Perron tests) did not reject, as expected, the stationarity hypothesis at the 5% level for all variables at hand. In addition, cointegration tests for the non-stationary output level, public and private capital stocks, did not show any evidence supporting this hypothesis.

14 Other potentially relevant variables, such as the U.S. growth rate per capita (which captures the international business cycle), the degree of openness of the Canadian economy (exports plus imports as % of GDP), private consumption and the budget deficit were utilized as potential control variables. However, none of these variables yielded statistically significant results in the empirical estimation.

15 Notice here that the standard Durbin-Watson tables are not applicable here, because the equation does not include a constant term. Instead, the modified tables provided by Farebrother (1980) should be used.
but this may be due to the omission of taxation, which under Ricardian equivalence eliminates
the impact of public consumption on output. Consistent with theory, taxation (as % of GDP)
enters with a negative sign in the estimated equations; see columns 5 and 6 of Table 1. In fact,
the hypothesis that the coefficients of government consumption and taxation in these two
specifications sum up to zero cannot be rejected, indicating that their combined impact is
neutral in the long run. Here, the coefficient on infrastructure is again significant, and the
hypothesis that it equals unity cannot be rejected at the 1% level.

Another variant of the model aims at capturing the strong open economy character of
the Canadian economy. Specifically, a measure of international competitiveness, namely the
real exchange rate vis-à-vis the United States, is included as explanatory variable. Columns 7
and 8 in Table 1 display the results from this specification and, as expected, the real exchange
rate enters with a statistically significant positive sign, whereas the hypothesis that the
coefficient on infrastructure equals unity cannot be rejected in the equation with a (statistically
significant) constant term. Finally, an attempt is made to incorporate all effects in the last
specification (columns 9 and 10), and the hypothesis of unity on the infrastructure coefficient
is accepted at the 1% level. In total, the coefficient on infrastructure is always significant at
the 1% significance level. The unity hypothesis is not rejected at the 5% level in two out of the
ten specifications, whereas it is not rejected in the remaining eight specifications at the 1%
level.

The results reported here are close to those of Kocherlakota and Yi (1997). These
authors show that if growth is exogenous (endogenous) a regression of growth on current and
lagged policy variables will yield zero (nonzero) coefficients which capture the absence
(presence) of permanent policy effects. Using long-run data from the United States and the
United Kingdom, the authors find evidence in favor of the endogenous growth hypothesis. In
the current paper, albeit the unit coefficient hypothesis is not unambiguously accepted, the
evidence provides strong support in favor of endogenous growth and shows that permanent
changes of governmental policies in Canada are likely to have permanent effects on the
growth rate of the economy. This also accords well with the findings of King and Levine
(1994) who use a sample of 67 non-oil countries and report that the long-run growth rate of
capital equals the growth rate of output during the 1980s. In their setup capital accumulation

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16 This also holds for the last specification (columns 9 and 10 of Table 1).
17 According to data from International Financial Statistics for Canada, the ratio of imports and exports relative to GDP,
which is frequently used to measure the openness of an economy, exceeds 83% for 1999 and is one of the largest figures for
OECD countries.
can only explain a part of the growth process, depending on the magnitude of the estimated capital elasticity in the production function.

On the other hand, the results reported here come in contrast with those reported by Jones (1995). Using data from 15 developed economies, Jones (1995) focuses on the time series properties of investment and output, and finds that persistent changes in investment rates are not associated with persistent changes in output. This is interpreted as evidence against endogenous growth models, where permanent changes in policy variables should lead to permanent evidence in growth. The evidence presented here indicates a potential source for this *prima facie* failure of endogenous growth models. Specifically, although standard growth models view public and private investment as perfect substitutes, if authorities pursue a target on public capital formation, then the public, rather than total, investment rate should be regarded as the main determinant of output growth over the long run.

As a second step in the investigation of the empirical validity of the model, the prediction is tested that the accumulation rate of private capital equals the accumulation rate of infrastructure in the long run, but adjustment towards equilibrium occurs more slowly. Table 2 presents the results from an autoregressive specification, where the accumulation rate of private (non-infrastructure) capital is explained by the accumulation rate of infrastructure and a lag of the dependent variable. Again, the estimates from several conditioning sets are reported according to the approach adopted earlier; the partial adjustment and the long-run coefficients can then be retrieved from these specifications. In all cases the hypothesis that the long-run coefficient equals unity is strongly supported by the data (see last row of Table 2), indicating full adjustment of private capital accumulation in the long run to changes in infrastructure accumulation rates.

In summary, the evidence reported in this section shows the following for the Canadian economy:

- The public capital accumulation rate is an important determinant for the growth rate of the economy. Although the estimates often tend to suggest a positive coefficient that is less than unity, there is substantial evidence in favor of the endogenous growth approach where governmental policies affecting public investment can, to a large extent, determine the growth rate.

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18 This specification is close to the standard partial adjustment model; here, the ‘desired’ accumulation rate of private capital is a function of the growth rate of infrastructure, while actual private capital accumulation takes place partially. Higher lag orders of the independent variables were also used, but none of these specifications yielded statistically significant results.
Private capital accumulation fully adjusts to the growth rate of infrastructural capital. This adjustment occurs with a delay, which is probably due to adjustment costs in private investment.

6. Conclusions and policy implications

A number of research papers during the last decade have sought to investigate the pattern of growth and explain differences among countries. Most agree that public capital plays an essential role for private capital accumulation and output growth. In the present paper, an attempt has been made to show how public capital formation generates endogenous output growth. More specifically, the effects of rules that target infrastructure formation were examined and it was shown that changes in infrastructure, which operate through the production function of firms, are reflected in changes of output. However, this effect is not immediate because of adjustment costs in private capital accumulation and a transition period is required during which the private sector experiences a changing marginal product of private capital. Private investment adjusts gradually until the economy ends in the new steady-state. In this sense public capital formation can become the engine of growth as higher public investment generates ongoing growth.

The predictions of the model were empirically tested for the economy of Canada. Using data for the period from 1955 to 1999 it was found that the growth rate of infrastructural capital is an important determinant of the growth rate of output. This evidence supports endogenous growth models by favouring the view that permanent policy changes in public investment trigger permanent changes in output growth. It was also found that the growth rate of public capital determines the corresponding one of private capital, which adjusts only gradually to its long-run level.

However, given the limitations of the theoretical analysis presented here (lack of welfare issues and absence of fiscal and external stance), it is essential to be careful in deriving policy implications from these findings. Still, keeping these caveats in mind, the empirical findings consistently point towards a substantial growth payoff from infrastructure formation. Practically, the results imply that the government can influence the long-run growth rate of the economy by setting an appropriate rate for infrastructural capital accumulation. This, however, does not imply that the government may choose any rate of accumulation, as in the current setup the world real interest rate places an upper bound in this policy target. Any rate above this boundary is inconsistent with steady-state convergence of
the economy, as the shadow price of capital becomes too high to be consistent with the economy’s private capital accumulation rate. Therefore, from a policy perspective authorities could adopt a high rate of infrastructure accumulation to enhance growth, provided that this rate is consistent with budgetary and balance of payments requirements and it is lower than the (fairly stable over the long run) world real interest rate.
DATA APPENDIX

The first part of the Data Appendix describes the components for each definition of infrastructural capital. All variables are given by the end-of-period capital stock.

1) **Transportation industries (CANSIM variable D991569):**
   - air transport, services incidental to air transport, railway transport and related service, water transport, services incidental to water transport, truck transport, public passenger transit systems, other transport industries, other services incidental to transportation, pipeline transport, storage and warehousing, grain elevator, other storage and warehousing industries.

2) **Communication and other utility industries (CANSIM variable D992037):**
   - communication, telecommunication broadcasting, telecommunication carriers, other telecommunication industries, postal and courier services, electric power systems, gas distribution systems, water systems, other utility industries n.e.c.

3) **Government service industries (CANSIM variable D992741):**
   - federal government, provincial and territorial government, local government.

4) **Education service industries (CANSIM variable D992883):**
   - elementary and secondary education, post-secondary non-university education, university education.

5) **Health and social service industries (CANSIM variable D993018):**
   - hospitals, other health and social service industries.

The second part of the Data Appendix describes the conditioning variables included in Tables 1 and 2. All variables were obtained as % of GDP (see text for the definition) from the IFS CD-ROM, December 2000 edition, except of the real exchange rate, which was constructed by the authors (see below).

1) **Public consumption:** Government consumption expenditure (IFS variable 15691F.CZF)

2) **Taxation:** Government revenue (IFS variable 15681.ZF)

3) **Real exchange rate:** Canada/US nominal exchange rate times US Wholesale Price Index divided by Canada Wholesale Price Index (Source: Global Financial Data, Annual Worksheets).
REFERENCES


APPENDIX

A1. Proof that the system of (11) and (12) is saddle path stable.

The stability of the system (11) and (12) can be examined by its eigenvalues. Linearizing around the steady state where $q^* = 1 + \phi(\delta + \theta)$:

$$\begin{bmatrix}
q \\
k
\end{bmatrix}
= \begin{bmatrix}
r - \theta & A\psi 1-\alpha \alpha (1-\alpha)(1-\beta) k^* (\alpha-2)+\beta (1-\alpha) \\
k^* & 0
\end{bmatrix}
\begin{bmatrix}
q - q^* \\
k - k^*
\end{bmatrix}$$

The eigenvalues given by the characteristic equation are:

$$\lambda_{1,2} = \frac{r - \theta \pm \sqrt{(r - \theta)^2 + 4A\psi 1-\alpha \alpha (1-\alpha)(1-\beta) k^* (\alpha-1)(1-\beta))\phi}}{2}$$

Both roots are real since the root term is positive. One root is positive (for the plus sign) and the other one is negative if:

$$r - \theta < \sqrt{(r - \theta)^2 + 4A\psi 1-\alpha \alpha (1-\alpha)(1-\beta) k^* (\alpha-1)(1-\beta))\phi}$$

and since the l.h.s. and r.h.s. terms are positive it also holds that:

$$(r - \theta)^2 < (r - \theta)^2 + 4A\psi 1-\alpha \alpha (1-\alpha)(1-\beta) k^* (\alpha-1)(1-\beta))\phi$$

which is true and the system is saddle path stable. Assume that $\lambda_1 < 0$ and $\lambda_2 > 0$ and that the elements of the coefficient matrix are denoted by $c_{ij}$ for the element of the $i^{th}$ row and the $j^{th}$ column. The solution of the system is given by:

$$q = q^* + \left(\frac{\lambda_1 - c_{11}}{c_{12}}\right) C_1 e^{\lambda_1 t} + \left(\frac{\lambda_2 - c_{11}}{c_{12}}\right) C_2 e^{\lambda_2 t}$$

$$k = k^* + C_1 e^{\lambda_1 t} + C_2 e^{\lambda_2 t}$$

where $C_1$ and $C_2$ are constants. For the solution to be bounded it must hold that $C_2 = 0$. The response of the jump variable $q$ after a permanent shock in $\theta$ is given by:
where the coefficient \( \frac{\lambda_1 - c_{11}}{c_{12}} \) is negative and denotes the slope of the stable saddle path.

Turnovsky (1995, p.276) shows that in the case of a temporary shock the solutions for \( q \) and \( k \) must coincide at the time that the policy is implemented so that the solution paths are continuous.

**A2. Proof that the system of (11) and (17) is saddle path stable.**

The system of equations (11) and (17) is written in matrix form:

\[
\begin{bmatrix}
q \\
k
\end{bmatrix}
= 
\begin{bmatrix}
\begin{pmatrix}
\lambda_1 - c_{11} \\
c_{12}
\end{pmatrix}
& \begin{pmatrix}
-A\psi^{1-\alpha}k^{*\alpha+\beta(1-\alpha)} \\
-A\psi^{1-\alpha}(1-\alpha)(1-\beta)k^{*\alpha(1-\beta)+\beta(1-\alpha)}
\end{pmatrix}
& 0
\end{bmatrix}
\begin{bmatrix}
q - q^* \\
k - k^*
\end{bmatrix}
\]

and the roots of the characteristic equation are:

\[
\lambda_{1,2} = \frac{r - \omega \pm \sqrt{(r - \omega)^2 + 4\alpha(1-\alpha)(1-\beta)A\psi^{1-\alpha}k^{*\alpha(1-\beta)+\beta(1-\alpha)}}}{2}
\]

where \( \omega = A\psi^{1-\alpha}k^{*\alpha+\beta(1-\alpha)} \) with one root positive and one negative as in Appendix A1.

**A3. Proof that \( k^* \) decreases with an increase of \( \gamma \).**

At equilibrium \( q^* = 1 + \phi\left[\delta + (A\psi^{1-\alpha}k^{\alpha+\beta(1-\alpha)})\right] \) and the steady-state value of \( k \) is given by the implicit function:

\[
(r + \delta)[1 + \phi(\delta + \omega)] - A\psi^{1-\alpha}[\alpha + \beta(1-\alpha)]k^{*\alpha-\beta(1-\alpha)} - \frac{\phi}{2}(\delta + \omega) = 0
\]

where \( \omega \) is defined above. It follows that \( \frac{\partial k^*}{\partial \gamma} < 0 \) since

\[
\Rightarrow \frac{\partial k^*}{\partial \gamma} = -\frac{r - \omega}{\alpha + \beta(1-\alpha)k^*[(r + \delta)(1-\alpha) + \beta(1-\alpha) + \gamma(r - \omega)]} < 0
\]
A4. Proof that $g^*_Y$ increases with an increase of $\gamma$.

By $g^*_Y = A\psi^{1-a}\gamma k^{\alpha+\beta(1-a)}$ it follows that $g^*_Y$ depends positively on $\gamma$ but also positively on $k^*$ which is a negative function of $\gamma$ by the previous proof. The total effect is:

$$\frac{\partial g^*_Y}{\partial \gamma} = A\psi^{1-a}k^{*\alpha+\beta(1-a)} \left[ \frac{[\alpha + \beta(1-\alpha)]\gamma \partial k^*}{k^*} + 1 \right]$$

The term $A\psi^{1-a}k^{*\alpha+\beta(1-a)}$ is positive, so the term in brackets is positive, i.e.

$$\left[ \frac{[\alpha + \beta(1-\alpha)]\gamma \partial k^*}{k^*} \right] > (-1).$$

By the previous proof:

$$\gamma \left[ \frac{(r - A\psi^{1-a}k^{*\alpha+\beta(1-a)})}{(r + \delta) + (1-\alpha) + \beta(1-\alpha) + \gamma(r - \eta\psi^{1-a}k^{*\alpha+\beta(1-a)})} \right] < 1$$

and since all terms are positive the inequality holds and $\frac{\partial g^*_Y}{\partial \gamma} > 0$. In a similar manner it can be shown that $q^* = 1 + \phi[\delta + (A\psi^{1-a}\gamma k^{\alpha+\beta(1-a)})]$ is a positive function of $\gamma$, i.e. $\frac{\partial q^*}{\partial \gamma} > 0$. 
FIGURE 1: A fixed rate of growth of public capital $\theta$ and the effects of a rise of $\theta$

$q = 1 + \varphi(r + \delta)$

$q^{**} = 1 + \varphi(\delta + \theta')$

$q^* = 1 + \varphi(\delta + \theta)$

$k^{**}$

$k^*$

$q = 0$

$k' = 0$

$k = 0$
FIGURE 2A: Effects of a rise of $\theta$ on the private to public capital ratio

FIGURE 2B: Effects of a rise of $\theta$ on output and private capital growth rates
FIGURE 3: A fixed share of public investment to output $\gamma$ and the effects of a rise of $\gamma$ 

\[ q = 1 + \varphi(r + \delta) \]

\[ q^{**} = 1 + \varphi(\delta + A \psi^{1-\alpha} \gamma k^{*\alpha + \beta(1-\alpha)}) \]

\[ q^* = 1 + \varphi(\delta + A \psi^{1-\alpha} \gamma k^{*\alpha + \beta(1-\alpha)}) \]
Table 1. Regression of output growth rate on infrastructure, Canada 1956-1999

Dependent variable: GDP per capita growth rate

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Simple model</th>
<th>Public consumption</th>
<th>Public consumption and taxation</th>
<th>Competitiveness</th>
<th>Public sector and competitiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<tr>
<td></td>
<td>1.922**</td>
<td>-</td>
<td>-</td>
<td>-17.609*</td>
<td>-3.363</td>
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<td></td>
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<td>(2.149)</td>
<td>(3.784)</td>
<td>(7.520)</td>
<td>(26.453)</td>
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<td>0.759**</td>
<td>0.735**</td>
<td>0.734**</td>
<td>0.726**</td>
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<td>(0.109)</td>
<td>(0.104)</td>
<td>(0.112)</td>
<td>(0.115)</td>
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<td></td>
<td>0.742**</td>
<td>0.742**</td>
<td>0.734**</td>
<td>0.726**</td>
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<tr>
<td></td>
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<td>(0.107)</td>
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<tr>
<td>Public consumption</td>
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<td>0.116**</td>
<td>0.231*</td>
<td>-</td>
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<td>-</td>
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<td>[0.042]</td>
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</table>

Notes:
1) The reported coefficients are from IV estimation with one-lag independent variables as instruments. Standard errors are in parentheses. A star denotes significance at the 5% level and two stars significance at the 1% level.
2) The Wald test is a test on the restriction that the coefficient of the infrastructure variable equals unity. The reported statistic is distributed as $\chi^2$ and probability values are in parentheses.
Table 2. Regression of private capital growth rate on infrastructure, Canada 1956-1999

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Simple model</th>
<th>Public consumption</th>
<th>Public consumption and taxation</th>
<th>Competitiveness</th>
<th>Public sector and competitiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
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<td>- 0.083</td>
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<td>-25.052*</td>
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<td>(0.410)</td>
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<td>(1.832)</td>
<td>(5.643)</td>
<td>(9.666)</td>
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<tr>
<td>Lagged private capital growth rate</td>
<td>0.294* (0.127)</td>
<td>0.278** (0.093)</td>
<td>0.277** (0.094)</td>
<td>0.277** (0.094)</td>
<td>0.244* (0.100)</td>
</tr>
<tr>
<td>Infrastructure formation rate</td>
<td>0.733** (0.147)</td>
<td>0.728** (0.116)</td>
<td>0.729** (0.115)</td>
<td>0.729** (0.117)</td>
<td>0.779** (0.127)</td>
</tr>
<tr>
<td>Public consumption</td>
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<td>0.007</td>
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<td>(0.300)</td>
<td>(0.263)</td>
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<tr>
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<td>-0.207</td>
<td>-0.284</td>
<td>-0.262</td>
</tr>
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<td>(0.293)</td>
<td>(0.344)</td>
<td>(0.293)</td>
<td>(0.344)</td>
<td>(0.295)</td>
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<tr>
<td>Real exchange rate</td>
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<td>(3.833)</td>
<td>(1.299)</td>
<td>(7.137)</td>
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<td>0.92</td>
<td>0.91</td>
<td>0.91</td>
<td>0.91</td>
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<td>(0.915)</td>
<td>(0.913)</td>
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<td></td>
<td>(0.701)</td>
<td>(0.704)</td>
<td>(0.983)</td>
<td>(0.567)</td>
<td>(0.983)</td>
</tr>
</tbody>
</table>

Notes:
1) The reported coefficients are from IV estimation with one-lag independent variables as instruments. Standard errors are in parentheses. A star denotes significance at the 5% level and two stars significance at the 1% level.
2) The Wald test is a test on the restriction that the ratio of the coefficient of infrastructural capital over one minus the coefficient of private capital equals unity. The reported statistic is distributed as $X^2$ and probability values are in parentheses.