Do States Optimize?
Public Capital and Economic Growth

by

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I. Introduction

In recent years, a substantial research effort has focused on estimating the contribution of public infrastructure capital to the productivity of private factors of production and to economic growth. This research initiative appears to have sprung from the recognition of two facts about public infrastructure spending in the United States. First, public nonmilitary capital accumulation, expressed as a percentage of output or of the government budget, peaked in the latter half of the 1960's and, as a result, has been seen as a potential explanatory force in the productivity growth slowdown of 1970's and 1980's. Second, over the past few decades the United States has devoted a smaller share of gross domestic product to public infrastructure than other industrialized countries, which has led to the possibility that public capital might partly explain the relatively low rate of productivity growth in the United States *vis-a-vis* other countries such as Japan and Germany.

The early empirical work in this area, conducted largely at the aggregate level, indicated quite high returns to public capital investment and led some researchers to strong conclusions about the role of public capital in the productivity slowdown. For instance, Munnell (1990a) boldly stated that "the drop in labor productivity [*sic*] has not been due to some mystical concept of multifactor productivity or technical progress. Rather, it has been due to a decline in the growth of public infrastructure."

As it now stands, the literature contains a relatively wide range of estimates, with a marginal product of public capital which is well in excess of that of private capital (*e.g.*, Aschauer (1989), Fernald (1992), and Kocherlakota and Yi (1996)), approximately equal to that of private capital (*e.g.*, Munnell (1990b)), well below that of private capital (*e.g.*, Eberts (1986) and Holtz-Eakin (1994)) and, in a couple of instances, even negative (*e.g.*, Evans and Karras (1994) and Hulten and Schwab (1991)). Some economists argue that the wide range of estimates render the results useless from the policy perspective (Aaron (1991)). Others point to a list of potential statistical problems--a reverse causation from productivity to public capital, a spurious correlation due to nonstationarity and/or to the omission of relevant variables--to argue that the empirical results are built on "fragile statistical foundations" and should be viewed with extreme skepticism (Jorgenson (1991)). A few economists go to the extreme and conclude that "there is no statistically significant relationship between public capital and private output" (Tatom (1993)).

Still, some economists involved in the debate about the macroeconomic effects of public capital have been convinced enough by the empirical results to assert that an increase in public investment spending can be safely expected to raise economic growth. Yet the finding that public capital is productive, even if valid, is not sufficient to ensure that boosting public investment spending will stimulate long term growth.[1] At least three considerations must be addressed. First, there is the question of whether a permanent increase in public investment induces a permanent, or merely a temporary, increase in economic growth. The traditional neoclassical growth model of Solow (1956) predicts that any positive effect of an increase in the national savings and investment rate on economic growth will be transitory; the steady-state growth rate is fully determined by population growth and exogenous technological progress. In the neoclassical setting, an increase in spending on productive public capital will induce a period of temporarily high investment, but the pace of capital accumulation, and of economic growth, will slow over time as the accumulation of capital diminishes the return to capital and the incentive for further investment. In the long run, the level of output will be higher but the growth rate of output will return to the same level as before the public spending initiative.

Second, the effect of an increase in public investment on economic growth is likely to depend on the relative marginal productivity of private versus public capital. In the neoclassical setting, an increase in public investment (at the expense of private investment) will raise or lower the economic growth rate depending on whether the marginal product of public capital exceeds, or, respectively, is exceeded by the marginal product of private capital.[2] This consideration validates the concerns of Aaron and others that the range of empirical estimates of the output elasticity of public capital is too large to be informative to the public policy process; we need to know, rather precisely, not only that public capital is *productive* but that it is *sufficiently productive* to be confident of a beneficial effect of increased public investment on economic growth.

Third, the effect of public investment on growth is likely to depend on how the increased spending is financed. Empirical studies such as Engen and Skinner (1996) find evidence that increases in tax rates reduce the rate of economic growth. Thus, it is to be expected that an increase in public capital--which, in most cases, will require a corresponding increase in tax rates--will stimulate economic growth only if the productivity impact of public capital exceeds the adverse tax impact.

This paper focuses on some of these considerations by investigating the relationship between public capital, productivity, and economic growth in an endogenous growth setting. The next section of the paper lays out a simple model of an economy with productive public capital. The subsequent section reports on empirical results linking the ratio of public and private capital to productivity growth. The final section concludes by suggesting directions for future research.

II. A Model of Productive Public Capital and Economic Growth

As is typical in recent work in economic growth, we begin with a consumer/producer who maximizes a constant intertemporal elasticity of substitution utility function over an infinite planning horizon as given by

$$V = \int_0^\infty \frac{c^{1-\sigma} - 1}{1-\sigma} e^{-\rho t} dt \tag{1}$$

where c represents consumption, $-\sigma$ the constant elasticity of the marginal utility of consumption, and ρ the rate of time preference.[3] The agent has access to a Cobb-Douglas production function

$$y = k^{\alpha_k} kg^{\alpha_{kg}} \qquad \alpha_k + \alpha_{kg} = 1 \tag{2}$$

where y is output, k is a *broad* measure of private capital (inclusive of tangible and human capital), and kg is public infrastructure capital.[4] All variables are expressed in per worker terms. Thus, the production function exhibits constant returns to scale across the private and public capital inputs, but increasing returns to scale across *raw* labor and capital. The model ignores technological progress, population growth, and depreciation of private or public capital in order to bring out the essential points in the clearest manner.

The government purchases and maintains the stock of public capital which enters as an input to the private sector production function (2). At an initial point in time, the government is viewed as choosing a particular level of public capital, g_0. The initial purchase of government sector capital is assumed to be financed by the sale of perpetuities at a coupon rate of r percent. Subsequently, the government is taken to maintain a particular ratio of public to private capital

$$\phi = \frac{kg}{k} \tag{3}$$

which requires an increase in the public capital stock over time at the rate

$$\dot{kg} = \gamma \cdot kg \tag{4}$$

where γ is the rate of growth of the private capital stock.

It is assumed that the government levies a tax on private production at rate θ for the purpose of financing (*i*) the on-going public expenditure needed to maintain the public capital stock ratio against growth in the private capital stock and (*ii*) the interest payments on the initial stock of debt. Accordingly, the government budget constraint is

$$kg_0 + \int_0^\infty \dot{kg}\, e^{-rt} dt = \int_0^\infty \theta \cdot y\, e^{-rt} dt. \tag{5}$$

Given steady state growth at the rate γ, the government budget constraint reduces to[5]

$$r \cdot kg_0 = \theta \cdot y_0. \tag{6}$$

The agent maximizes utility as given in equation (1) taking the public capital stock and the tax rate as beyond his influence. The maximization of utility is subject to a standard resource constraint which determines the level of private capital accumulation as the difference between after-tax income from production and private consumption[6]

$$\dot{k} = (1-\theta)k^{\alpha_k}kg^{\alpha_{kg}} - c. \tag{7}$$

In this environment, the steady state equilibrium involves a common growth rate of consumption, public and private capital, and per worker output given by

$$\gamma = \frac{1}{\sigma}[(1-\theta)(1-\alpha_{kg})\phi^{\alpha_{kg}} - \rho]. \tag{8}$$

Evidently, the common growth rate of consumption, capital, and output depends positively on the ratio of public to private capital and negatively on the tax rate. In order to determine the *net* effect of government capital accumulation on economic growth, it is necessary to eliminate the tax rate from the growth rate expression in equation (8).

This elimination of the tax rate is accomplished in the following manner. First, note that in equilibrium the government's maintenance of a particular ratio of public to private capital, ϕ, implies that private sector output may be written as

$$y = k^{\alpha_k}kg^{\alpha_{kg}} = k^{\alpha_k}(k\phi)^{\alpha_{kg}} = k^{\alpha_k+\alpha_{kg}}\phi^{\alpha_{kg}} = k\phi^{\alpha_{kg}}. \tag{9}$$

As a further equilibrium condition, the agent must be willing to hold the available stocks of debt and private capital. Consequently, the interest rate on government perpetuities must equal the net of tax return to private capital, so that

$$r = (1-\theta)(1-\alpha_{kg})\phi^{\alpha_{kg}}. \tag{10}$$

The steady state budget constraint in equation (6) and the level of output in equation (9) may be solved for the tax rate as a function of the interest rate on public debt and the public capital stock ratio

$$\theta = r \cdot \phi^{\alpha_k} \tag{11}$$

which, after substituting into equation (10) allows us to obtain the steady state equilibrium interest rate as

$$r = \frac{(1-\alpha_{kg})\phi^{\alpha_{kg}}}{1+(1-\alpha_{kg})\phi}. \tag{12}$$

Finally, from equations (8) and (12) we get the solution for the growth rate of per worker output as a function of the public capital ratio:

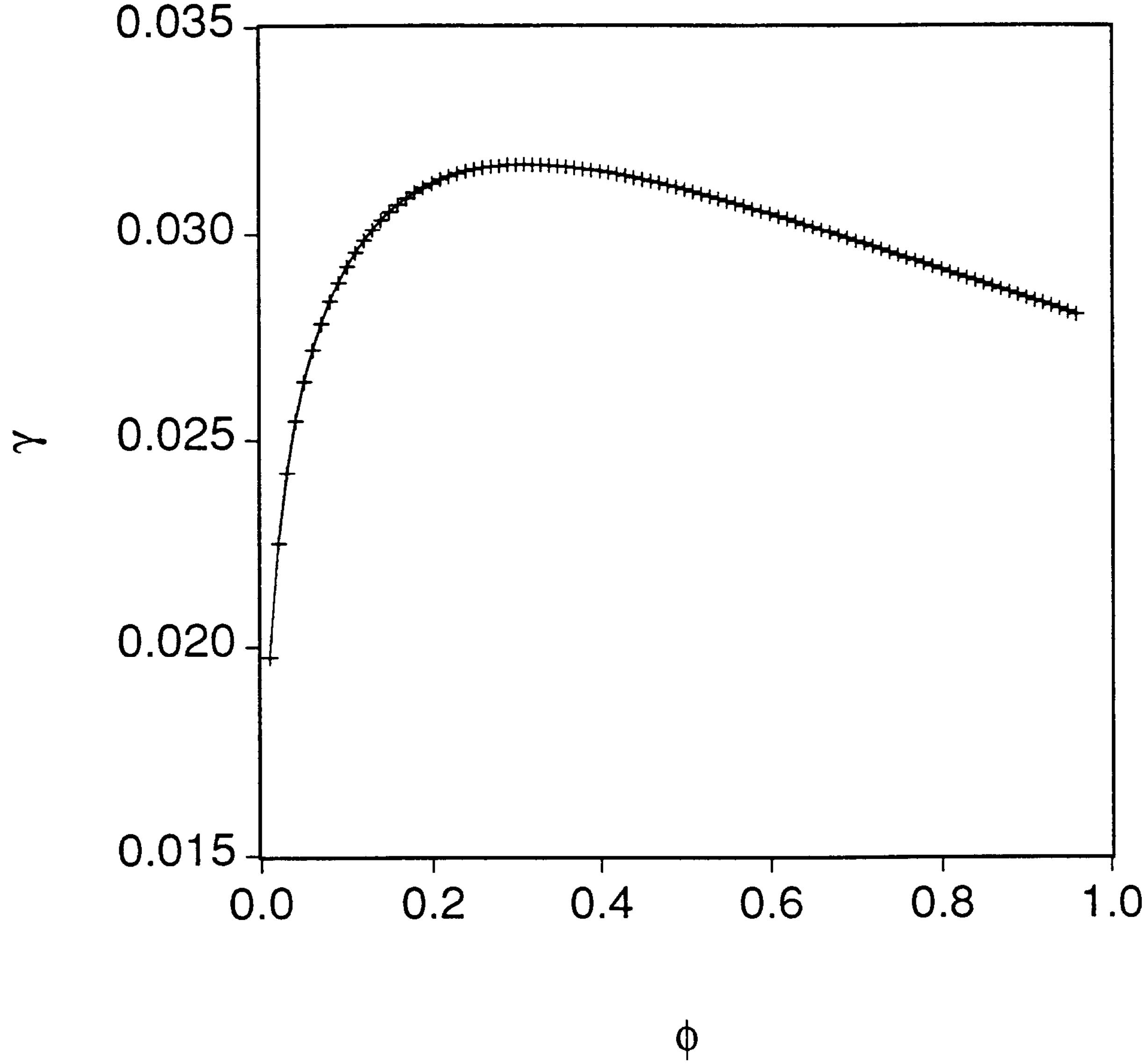
$$\gamma = \frac{1}{\sigma}\left[\frac{(1-\alpha_{kg})\phi^{\alpha_{kg}}}{(1+(1-\alpha_{kg})\phi)} - \rho\right]. \tag{13}$$

Figure 1 traces out the relationship between the growth rate, γ, and the ratio of public to private capital, ϕ, for an output elasticity of public capital equal to 0.2. The growth rate initially rises with the ratio of public to private capital, reaches a maximum, and then falls toward zero. The intuition, similar to that described for flow government spending in Barro (1990), is straightforward. Consider an increase in ϕ induced by a marginal increase in the public capital stock. For a given tax rate, the increase in the ratio of public to private capital increases the after- tax marginal product of capital in the amount[7]

$$\frac{d[(1-\theta)mp_k]}{d\phi}\Big|_{\theta = \bar{\theta}} = \frac{\alpha_{kg}\phi^{\alpha_{kg}-1}}{1+(1-\alpha_{kg})\phi}. \tag{14}$$

where mp_k represents the marginal product of private capital. Taken alone, this increase in the marginal product of capital would be conducive to growth. However, the increase in the public capital stock also requires a rise in the tax rate which, in turn, reduces the after-tax return to capital in the amount

Figure 1
Growth and Government Capital
(theoretical relation)



$$\frac{d[(1-\theta)mp_k]}{d\phi}\Big|_{mp_k=\overline{mp}_k} = -\frac{(1-\alpha_{kg})\phi^{\alpha_{kg}}}{(1+(1-\alpha_{kg})\phi)^2}. \qquad (15)$$

This decrease in the after-tax marginal product of capital, when taken by itself, would deter growth. At low levels of ϕ, the productivity effect in equation (14) dominates the tax rate effect in equation (15), and the after-tax marginal product of capital rises. This rise in the return to investment, in turn, stimulates private capital accumulation and raises the growth rate. But at sufficiently high levels of ϕ, the tax effect overwhelms the productivity effect, the after-tax return to capital is depressed, and private investment and the growth rate decline.[8]

Specifically, the growth rate rises with the ratio of public to private capital from a minimum of $\gamma^{min} = -\rho/\sigma$ to reach a maximum of

$$\gamma^{max} = \frac{1}{\sigma}[\ (1-\alpha_{kg})^{2(1-\alpha_{kg})}\alpha_{kg}^{\alpha_{kg}} - \rho]. \qquad (16)$$

Equations (14) and (15) can be used to show that the maximal growth rate of per worker output, γ^{max}, corresponds to a ratio of public to private capital given by

$$\phi^{\max} = \frac{\alpha_{kg}}{(1-\alpha_{kg})^2}. \qquad (17)$$

When the tax rate function (14) is evaluated at the ratio of public to private capital which maximizes the economic growth rate, $\phi^{\max}$, we obtain the result that the tax rate should be set equal to the output elasticity of government capital, or

$$\theta^{\max} = \alpha_{kg}. \qquad (18)$$

Combining equations (17) and (18) then yields the result that the economic growth rate is maximized when the government chooses a ratio of public to private capital so as equate the *after-tax* marginal product of private capital to the marginal product of public capital:

$$(1-\theta)mp_k = mp_{kg} \qquad (19)$$

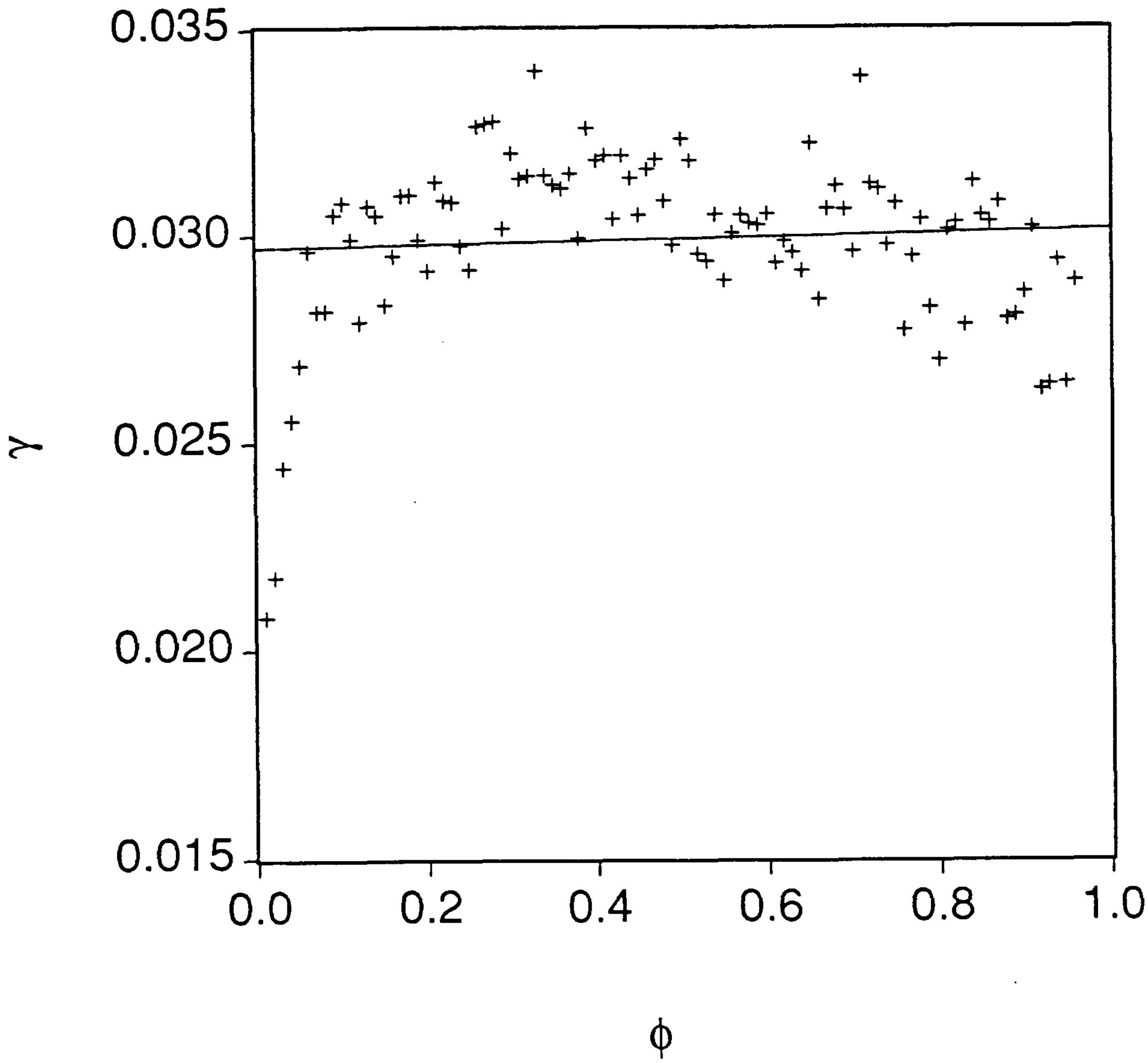
where mp_x denotes the marginal product of input x ($x = k, kg$) and we have used the fact that for the Cobb-Douglas specification of the production function the output elasticities of private and public capital are equal to α_k and a_{kg}, respectively.

Thus, the model of this section implies that there is a non-linear relationship between public capital and economic growth such that permanent increases in the public capital ratio bring forth permanent increases in growth--but only if the marginal product of public capital exceeds the after-tax marginal product of private capital. It may be important to take into account this predicted non-linearity between public capital and growth when performing empirical work. Consider, for example, Figure 2. This figure shows hypothetical data on economic growth, ranging from 2.0 to 3.5 percent per annum, and the ratio of public capital to private capital, running from 0.0 to 1.0. The former data series was produced using a random number generator to obtain a random term, η, along with the formula (representing a stochastic version of the theoretical model and equation (13) with parameter values α_{kg}= 0.2 and ρ = 0)

$$\gamma = (.05)\cdot(\frac{\phi^{.2}}{1+.8\phi}) + \eta \equiv b\cdot f + \eta. \tag{20}$$

By construction, these hypothetical data contain a strong relationship between economic growth, γ, and *suitably transformed* public capital, f; an OLS regression of γ on f yields a coefficient estimate of 0.0499 with an associated standard error of 0.0002 and has an adjusted coefficient of determination of 0.6474. Yet, as the figure indicates, these hypothetical data contain no statistical relationship between economic growth and *untransformed* public capital; an OLS regression of γ on ϕ gives a coefficient estimate of 0.0004 with an associated standard error of 0.0008 and has an adjusted coefficient of determination of -0.0072. Consequently, it can be seen that a simple non-linear regression of economic growth on public capital may convey the incorrect impression that public capital is unproductive and is incapable of affecting growth when, in fact, it is productive and--at least for a good portion of the sample--is capable of stimulating growth.

Figure 2
Growth and Government Capital
(hypothetical data)



III. Empirical Evidence on Productive Public Capital and Economic Growth

This section contains an empirical investigation of the relationship between public capital and economic growth using data for the 48 contiguous United States during the decades of the 1970s and 1980s. Table 1 provides descriptive statistics on the variables used in this study. Economic growth [γ] is measured as average annual growth in real gross state product per employed person; the basic data on current dollar gross state product were obtained from various issues of the *Survey of Current Business* (Renshaw, Trott, and Friedenberg (1988); Beemiller and Dunbar (1993)) and were placed in constant (1982) dollar, per worker terms using the deflator for gross domestic product from the *Survey of Current Business* (U.S. Bureau of Economic Analysis (annual)) and non-agricultural employment from *Employment, Hours, and Earnings, State Areas* (U.S. Bureau of Labor Statistics (annual)). As measured, economic growth ranged from a high of 3.1 percent per year (Massachusetts in the 1980s) to a low of -2.6 percent per year (Wyoming in the 1980s). The initial level of output per worker [y] is represented as the logarithm of real gross state product per employed person in 1970 and 1980, respectively, and also was obtained from the above-mentioned sources. The public capital variable [kg/k] is measured as the ratio of public capital to private capital (both in constant (1982) dollars) and was constructed using data from Munnell (1990b). This variable is expressed in initial year (1970, 1980) values in order to eliminate, or at least minimize, a potential endogeneity of the public capital stock. On average over the 48 states and the decades of the 1970's and 1980's, the public capital stock was 44.6 percent as large as the private capital stock, and took on a minimum value of 19.4 percent (Wyoming in 1980) and a maximum value of 79.3 percent (Rhode Island in 1970). The flow government spending variable [g/k] is measured as

Table 1
Descriptive Statistics

	Mean	Maximum	Minimum	Standard Deviation
γ	.004	.031	-.026	.011
y	10.416	11.201	10.121	.176
kg/k	.446	.793	.194	.136
g/k	.139	.293	.049	.049
kg(core)/k	.267	.522	.128	.075
kg(other)/k	.179	.451	.047	.082

the ratio of total general government expenditure to private capital (both in constant (1982) dollars), with the former variable being obtained from *Governmental Finances* (U.S. Bureau of the Census (annual)). This variable averaged 13.9 percent and ran from a low of 4.9 percent (Wyoming in 1970) up to a high of 29.3 percent (New York in 1970). The core public capital ratio [kg(core)/k], which is expressed as the ratio of highway and water and sewer capital to private capital, averaged 26.7 percent and attained a minimum of 12.8 percent (Louisiana in 1970) and a maximum of 52.2 percent (Rhode Island in 1970). Finally, the other public capital variable [kg(other)/k], measured as total public capital minus core public capital as a ratio to private capital, reached a low of 4.7 percent (Wyoming in 1980), a high of 45.1 percent (New York in 1970), and averaged 17.9 percent over the entire sample.

A. Growth and Government Capital: Linear Impact

We begin the empirical analysis by considering the regression equation

$$\gamma_{it} = a + b \cdot \phi_{it} + \underline{c} \cdot \underline{z}_{it} + \varepsilon_{it} \qquad (21)$$

where *a, b,* and $\underline{c}$ are coefficients to be estimated, ϕ = kg/k, $\underline{z}$ represents control variables such as the logarithm of initial output per worker and the unemployment rate, *i* refers to individual states, and *t* refers to particular decades. Table A.1 indicates a rather sizeable and statistically significant relationship between the public capital ratio and economic growth, with a coefficient estimate for kg/k ranging between 0.020 and 0.041. These estimates suggest that a one standard deviation

Table A.1 Growth and Government Capital OLS Regressions				
ϕ	.040 (.007, .009)	.020 (.006, .007)	.041 (.007, .009)	.021 (.006, .007)
y	——	-.035 (.005, .005)	——	-.034 (.005, .005)
u	——	——	.002 (< .001, < .001)	.002 (< .001, < .001)
R^2	.242	.498	.293	.545
SER ($x10^{-3}$)	9.384	7.635	9.059	7.265
LL	312.994	333.304	316.894	338.591

Notes: All regressions also contain a constant term. Ordinary and White heteroskedasticity corrected standard errors are in parentheses.

increase in the public capital ratio--say from its average value of 0.446 to 0.582--would induce a contemporaneous 0.27 to 0.54 standard deviation increase in economic growth of between 0.003 and 0.006 percentage points per year. Table A.1 also indicates a strong convergence of output per worker across states, with a coefficient estimate on the logarithm of initial year output per worker of -0.034 or -0.035. This result suggests that an increase in public capital will have transitory, but not permanent, effects on economic growth. Nevertheless, there would be a significant effect on the level of output; the same one standard deviation increase in the public capital ratio would cumulate to a 8.4 percent increase in output per worker in the long run.[9] Finally, the regressions in the last two columns of the table allow for an influence of the unemployment rate [u] on economic growth. One might suspect that the inclusion of the unemployment rate would help to ensure that the regression of economic growth on public capital would be picking up long-run (or secular) effects rather than short-run (or cyclical) effects, in which case the estimated coefficient on the unemployment rate would be expected to be positive. Specifically, the rate of growth as the economy emerges from a recession (and its associated high level of unemployment) can be expected to be higher than growth on the normal transition path to the steady state. While the unemployment rate carries the appropriate positive sign in these regressions to substantiate this argument, the effect is quantiatively small and statistically weak.

Table A.2 allows for a separate effect of the decade of the 1970s on the rate of economic growth by adding a dummy variable [d70s] to the regression equation. As might have been expected, the average rate of growth--conditional on the public capital ratio, the initial level of ouptut per worker,

Table A.2
Growth and Government Capital
OLS Regressions with Time Effect

ϕ	.045 (.007, .008)	.026 (.006, .006)	.045 (.007, .008)	.026 (.006, .006)
y	——	-.033 (.004, .005)	——	-.033 (.004, .005)
u	——	——	< .001 (.001, .001)	< .001 (.001, < .001)
d70s	-.008 (.002, .002)	-.007 (.001, .001)	-.007 (.002, .002)	-.006 (.002, .002)
R^2	.370	.599	.485	.597
SER ($x10^{-3}$)	8.549	6.825	8.587	6.841
LL	322.447	344.586	322.548	344.886

Notes: See Table A.1.

and the unemployment rate--was significantly lower during the 1970s than the 1980s, in the range of 0.006 to 0.008 percentage points per year. Nevertheless, the introduction of the time period dummy has only a minor impact on the estimated coefficients (and associated standard errors) of either the public capital ratio or the inital level of output per worker.

Table A.3 introduces separate fixed effects for the individual states in the sample and, in doing so, communicates a far different message for the role of public capital in determining economic growth rates. While the sign and magnitude of the impact of public capital on growth remains in the same neighborhood as the previous estimates--between 0.031 and 0.039--the associated standard errors increase by a factor of 5 or 6 which, in turn, renders the relationship statistically insignicant. Thus the previous finding of a significant role for public capital--at least in this linear form--cannot be taken as robust to estimation methods.

A similar message is conveyed for the role of the initial level of per worker output. In this case, the estimated coefficients become somewhat smaller in magnitude--in absolute terms, between 0.018 and 0.028--and also are rendered statistically insignificant. This is a result of independent interest, as it implies a lack of convergence in productivity levels across states economies--a finding in sharp contrast to other empirical studies of state economic growth (such as Barro and Sala-i-Martin (1991)). Presumably, the difference in results is due to the inclusion (in the present case) and exclusion (as in Barro and Sala-i-Martin (1991)) of individual state effects.

Table A.3 Growth and Government Capital Fixed Effect Regressions				
ϕ	.039 (.032, .033)	.034 (.033, .034)	.038 (.033, .034)	.031 (.034, .035)
y	——	-.018 (.027, .024)	——	-.028 (.031, .027)
u	——	——	< .001 (.001, .001)	.001 (.001, .001)
d70s	-.008 (.002, .002)	-.007 (.002, .002)	-.007 (.003, .003)	-.005 (.004, .004)
R^2	.410	.402	.398	.396
SER ($x10^{-3}$)	8.279	8.329	8.360	8.375
LL	359.322	359.800	359.440	360.350

Notes: See Table A.1.

B. Growth and Government Capital: Non-linear Impact

We next consider equations of the general form

$$\gamma_{it} = a + b \cdot f_{it} + \underline{c} \cdot \underline{z}_{it} + \varepsilon_{it} \tag{22}$$

where the variable f denotes transformed public capital as given by

$$f_{it} = \frac{\phi_{it}^{\alpha_{kg}}}{1 + (1 - \alpha_{kg})\phi_{it}} \tag{23}$$

and, as before, z represents other explanatory variables. Table B.1 contains OLS regressions of economic growth on transformed public capital under the maintained assumption that the output elasticity of public capital equals 0.30--an elasticity estimate lying between that of Aschauer (1989) at 0.39 and that of Munnell (1990b) at 0.15.[10] As with the estimates in Table A.1, there is a strong positive effect of public capital on the growth rate of output per worker; there is evidence of convergence effects across state economies; and there is little substantive role for the unemployment rate. Comparing the adjusted coefficients of determination of the analogous equations in the two tables (A.1 and B.1) indicates no clear preference for the linear or non-linear version of the relationship; for instance, the estimates contained in the first column of each table suggest a preference for the non-linear version, while the estimates contained in the fourth column of each table indicate a preference for the linear version.

Table B.2 , like Table A.2, introduces a separate time effect for the growth experience of the 1970s.

Table B.1
Growth and Government Capital
OLS Regressions
(elasticity = .30)

f	.446 (.059, .055)	.202 (.074, .065)	.455 (.057, .053)	.217 (.071, .064)
y	——	-.030 (.006, .006)	——	-.029 (.006, .006)
u	——	——	.002 (< .001, < .001)	.001 (< .001, < .001)
R^2	.367	.487	.419	.534
SER ($x10^{-3}$)	8.570	7.714	8.210	7.359
LL	321.701	332.321	326.332	337.366

Notes: All regressions include a constant term. Ordinary and White heteroskedasticity corrected standard errors in parentheses.

Table B.2
Growth and Government Capital
OLS Regressions with Time Effect
(elasticity= .30)

f	.484 (.054, .054)	.264 (.068, .064)	.482 (.054, .053)	.261 (.068, .065)
y	——	-.026 (.006, .006)	——	-.026 (.006, .006)
u	——	——	< .001 (.001, < .001)	< .001 (.001, < .001)
d70s	-.008 (.002, .002)	-.007 (.001, .002)	-.007 (.002, .002)	-.006 (.002, .002)
R^2	.489	.582	.485	.580
SER ($x10^{-3}$)	7.701	6.970	7.729	6.983
LL	332.480	342.578	332.646	342.916

Notes: See Table B.1.

The transformed public capital ratio remains as a positive and statistically significant explanatory factor for growth, and the results indicate important convergence effects. The role of the unemployment rate is attenuated, and the time effect is significantly negative. Once again, comparing the results contained in Tables A.2 and B.2 yields no clear preference for the linear or non-linear versions of the relationship between public capital and growth.

Just as with Table A.3, Table B.3 allows for individual state effects--yet with dramatically different results. The introduction of separate state effects in Table A.3 did not change, in any marked fashion, the coefficient estimates on the public capital ratio but did raise the standard errors of the coefficient estimates and left no statistically significant role for public capital. The addition of individual state effects in Table B.3, however, not only leaves a statistically significant role for public capital but raises the coefficient estimates from Tables B.1 and B.2 by a factor of 2 to 3--comparing the estimates in the last column of each of these tables, from 0.217 (Table B.1) and 0.261 (Table B.2) to 1.220 (Table B.3). Further, the results of Table B.3 provide little support for a significant convergence effect across states economies; the coefficient estimates on the initial output per worker variable carry the appropriate sign and magnitude, but are not significantly different from zero at conventional levels. Finally, the explanatory power of the regression--as measured by the adjusted coefficient of determination--is considerably higher for the equations contained in Table B.3 than for the analogous equations in Table A.3, in the range of 61 to 62 percent (Table B.3) as opposed to 40 to 41 percent (Table A.3). Consequently, a rather strong justification exists for a preference for the non-linear over the linear version of the relationship between public capital and

Table B.3 **Growth and Government Capital** **Fixed Effect Regressions** **(elasticity= .30)**				
f	1.226 (.237, .275)	1.224 (.236, .262)	1.225 (.239, .282)	1.220 (.237, .262)
y	——	-.023 (.021, .017)	——	-.033 (.024, .022)
u	——	——	< .001 (.001, .001)	.001 (.001, .001)
d70s	-.011 (.002, .002)	-.011 (.002, .002)	-.010 (.002, .003)	-.009 (.003, .003)
R^2	.616	.617	.608	.616
SER ($x10^{-3}$)	6.680	6.669	6.744	6.679
LL	379.931	381.145	380.062	382.072

Notes: See Table B.1.

growth.

Table B.4 contains estimation results for various parameterizations of *f*, where the output elasticity of public capital equals 0.20, 0.25, 0.30, and 0.35, respectively. Each of these equations in the table also contains (but does not report coefficient estimates for) a constant term, the initial level of the logarithm of output per worker, the initial unemployment rate, and a separate time effect for the 1970s.[11] Of these values for the output elasticity of public capital, the log likelihood function is maximized for the previously assumed value of 0.30. Values for the output elasticity of public capital either lower or higher than 0.30 yield lower (and often markedly less significant) coefficient estimates for the impact of public capital on growth. Figure 3 extends the results of Table B.4 by illustrating the values of the log likelihood function for output elasticities of public capital ranging in intervals of 0.01 from 0.18 up to 0.60; as the figure shows, the ascent and descent of the log likelihood values is quite steep around the maximizing value of 0.30.

Figure 4 illustrates the relationship between *f*--the transformed public capital ratio assuming an output elasticity of public capital equal to 0.30--and the actual values for the public capital ratio in the sample. The graph of this relationship peaks at

$$\phi^{max} = \frac{\alpha_{kg}}{(1-\alpha_{kg})^2} = \frac{.3}{(0.7)^2} = 0.612 \qquad (24)$$

which suggests that for most of the sample--specifically, for 87 of 96 observations--the actual public

Table B.4
Growth and Government Capital
Fixed Effect Regressions
(Varying elasticity)

elasticity	.20	.25	.30	.35
f	.284 (.253, .267)	1.040 (.297, .349)	1.220 (.237, .266)	.821 (.179, .204)
R^2	.401	.519	.616	.583
SER ($x10^{-3}$)	8.339	7.746	6.679	6.955
LL	360.767	371.250	382.072	378.184

Notes: See Table B.1.

Figure 3
Log Likelihood Values: Varying kg/k

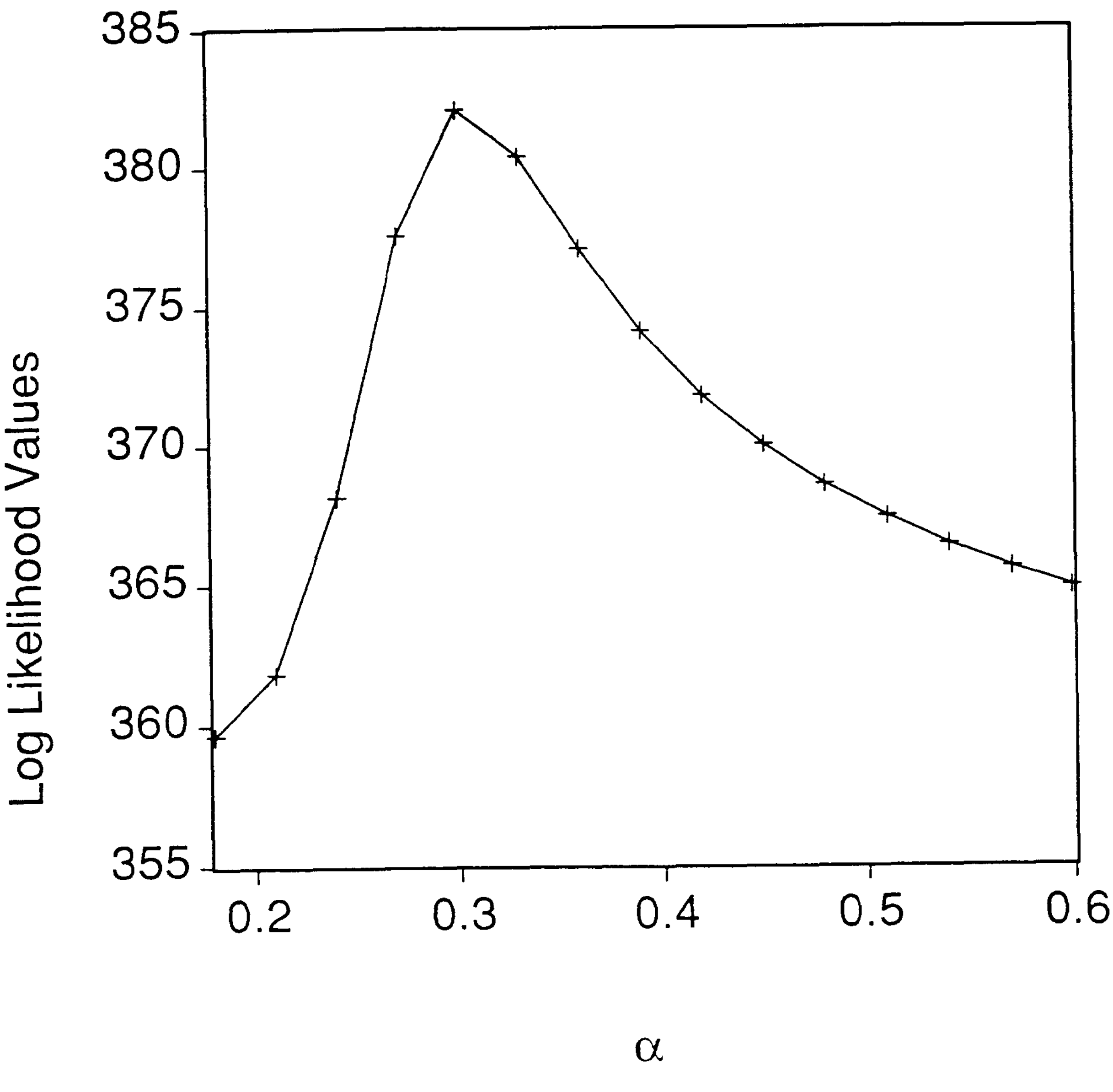
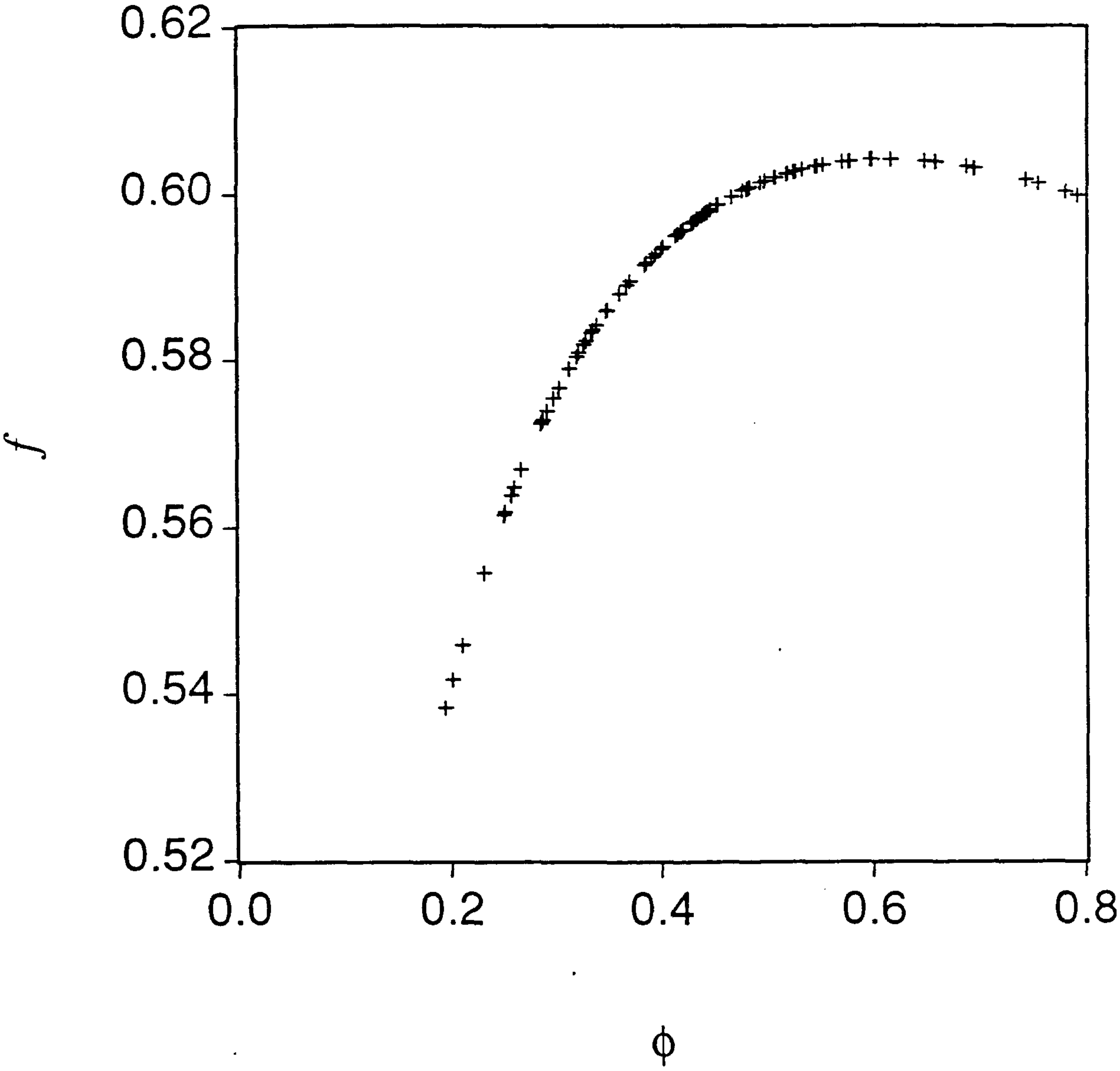


Figure 4
Deficient Public Capital?



capital ratio falls below the growth maximizing value of the public capital ratio of 0.612. In this sense it can be said that the government capital stock is deficient; for these 87 observations an increase in the public capital ratio would have increased the economic growth rate.

The precise magnitude of the effect of a change in the public capital ratio on growth can be obtained by differentiating equation (13) and can be shown to be given by

$$d\gamma/d\phi = \left[\frac{b\cdot(1-\alpha_{kg})^2\cdot\phi^{\alpha_{kg}-1}}{(1+(1-\alpha_{kg})\phi)}\right]\cdot[\phi^{\max}-\phi]. \qquad (25)$$

Consequently, for $b = 1.220$ and $\alpha_{kg} = 0.3$, a one standard deviation increase in the public capital ratio from its sample average value of 0.446 induces a 1.25 standard deviation increase in the growth rate of output per worker, equal to 0.014 percent per year. This is a fairly sizeable impact and suggests that for many states an insufficient level of investment in public capital may have been responsible for relatively sluggish productivity growth in recent decades.

C. Public Capital, Government Spending, and Economic Growth

In recent empirical work, a number of authors have found that economic growth rates are adversely affected by higher levels of government spending. For example, using cross-country data over the period 1960 to 1985 Barro (1991) and Barro and Sala-i-Martin (1995) find that a 6.5 percentage point rise in government consumption spending--defined as total government consumption spending minus defense and non-capital expenditures on education--is associated with a drop in the growth

Table C.1
Growth, Government Capital, and Government Spending
Fixed Effect Regressions
(public capital elasticity = .33, government spending elasticity = .05)

f_{kg}	1.019 (.182, .225)	1.001 (.180, .211)	1.019 (.184, .229)	.993 (.181, .212)
f_g	..354 (.120, .121)	.390 (.121, .125)	..352 (.121, .125)	.394 (.121, .129)
y	——	-.029 (.020, .015)	——	-.039 (.023, .019)
u	——	——	< .001 (.001, .001)	.001 (.001, .001)
d70s	-.012 (.002, .002)	-.012 (.002, .002)	-.011 (.002, .003)	-.010 (.003, .003)
R^2	.666	.674	.659	.673
SER ($x10^{-3}$)	6.224	6.155	6.295	6.160
LL	387.695	389.911	387.751	390.947

Notes: All regressions also contain a constant term. Ordinary and White heteroskedasticity corrected standard errors in parentheses.

rate of 0.7 percent per year. This suggests that such spending is either unproductive by nature or, if productive, has been taken well beyond its growth maximizing level.

To investigate the impact of flow government expenditures on economic growth in the present context, we postulate the regression equation

$$\gamma_{it} = a + b_{kg} \cdot f_{kg,it} + b_g \cdot f_{g,it} + \underline{c} \cdot \underline{z}_{it} + \varepsilon_{it} \tag{26}$$

where transformed government capital (as before) is given by

$$f_{kg,it} = \frac{\phi_{it}^{\alpha_{kg}}}{1 + (1 - \alpha_{kg})\phi_{it}} \tag{27}$$

transformed government spending is expressed as

$$f_{g,it} = \phi_{g,it}^{\alpha_g} \cdot (1 - \phi_{g,it}^{1-\alpha_g}) \tag{28}$$

and ϕ_g denotes the ratio of government spending to private capital. We note that the difference in form between the transformed government capital and government spending variables arises because the former involves the *stock* of government capital whereas the latter involves the *flow* of government spending.

Table C.1 shows the results of fixed effects regressions of equation (26) under the assumption that the output elasticities of public capital and government spending are equal to 0.33 and 0.05, respectively. Regardless of the inclusion or exclusion of one or both of the initial output per worker or unemployment variables, each of the transformed public sector variables f_{kg} and f_g is significantly associated with output growth. As with the results in the previous section, these fixed effects regressions allow little explanatory power for the initial level of output per worker, casting further doubt on the existence of strong convergence effects across state economies. Furthermore, the lack of a significant effect for the initial output variable implies that a permanent increase in either of the transformed governmental variables f_{kg} or f_g may well have a permanent, rather than a temporary, positive effect on economic growth--a result in agreement with Kocherlakota and Yi (1996).

Table C.2 and Figures 5 and 6 indicate the effects of varying the output elasticities of public capital and government spending away from the assumed values of 0.33 and 0.05, respectively. As the table indicates, values of the output elasticites smaller or larger than 0.35 and 0.02, respectively, produce poorer estimation results (as measured by the log likelihood value or the adjusted coefficient of determination). Figure 5 shows the partial effect of varying the output elasticity of public capital (conditional on an output elasticity of government spending equal to 0.05) on the values of the log likelihood of the regression; consistent with the results in Table C.1, the log likelihood function takes on its maximum value when the output elasticity of public capital equals 0.33. In turn, Figure 6 shows the partial effect of varying the output elasticity of government spending (conditional on an output elasticity of public capital equal to 0.33) on the log likelihood value; again, consistent with the previous results, the log likelihood is maximized when the output elasticity of government spending equals 0.05. Note, however, that the log likelihood function is much more sharply peaked

Table C.2
Growth, Government Capital, and Government Spending
Fixed Effect Regressions
(Varying elasticities)

		g/k			
	elasticity	.00	.02	.04	.06
kg/k	.25	.893 (.305, .338) .203 (.125, .129) .536 7.334 374.136	.893 (.304, .335) .234 (.141, .147) .537 7.333 374.213	.895 (.303, .333) .269 (.160, .167) .538 7.327 374.286	.899 (.302, .33) .309 (.183, .190) .538 7.322 374.348
	.30	1.171 (.223, .242) .268 (.102, .103) .661 6.275 389.167	1.172 (.223, .241) .305 (.116, .118) .661 6.270 389.249	1.172 (223, 239) .348 (.132, .136) .662 6.266 389.297	1.174 (.223, .238) .398 (.151, .157) .662 6.267 389.290
	.35	.863 (.160, .192) .353 (.101, .109) .668 6.210 390.165	.862 (.160, .191) .400 (.115, .125) .668 6.210 390.167	.861 (.160, .190) .455 (.131, .144) .667 6.215 390.086	.859 (.161, .189) .515 (.150, .168) .666 6.228 389.883
	.40	.611 (.124, .148) .394 (.106, .117) .643 6.435 385.745	.609 (.124, .147) .447 (.120, .135) .643 6.439 386.693	.607 (.125, .147) .506 (.137, .156) .642 6.448 386.537	.604 (.125, .146) .572 (.157, .182) .639 6.470 386.233

Note: In each cell, the first entry represents the effect of transformed government capital on growth, the second entry the effect of transformed government spending on growth, the third entry the adjusted coefficient of determination, the fourth entry the standard error of the regression ($x10^3$), and the fifth entry the log likelihood value.

Figure 5
Log Likelihood Values: Varying kg/k
(conditional on g/k)

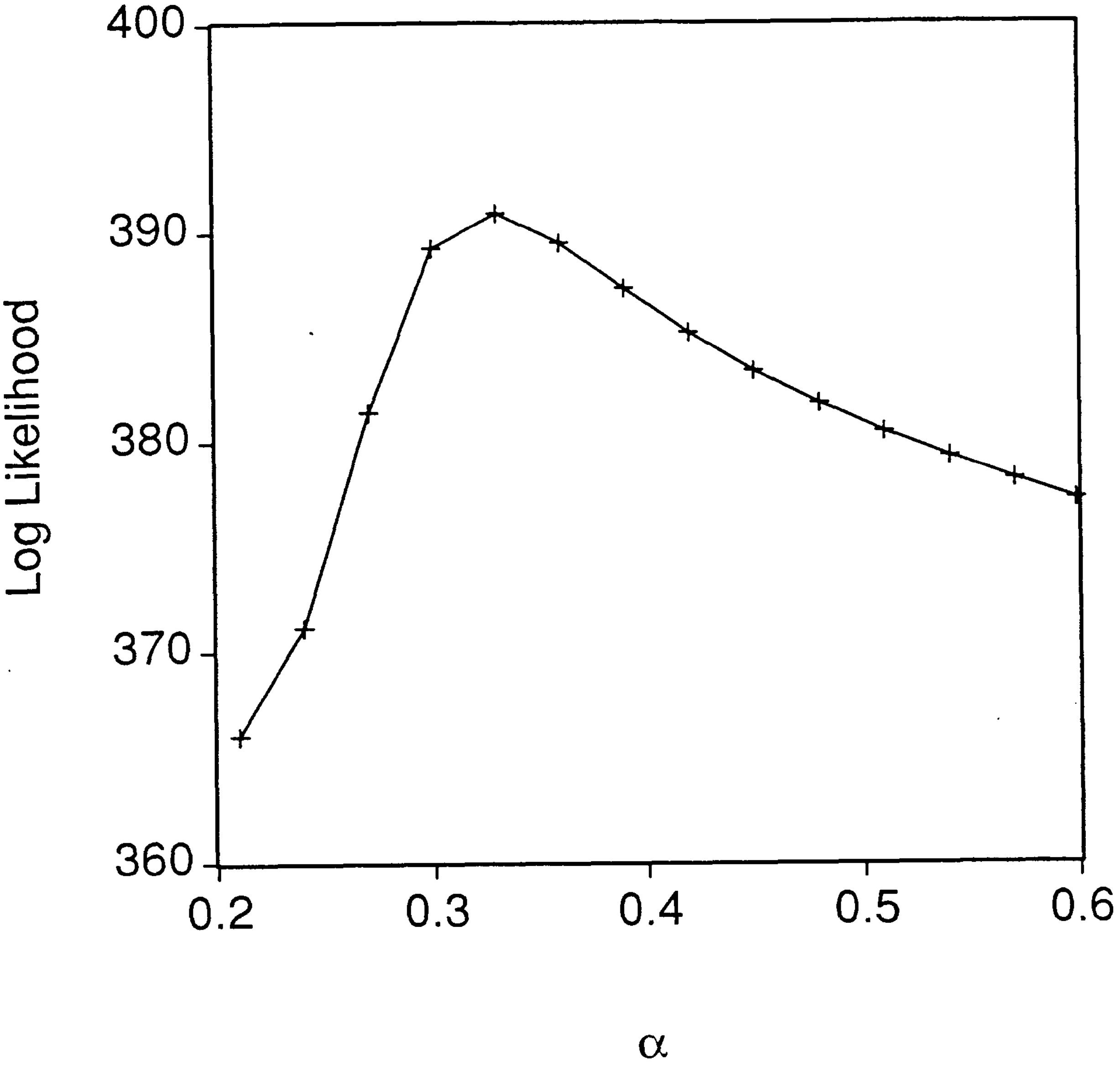
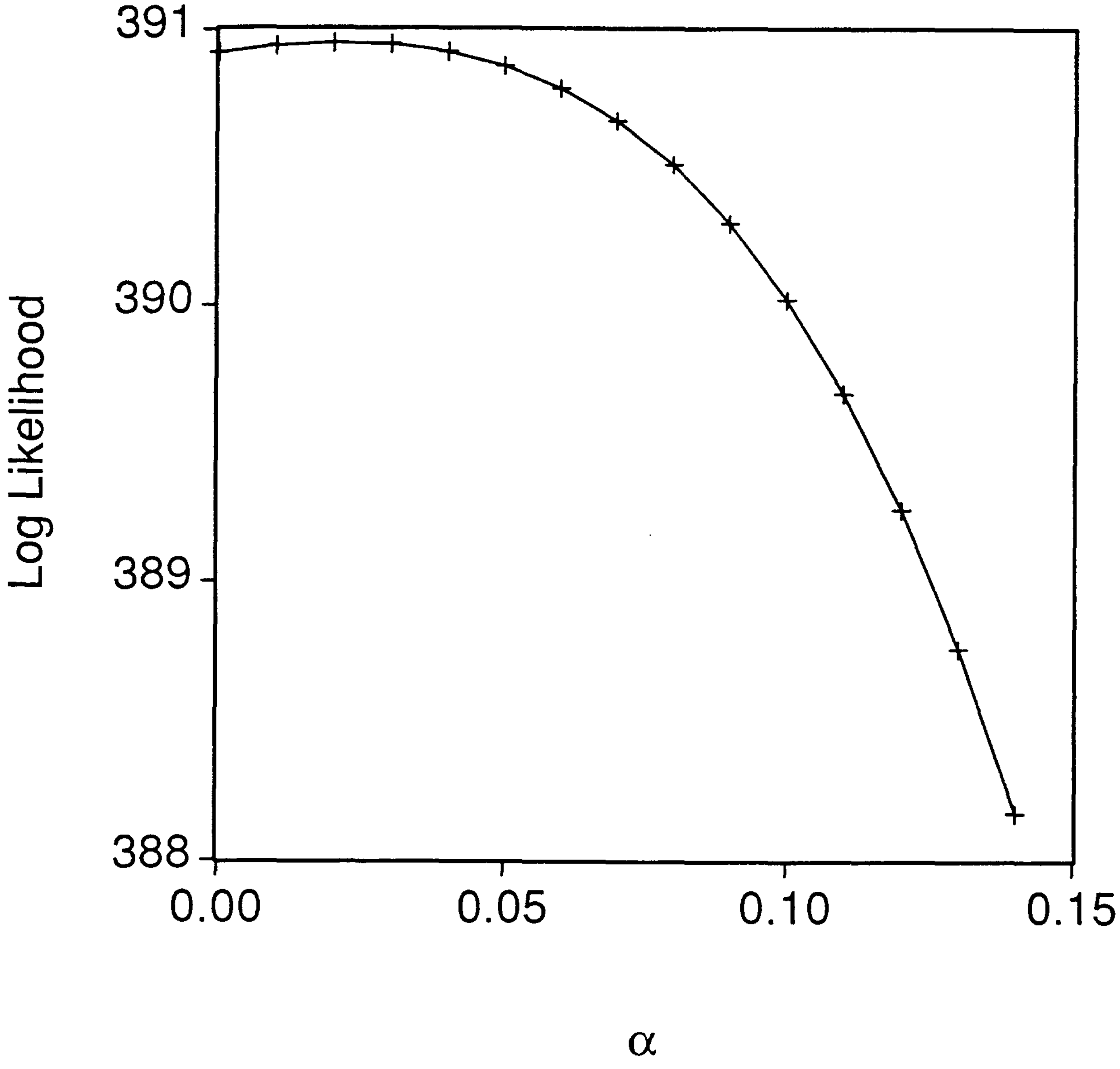


Figure 6
Log Likelihood Values: Varying g/k
(conditional on kg/k)



in Figure 5 than in Figure 6, so that we may have more confidence in the precision of the estimate of the output elasticity of public capital than of the output elasticity of government spending.

Figures 7 and 8 illustrate the relationship between the transformed and actual ratios of public capital and government spending, respectively, to private capital. Figure 7 is based on an assumed value of the output elasticity of public capital of 0.33 and indicates that for 92 of 96 observations the level of government capital lies below the growth maximizing level given by

$$\phi_{kg}^{\max} = \frac{\alpha_{kg}}{(1-\alpha_{kg})^2} = 0.735 \tag{29}$$

so that--at least in this sense--the public capital stock once again may be seen as deficient. Figure 8 is generated using an assumed value of the output elasticity of government spending equal to 0.05 and reveals that all 96 observations on the ratio of government spending rest above the growth maximizing level determined by[12]

$$\phi_{g}^{\max} = \alpha_g^{\frac{1}{1-\alpha_g}} = 0.043 \tag{30}$$

so that--again, from the limited perspective of maximizing growth--the level of government spending may be seen as excessive.

The effects on economic growth of increases in public capital and government spending, respectively, may be determined (in a fashion analogous to the discussion surrounding equation (25)

Figure 7
Deficient Public Capital?

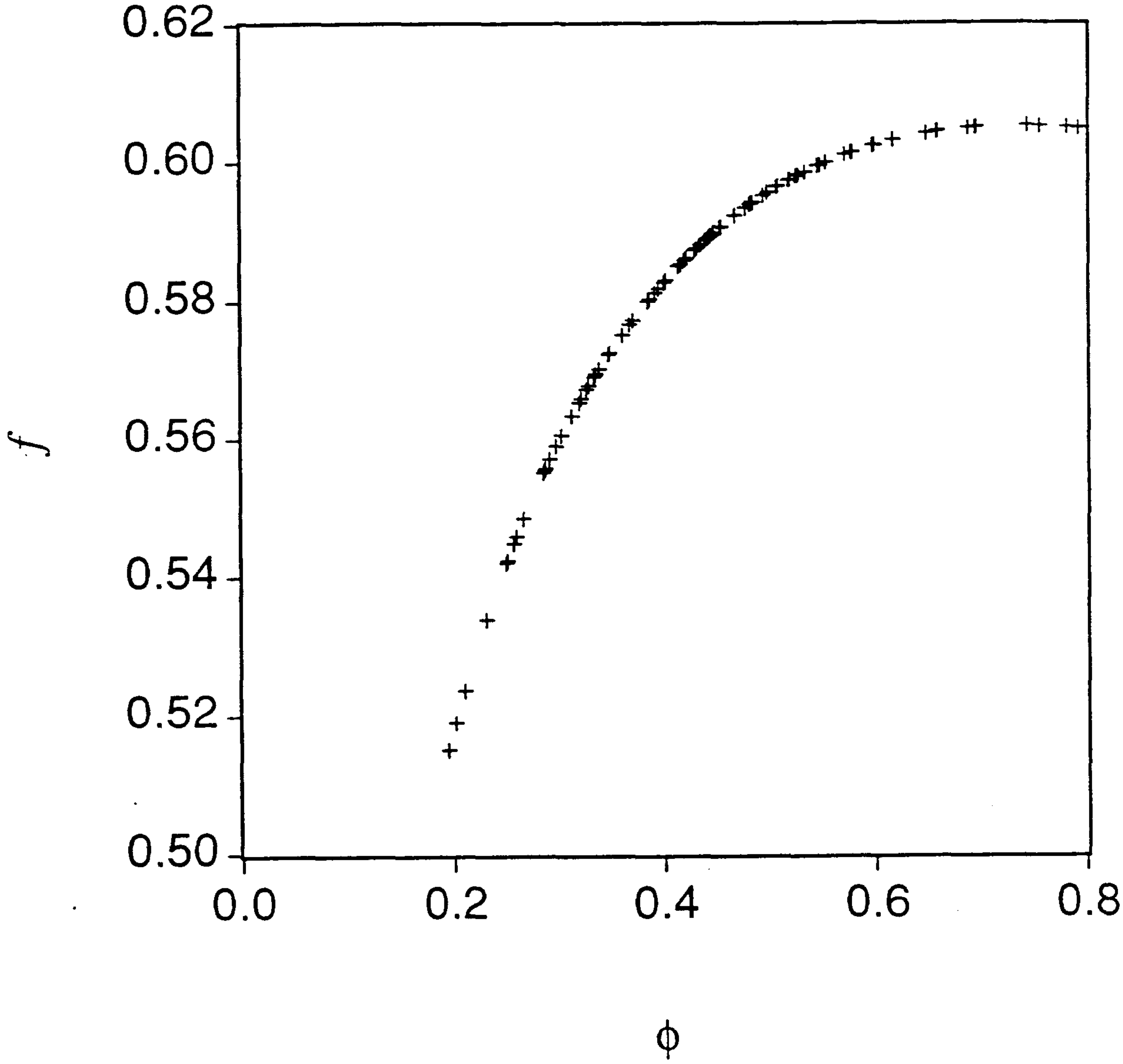
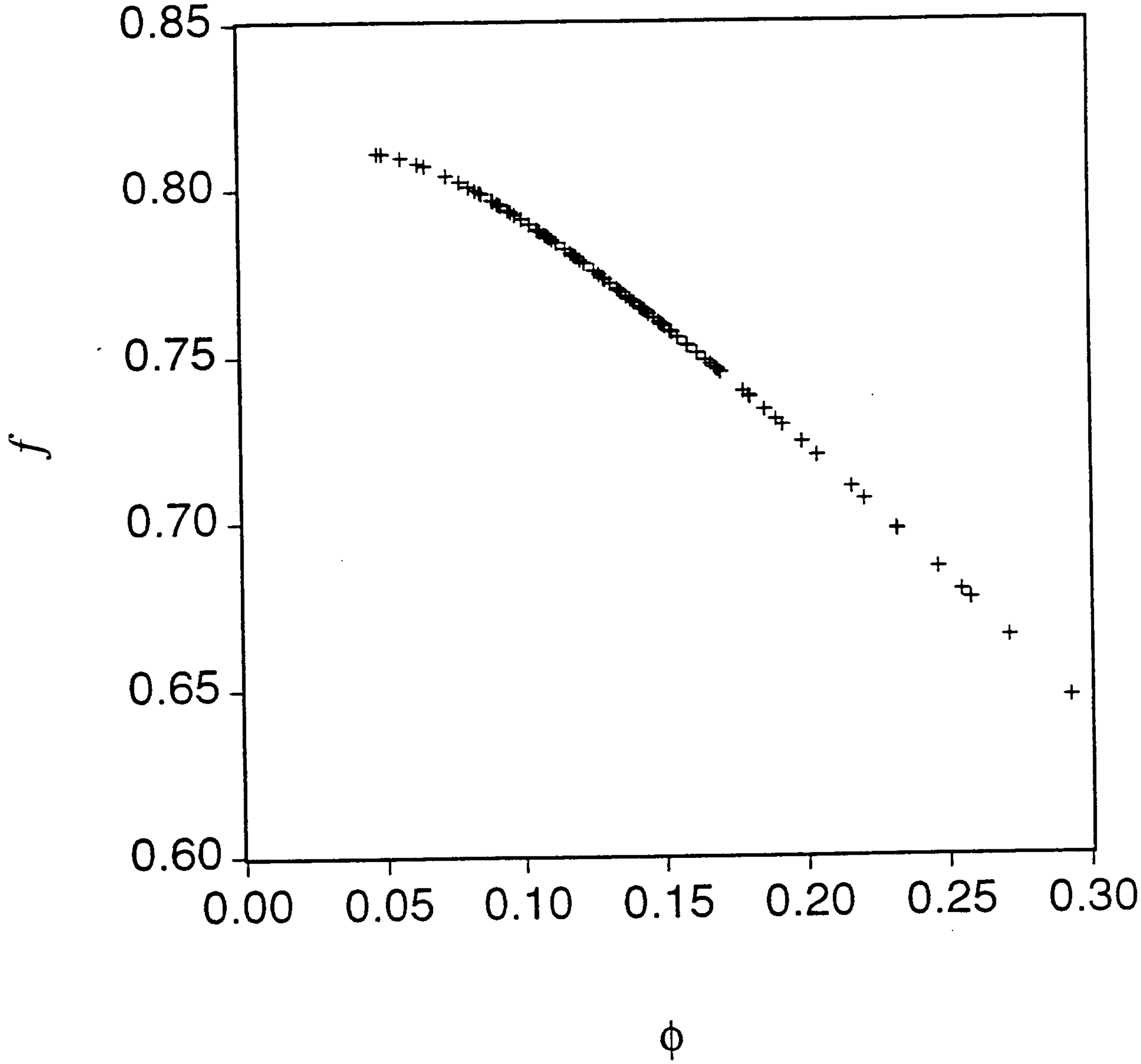


Figure 8
Excessive Government Spending?



above) as

$$d\gamma/d\phi_{kg} = 0.224 \tag{31}$$

and

$$d\gamma/d\phi_{g} = -0.266. \tag{32}$$

Accordingly, a one standard deviation increase in the public capital ratio from its mean value of 0.446 can be expected to *raise* economic growth in an amount equal to 0.030 percentage points per year (or some 2.727 standard deviations of output growth), while a one standard deviation increase in the government spending ratio from its mean value of 0.139 can be predicted to *lower* economic growth by an amount equal to 0.013 percentage points per annum (or some 1.185 standard deviations of output growth).

D. Core Public Capital, Other Public Capital, and Economic Growth

This section allows a distinction between what has been termed *core* public capital and *other* types of public capital. Here, core public capital is defined as the composite of streets and highways, and water and sewer systems, while other public capital (as a residual measure) includes educational buildings, office buildings, and conservation and development structures. In the literature (*e.g.*, Aschauer (1989) and Munnell (1990b)) core public capital has been found to have a larger estimated output elasticity than other types of public capital.

Accordingly, the final set of regressions are of the form

$$\gamma_{it} = a + b_{kg(core)} \cdot f_{kg(core),it} + b_{kg(other)} \cdot f_{kg(other),it} + b_g \cdot f_{g,it} + \underline{c} \cdot \underline{z}_{it} + \varepsilon_{it} \tag{33}$$

where $f_{kg(core)}$, $f_{kg(other)}$, and f_g represent transformed ratios of core public capital, other public capital, and government spending to private capital, respectively. Here, the transformed ratios of core and other public capital are given as

$$f_{kg(x),it} = \frac{\phi_{kg(x),it}^{\alpha_{kg(x)}}}{1 + (1 - \alpha_{kg(x)})\phi_{kg(x),it}} \tag{34}$$

where x = core and other, respectively, and the transformed ratio of government spending is measured as[13]

$$f_{g,it} = \phi_{g,it}^{\alpha_g} \cdot (1 - \phi_{g,it}^{\alpha_g}). \tag{35}$$

Table D.1 presents estimates of the impact of transformed core and other public capital and government spending on growth in per worker output under the assumption that the output elasticities of core public capital, other public capital, and government spending equal 0.25, 0.20, and 0.05, respectively. All of the government policy variables are significantly related to economic growth, with the largest quantitative effects for core public capital, then other public capital and, finally, government spending. In absolute value, the estimated coefficient on the initial level of per capita output is quantitatively (now in the range of 0.008 to 0.017) and statistically minor, indicating weak or even nonexistent convergence effects.

Table D.1 **Growth, Government Capital, and Government Spending** **Fixed Effect Regressions** **(core elasticity = .25, other elasticity = .20, government spending elasticity = .05)**				
$f_{kg(core)}$	.764 (.213, .233)	.772 (.216, .243)	.726 (.219, .243)	.728 (.220, .252)
$f_{kg(other)}$	.651 (.191, .176)	.662 (.209, .200)	.700 (.201, .196)	.655 (.212, .206)
f_g	.452 (.138, .144)	.458 (.141, .147)	..454 (.139, .149)	.467 (.141, .152)
y	——	-.008 (.022 , .014)	——	-.017 (.024, .016)
u	——	——	.001 (.001, .001)	.001 (.001, .001)
d70s	-.012 (.002, .003)	-.012 (.002, .003)	-.010 (.003, .004)	-.010 (.003, .004)
R^2	.670	.663	.667	.663
SER ($x10^{-3}$)	6.190	6.252	6.217	6.253
LL	389.372	389.515	390.063	390.631

Notes: All regressions also contain a constant term. Oridinary and White heteroskedasticity corrected standard errors in parentheses.

Tables D.2 through D.4 allow for different assumed values for the output elasticities of core public capital (ranging from 0.20 to 0.30), other public capital (ranging from 0.15 to 0.25), and government spending (ranging from 0.04 to 0.06). As the tables indicate, a departure of either of the two public capital elasticities from the values assumed in Table D.1--0.25 and 0.20, respectively--causes a rather significant deterioration in the fit of the regressions (as measured by the adjusted coefficients of determination or the log likelihood values) and tends to reduce the statistical significance of one or both of the transformed public capital variables. On the other hand, assuming different values for the output elasticity of government spending has little impact on the explanatory power of the regressions or on the magnitudes or statistical significance of the government policy variables.

Figures 9, 10, and 11 show the relationships between transformed and actual ratios of core public capital, other public capital, and government spending, respectively, assuming the output elasticities contained in Table D.1. These elasticity values imply growth-maximizing values of core public capital, other public capital, and government spending of 0.444, 0.313, and 0.043, respectively, to be compared with actual sample average values of 0.267, 0.179, and 0.139. Figures 9 and 10 then indicate that there has been a deficient level of public capital accumulation--from the perspective of economic growth--for 94 of the 96 observations (for core capital) and 90 of the 96 observations (for other capital); Figure 11 shows that there has been an excessive level of government spending for 94 of 96 total observations.

The corresponding effects of changes in these governmental variables on growth can be shown to

Table D.2
Growth, Core Government Capital, and Other Government Capital
Fixed Effect Regressions
(Varying public capital elasticities, government spending elasticity = .04)

		kg(other)/k		
	elasticity	.15	.20	.25
kg(core)/k	.20	.816 (.308, .329) .595 (.365, .409) .288 (.185, .165) .567 7.093 378.533	.752 (.276, .241) .736 (.215, .214) .410 (.138, .145) .640 6.465 387.425	.813 (.271, .233) .482 (.139, .141) .470 (.140, .151) .642 6.446 387.708
	.25	.850 (.227, .270) .648 (.333, .367) .316 (.145, .148) .621 6.635 384.946	.727 (.220, .252) .656 (.212, .207) .438 (.132, .141) .663 6.253 390.637	.739 (.222, .252) .410 (.141, .134) .489 (.137, .152) .656 6.319 389.622
	.30	.650 (.170, .227) .756 (.328, .341) .333 (.144, .147) .624 6.605 389.377	.526 (.171 .222) .661 (.216, .206) .463 (.134, .147) .654 6.337 389.350	.523 (.176, .226) .401 (.146, .137) .512 (.139, .159) .641 6.456 387.569

Note: in each cell, the first entry represents the effect of transformed government core capital on growth, the second entry the effect of transformed government other capital, the third entry the effect of transformed government spending on growth, the fourth entry the adjusted coefficient of determination, the fifth entry the standard error of the regression ($x10^3$), and the sixth entry the log likelihood value.

Table D.3
Growth, Core Government Capital, and Other Government Capital
Fixed Effect Regressions
(Varying public capital elasticities, government spending elasticity = .05)

		kg(other)/k		
	elasticity	.15	.20	.25
		.820 (.307, .327)	.758 (.275, .238)	.818 (.271, .230)
	.20	.591 (.365, .410)	.735 (.214, .213)	.482 (.139, .140)
		.310 (.165, .177)	.439 (.147, .155)	.504 (.150, .163)
		.567	.640	.643
		7.089	6.460	6.438
		378.586	387.507	387.827
		.851 (.222, .270)	.728 (.220, .252)	.740 (.222, .251)
	.25	.647 (.333, .347)	.655 (.212, .206)	.409 (.141, .134)
		.338 (.155, .158)	.467 (.141, .152)	.523 (.146, .163)
kg(core)/k		.621	.663	.656
		6.635	6.253	6.319
		384.943	390.631	389.629
		.649 (.171, .227)	.526 (.171 .222)	.522 (.176, .225)
	.30	.756 (.328, .341)	.661 (.216, .205)	.400 (.146, .137)
		.354 (.154, .157)	.493 (.143, .159)	.546 (.149, .172)
		.624	.653	.640
		6.610	6.343	6.461
		385.304	389.261	387.487

Note: in each cell, the first entry represents the effect of transformed government core capital on growth, the second entry the effect of transformed government other capital, the third entry the effect of transformed government spending on growth, the fourth entry the adjusted coefficient of determination, the fifth entry the standard error of the regression ($x10^3$), and the sixth entry the log likelihood value.

Table D.4
Growth, Core Government Capital, and Other Government Capital
Fixed Effect Regressions
(Varying public capital elasticities, government spending elasticity = .06)

		kg(other)/k		
	elasticity	.15	.20	.25
kg(core)/k	.20	.825 (.307, .325) .587 (.365, .411) .333 (.177, .189) .568 7.086 378.634	.764 (.275, .236) .733 (.214, .211) .471 (.157, .161) .641 6.456 387.573	.825 (.270, .228) .482 (.138, .140) .540 (.160, .174) .644 6.432 387.926
	.25	.852 (.227, .270) .646 (.333, .367) .361 (.165, .169) .621 6.636 384.926	.730 (.220, .251) .654 (.212, .205) .499 (.151, .164) .663 6.255 390.596	.742 (.222, .250) .409 (.141, .133) .558 (.156, .177) .656 6.321 389.601
	.30	.649 (.171, .226) .756 (.328, .341) .376 (.165, .169) .623 6.616 385.212	.525 (.171 .221) .660 (.216, .204) .524 (.153, .172) .653 6.351 389.134	.521 (.177, .224) .400 (.146, .137) .581 (.159, .186) .639 6.470 387.362

Note: in each cell, the first entry represents the effect of transformed government core capital on growth, the second entry the effect of transformed government other capital, the third entry the effect of transformed government spending on growth, the fourth entry the adjusted coefficient of determination, the fifth entry the standard error of the regression ($x10^3$), and the sixth entry the log likelihood value.

Figure 9
Deficient Core Capital?

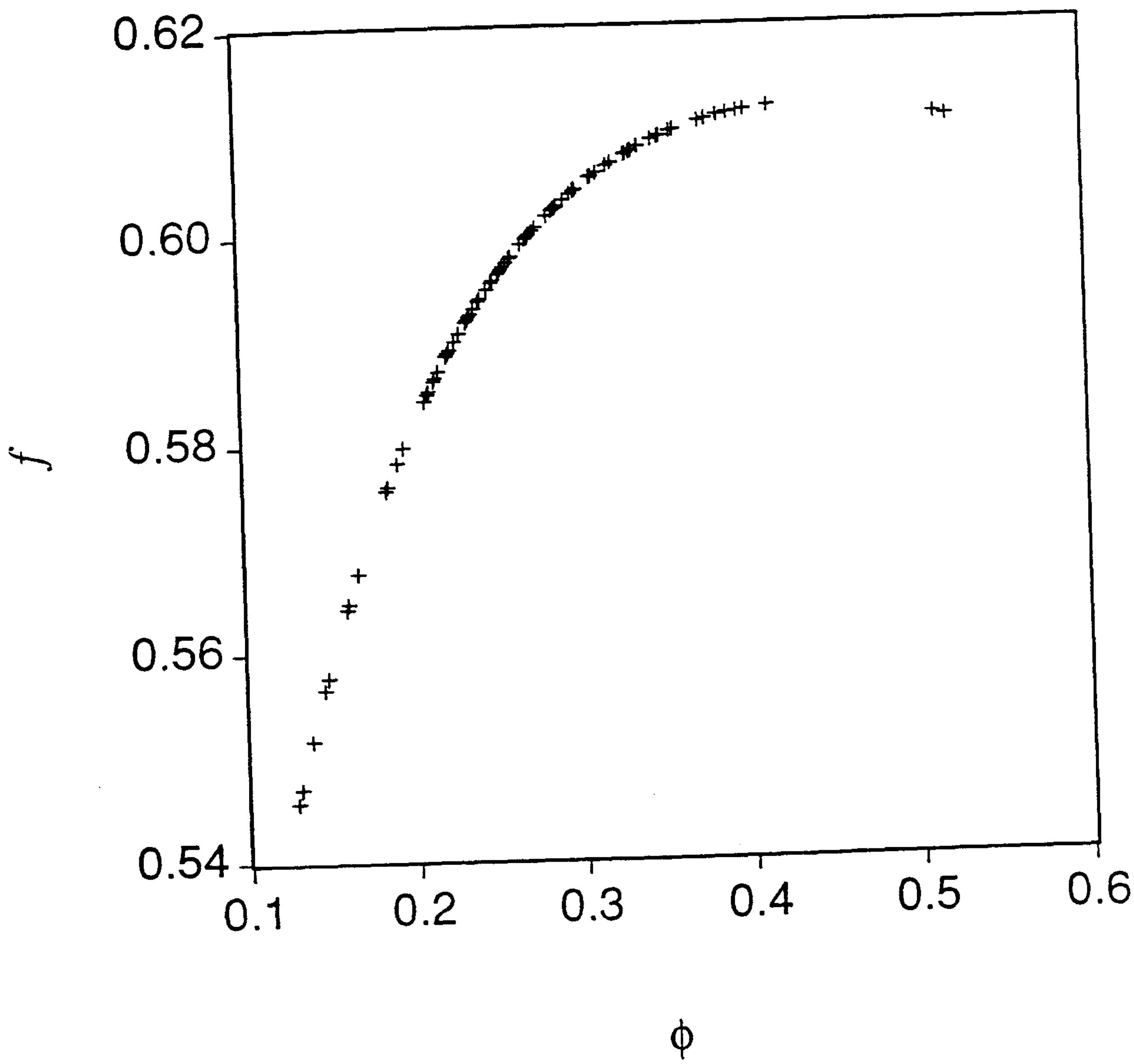


Figure 10
Deficient Other Capital?

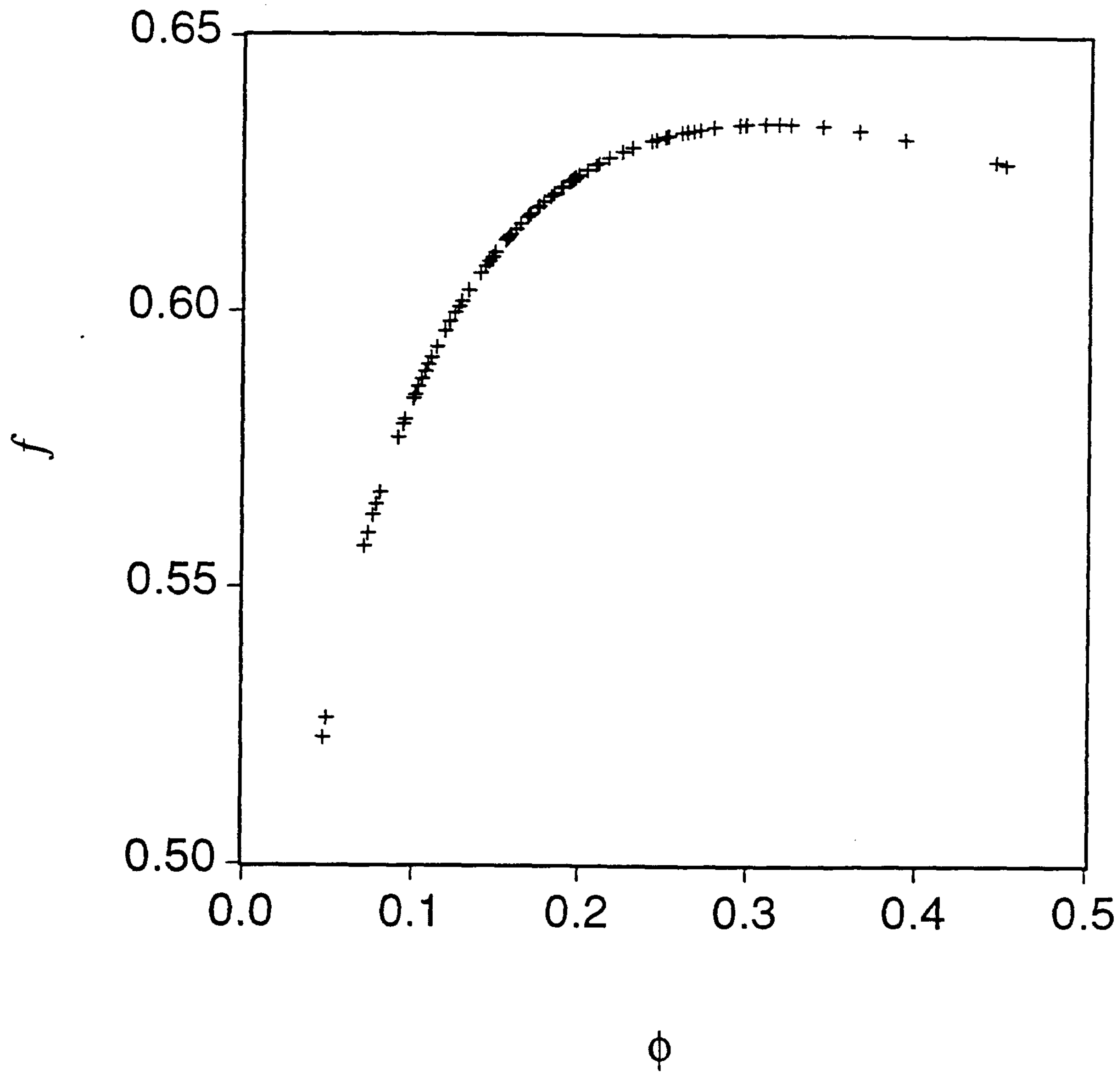
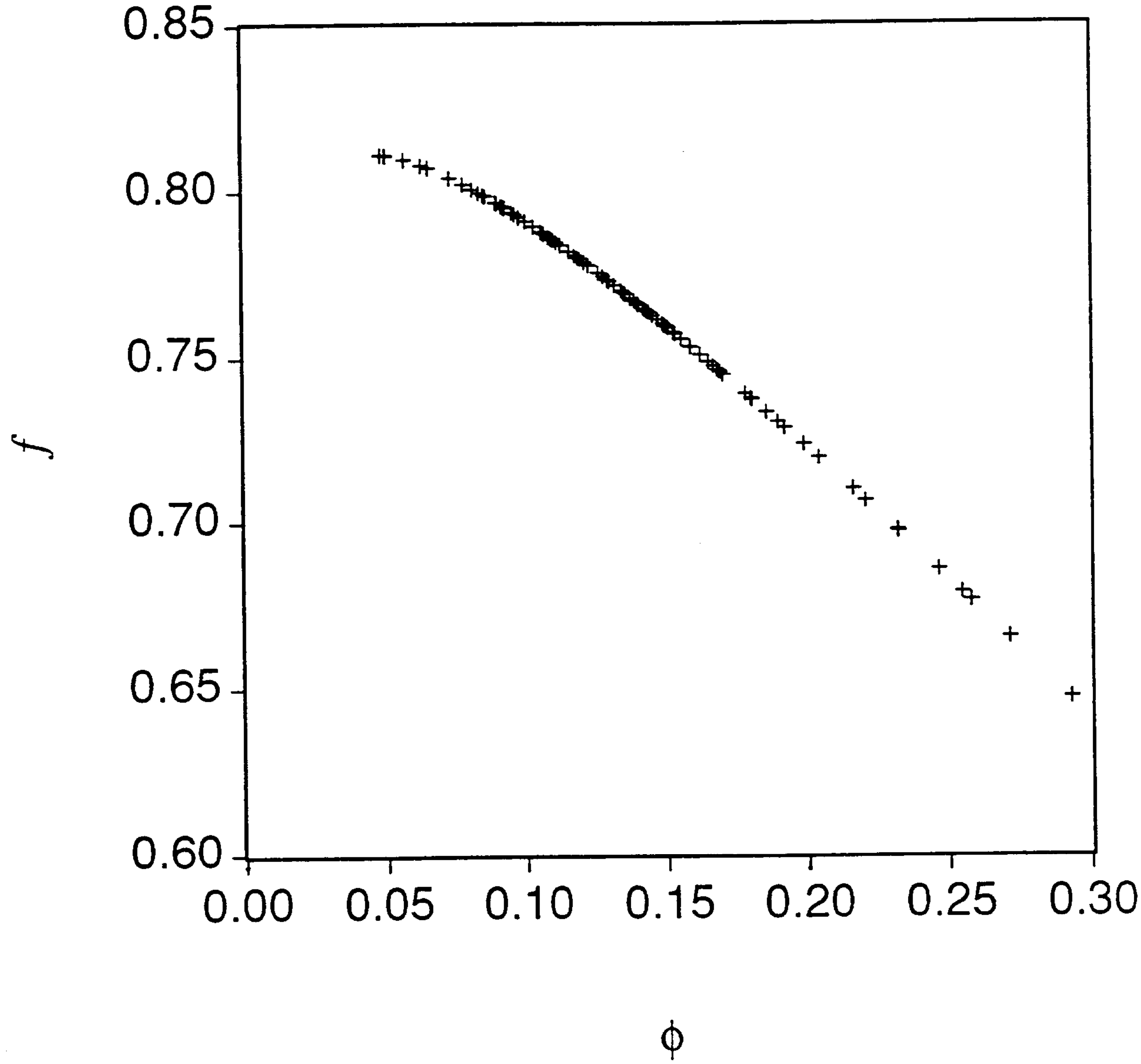


Figure 11
Excessive Government Spending?



be

$$d\gamma/d\phi_{kg(core)} = 0.045$$

$$d\gamma/d\phi_{kg(other)} = 0.061$$

$$d\gamma/d\phi_{g} = -0.315.$$

Perhaps surprisingly, the economic growth effects of core public capital are exceeded by the effects of other public capital. Specifically, a one standard deviation increase in core capital can be expected to induce roughly a one-third standard deviation increase in output growth (equal to 0.003 percent per year) while a one standard deviation increase in other capital can be predicted to bring forth approximately a one-half standard deviation increase in economic growth (equal to 0.005 percent per year). As in the previous section, however, a one standard deviation increase in government spending is associated with more than a one standard deviation decrease in output growth (equal to 0.015 percent per year).

IV. Conclusions and Directions for Further Research

The results of this paper indicate that for most of the United States during the 1970s and 1980s the actual levels of public *capital* were below the levels which would have maximized the rate of productivity growth. Specifically, the growth maximizing ratio of public capital to private capital is estimated to equal 0.444 for core public capital and 0.313 for other public capital, while the actual sample averages equal the smaller values of 0.267 and 0.179, respectively. Thus, the empirical results suggest that a one standard deviation increase in either core or other public capital would stimulate a one-third to one-half standard deviation *increase* in output growth per worker.

At the same time, the results suggest that for nearly all states the actual levels of government *spending* were above the levels that would maximize productivity growth. While the growth maximizing ratio of government spending to private capital is estimated to equal 0.043, the sample average ratio equals a much larger 0.139. Consequently, a one standard deviation increase in government spending is estimated to induce somewhat more than a one standard deviation *decrease* in the rate of economic growth.

Statistically (though not necessarily quantiatively) the empirical results of this paper also indicate a lack of *convergence* effects across state economies. From a policy perspective, this implies that permanent changes in government policy variables--such as a permanent increase in public capital or a permanent decrease in government consumption spending--are consistent with permanent changes in economic growth rates. This result is compatible with some recent empirical work, such as Kocherlakota and Yi (1996), but stands in stark contrast with other work, such as Barro and Sala-I-Martin (1995). In subsequent research, therefore, it would be of some value to further investigate the role of convergence effects in order to obtain a more accurate assessment of the impact of public capital and spending levels on economic growth rates.

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Endnotes

1. Nor is it a necessary condition. See, for example, Flores de Frutos and Periera (1992).

2. On the transition path between steady states we have

$$\frac{d\gamma_y}{d\dot{kg}}\Big|_{d\dot{kg} = -d\dot{k}} = \frac{[mp_{kg} - mp_k]}{y}$$

where γ_y = growth rate of output per worker, kg = public capital, k = private capital, mp_x = marginal product of input x ($x = kg, k$), y = output per worker, and dots denote time derivatives.

3. The approach expands on the model in Barro (1990) by focusing on the productive services of public *capital* rather than of flow government spending. Although fairly subtle, the distinction is important from theoretical and policy perspectives. For instance, some researchers have drawn the (incorrect) conclusion from Barro's model that the "condition for productive efficiency is that the share of government capital in output is equal to its elasticity" and have performed "back-of-the-envelope" calculations to show that the U.S. has grossly underinvested in government capital (Ho and Sorenson (1993)).

4. It is straightforward to extend the analysis using a constant elasticity of substitution production function.

5. In this expression, the tax rate, θ, can be viewed as consisting of two components. The government needs to service the initial stock of debt at the interest rate r, but due to output growth and a rising tax base the required tax rate would be given by

$$\theta_{kg_0} = \frac{(r - \gamma)\cdot kg_0}{y_0}.$$

In addition, the government must finance on-going public investment at rate γ to maintain the public capital ratio, necessitating a tax rate of

$$\theta_{\dot{kg}} = \frac{\gamma\cdot kg_0}{y_0}.$$

The overall tax rate is then given by

$$\theta = \theta_{kg_0} + \theta_{\dot{kg}} = \frac{(r - \gamma)\cdot kg_0}{y_0} + \frac{\gamma\cdot kg_0}{y_0} = \frac{r\cdot kg_0}{y_0}$$

which is consistent with equation (6) in the text.