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Public investment multipliers revisited: the role of production complementarities

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Abstract
This paper revisits the issue of the public investment multiplier through the lens of complementarity or substitutability between private inputs and public infrastructure capital. Our main result is that public investment multipliers are much larger than in the literature when private inputs and public capital are good complements relative to the canonical Cobb–Douglas case where the degree of complementarity is unity, and, at the same time, public capital is in relative shortage, meaning that it acts as a 'weak link' in production. Within this framework, the stronger the degree of complementarity (respectively substitutability), the larger (respectively smaller) the size of the multiplier. The model is solved numerically by choosing its parameters according to UK data. The model's positive and normative implications are then compared to current values of policy variables in the UK economy.

KEYWORDS
fiscal policy, production, firm behaviour

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E62; E23; D21

1 | INTRODUCTION

Most policymakers seem to have great faith in spending on public infrastructure as a means to support durable economic growth and hence avoid unpleasant public finance decisions. Examples include the policy agenda of the Labour government in the UK, the Draghi Report on the European Economy, and the infrastructure stimulus of the previous US administration. In the academic literature, on the other hand, this is less clear. The macroeconomic impacts of higher public investment spending, and hence the size of the public investment multiplier, are sensitive to a wide range of factors, such as the public financing scheme, implementation lags, the stance of monetary policy, input–output interactions, the maturity of public debt, and the state of the economy (for a review, see, for example, Leeper 2011). Nevertheless, although public investment multipliers can differ, a rather general result is that the neoclassical growth model, as well as most of its popular extensions, cannot produce large multipliers.[1]

This paper sheds light on another factor that appears to be crucial to the size of the public investment multiplier. Building on the work of Caselli (2005), Baier and Glomm (2001), Jones (2011) and Chang and Lee (2024), it shows that the degree of complementarity or substitutability between private inputs and public capital—where the latter is augmented by public investment spending—together with the relative scarcity or abundance of public capital, plays a key role in determining the size of the public investment multiplier. To do this, we use the standard neoclassical growth model augmented with a more flexible constant elasticity of substitution (CES) production function that allows for various degrees of substitutability or complementarity between private inputs and public capital. When we solve the model numerically, we parametrize it using annual economy-wide data for the UK.

Our main results are as follows. When private inputs and public infrastructure capital are good complements relative to the widely-used Cobb–Douglas case in which the degree of complementarity is unity, an increase in public investment not only increases public capital, but also enhances substantially the usage of private inputs. These combined effects result in public investment spending multipliers that are substantially larger than those in the Cobb–Douglas case. Actually, the stronger the degree of complementarity, the larger the multiplier. Or, reversing the argument, the stronger the degree of substitutability, the smaller (even negative) the multiplier.[2] We show that these results hold both at steady state and along the transition path, as well as with both permanent and temporary rises in public investment spending. While these results are similar to those in, for example, Baier and Glomm (2001) and Chang and Lee (2024), our counterfactual experiments also reveal that they hold provided that public capital is in shortage relative to private inputs and private capital in particular; if, instead, public capital happens to be in relative abundance, then the results are reversed, meaning that in this case, the stronger the degree of complementarity, the smaller the size of the public investment multiplier.[3] In other words, this intuitive result holds to the extent that public capital is the 'weak link' in production according to the terminology of Jones (2011), where here by weak link we mean that public capital is scarce relative to private capital. We believe that this is consistent with the insight of Jones (2011) that 'a stronger degree of complementarity puts more weight on the weakest link', as well as with Caselli (2005), who says that with complementarity, 'allocative efficiency calls for boosting the overall efficiency units provided by the low-efficiency factor'. It should be stressed that the solutions of our model—which, as we have said, is calibrated to UK economy-wide data—lie in the region of relative shortage of public capital.

Then several policy implications follow naturally. A first one is that before increasing public investment spending, policymakers should examine both the degree of complementarity or substitutability and the relative scarcity or abundance of public capital. Another policy implication is that if the economy is hit by an adverse shock triggering a downturn, then countercyclical policy in the form of an increase in public investment spending can be productive only under complementarity and relative shortage of public capital; otherwise, such a fiscal stimulus would make the economic downturn even deeper relative to a no-change policy. Finally, to the extent that public capital is in relative shortage, as the degree of complementarity rises, the socially optimal (Ramsey-type) public investment to output ratio, as well as the associated public to private capital ratio, gets bigger. On the other hand, our optimal solutions also infer that a public investment spending to GDP ratio higher than that in the current UK data can be rationalized only under a relatively strong degree of complementarity between private inputs and public infrastructure.

We wish to clarify one point from the outset. As already said above, the size of fiscal policy multipliers depends on a wide range of factors. Therefore here we do not wish to take a stance on the exact size of the public investment multiplier. Instead, our aim is to demonstrate that ignoring the complementarity or substitutability between public capital and private inputs, as well as the relative scarcity or abundance of public capital, can severely distort the estimated values of public investment multipliers.

Our paper belongs to the vast and still growing literature on the determinants of fiscal policy multipliers. More specifically, it belongs to the literature on the macroeconomic effects of changes in public investment spending and public infrastructure capital. Within this literature, papers that have also worked within a CES framework to emphasize the importance of the degree of complementarity/substitutability between public capital and private inputs, and especially private capital, for the US economy, are Baier and Glomm (2001) and Chang and Lee (2024).[4] Here, since there is a wide range of estimates for the degree of substitutability or complementarity between public capital and private inputs,[5] following, for example, Baier and Glomm (2001) and Caselli (2005), we experiment with a variety of values of this degree around the baseline value unity that corresponds to the popular Cobb–Douglas case. Putting all this into perspective, our study for the UK differs from the related US studies of Baier and Glomm (2001) and Chang and Lee (2024) in that: first, we show that complementarity alone is not sufficient to generate large public investment multipliers—public capital must also be in relative shortage serving as a weak link in the production process; second, we identify the potential policy consequences of our positive findings. It should finally be said that our work is related to a wider literature that has stressed the importance of using CES (production and utility) functions instead of Cobb–Douglas ones; see, for example, Caselli 2005), Ngai and Pissarides (2007), Jones (2011) and Cantore *et al.* (2013, 2014), although these papers work in different economic environments and/or address different issues.

The remainder of the paper is organized as follows. Section 2 presents the model. Section 3 describes the parameter and policy values, as well as the initial steady-state solution. Section 4 presents the main results. Normative implications are in Section 5, and Section 6 searches for the drivers of our results. Section 7 considers a richer policy scenario. Section 8 concludes.

2 | MODEL

This section presents a simplified version of the model used by Leeper *et al.* (2010b), which is a well-cited paper in the literature on public investment multipliers. To make our main points as clear as possible, we abstract from several frictions that appear in the Leeper *et al.* (2010b) model since they are not important to our main subject.

2.1 | Households

There is a representative household whose aim is to maximize

$$\sum_{t=0}^{\infty} \beta^t \, u(c_t, l_t), \tag{1}$$

where c_t and l_t are consumption and work hours, and $0 < \beta < 1$ is the time discount factor.

The utility function is

$$u(c_t, l_t) = \frac{(c_t)^{1-\nu}}{1-\nu} - \mu \, \frac{(l_t)^{1+1/\kappa}}{1+1/\kappa}, \tag{2}$$

where ν is a risk-aversion parameter, $\mu > 0$ is a preference parameter, and $\kappa > 0$ is the Frisch elasticity of labour supply.

The budget constraint is

$$(1+\tau_t^c)c_t + i_t + b_t = (1-\tau_t^y)(w_t l_t + r_{t-1}^k k_{t-1} + \pi_t) + (1+r_{t-1}^b)b_{t-1} + g_t^t, \tag{3}$$

where i_t is investment in physical capital, b_t is one-period government bonds purchased at t, w_t is the wage rate, r_{t-1}^k denotes the return to accumulated physical private capital, r_{t-1}^b is the return to outstanding bonds, π_t is dividends distributed by firms, g_t^t is a lump-sum transfer from the government, and $0 \leq \tau_t^c, \tau_t^y < 1$ are tax rates on consumption and personal income. We assume that interest income from bonds is untaxed.

Private capital evolves as

$$k_t = (1-\delta_p)k_{t-1} + i_t, \tag{4}$$

where $0 < \delta_p < 1$ is a parameter.

Using equation (4), the standard first-order conditions for c_t, l_t, b_t and k_t are, respectively,

$$\lambda_t = \frac{1}{(1+\tau_t^c)c_t^\nu}, \tag{5}$$

$$\mu(l_t)^{1/\kappa} = \lambda_t(1-\tau_t^y)w_t, \tag{6}$$

$$\lambda_t = \beta\lambda_{t+1}(1+r_t^b), \tag{7}$$

$$\lambda_t = \beta\lambda_{t+1}\left[1-\delta_p + (1-\tau_{t+1}^y)r_t^k\right], \tag{8}$$

where λ_t is the multiplier associated with equation (3).

2.2 | Firms

There is a representative firm whose production function is assumed to take a normalized CES form

$$y_t = A_t\left[(1-\sigma)(k_{t-1}^\alpha l_t^{1-\alpha})^{(\varepsilon-1)/\varepsilon} + \sigma(k_{g,t-1})^{(\varepsilon-1)/\varepsilon}\right]^{\varepsilon/(\varepsilon-1)}, \tag{9}$$

where $k_{g,t-1}$ is the outstanding stock of public capital acting as a positive production externality, $\sigma \geq 0$ is the relative importance of public capital in production, $0 < \alpha < 1$ is an efficiency parameter, $A_t > 0$ is total factor productivity (TFP), and the parameter $\varepsilon > 0$ is the elasticity of substitution or complementarity between a composite Cobb–Douglas bundle of private inputs on one hand, and public infrastructure capital[6] on the other hand.[7]

As pointed out by, for example, Baier and Glomm (2001), Caselli (2005), Acemoglu (2009, ch. 15) and Jones (2011), this CES function delivers several popular cases as special cases. For instance, when $\varepsilon \to 1$, the specific CES form smoothly converges to the following Cobb–Douglas specification in the limit:[8]

$$y_t = A_t(k_{t-1}^a l_t^{1-a})^{1-\sigma}(k_{g,t-1})^\sigma, \tag{10}$$

which is similar to the Cobb–Douglas function used by, for example, Lansing (1998) and Cassou and Lansing (1998). Notice that when $\varepsilon > 1$, private inputs and public capital are gross substitutes relative to the Cobb–Douglas case, while when $0 < \varepsilon < 1$, private inputs and public capital are gross complements relative to the Cobb–Douglas case. As ε gets smaller, so that substitution becomes more difficult, more weight is put on the smallest level of the inputs used, or what Jones (2011) calls the weak links (see below). Also notice that both the CES in equation (9) and its limiting Cobb–Douglas version in equation (10) exhibit constant returns to scale (CRS) to all factors, including public capital.[9]

The firm's profit is

$$\pi_t = y_t - w_t l_t - r^k_{t-1} k_{t-1}. \tag{11}$$

The firm's first-order conditions for the two private inputs are

$$w_t = (1-\alpha)(1-\sigma)\, k_{t-1}^{\alpha(\varepsilon-1)/\varepsilon}\, l_t^{((1-\alpha)(\varepsilon-1)/\varepsilon)-1}\, A_t^{(\varepsilon-1)/\varepsilon}\, y_t^{1/\varepsilon}, \tag{12}$$

$$r^k_{t-1} = \alpha(1-\sigma)\, k_{t-1}^{(\alpha(\varepsilon-1)/\varepsilon)-1}\, l_t^{(1-\alpha)(\varepsilon-1)/\varepsilon}\, A_t^{(\varepsilon-1)/\varepsilon}\, y_t^{1/\varepsilon}. \tag{13}$$

2.3 | Government budget constraint

The budget identity of the government is

$$g^i_t + g^c_t + g^t_t + r^b_{t-1} b_{t-1} = b_t - b_{t-1} + \tau^c_t c_t + \tau^y_t (w_t l_t + r^k_{t-1} k_{t-1} + \pi_t), \tag{14}$$

where g^i_t is public investment, and g^c_t is public consumption.[10]

Public investment augments the stock of public capital whose motion is

$$k_{g,t} = (1-\delta_g) k_{g,t-1} + g^i_t, \tag{15}$$

where $0 < \delta_g < 1$ is a parameter.

2.4 | Macroeconomic system

Collecting equations, the equilibrium system consists of 12 equations—specifically, equations (3)–(9), (11)–(15)—in 12 variables, $\{c_t, l_t, k_t, i_t, r^b_t, \lambda_t, y_t, w_t, r^k_t, \pi_t, k_{g,t}, \tau^y_t\}_{t=0}^{\infty}$. This is given initial conditions for the state variables and the values of the independently set policy instruments, $\{g^t_t, g^i_t, g^c_t, \tau^c_t, b_t\}_{t=0}^{\infty}$. Notice that we choose to treat public debt b_t—or strictly speaking the public debt to GDP ratio b_t/y_t—as an exogenous variable, and instead allow τ^y_t to close the government budget constraint in each period. (This is not important to our results, and is discussed further in Subsections 3.2 and 3.3.) Also note that in what follows, to bring the model closer to the fiscal data, we will re-express the public spending items as shares of GDP; in particular, we define $g^t_t = s^t_t y_t$, $g^i_t = s^i_t y_t$ and $g^c_t = s^c_t y_t$, so that s^t_t, s^i_t and s^c_t replace g^t_t, g^i_t and g^c_t in the equations above.

3 | PARAMETERIZATION AND INITIAL STEADY-STATE SOLUTION

To the extent that this is possible, we will pin down parameter values so as to be close to annual data targets of the UK economy.[11] Otherwise, we will look for evidence and practice elsewhere in the literature.

3.1 | Parameter values

Baseline parameter values, calibrated to UK data or set as in related studies, are listed in Table 1. Regarding households, their time discount factor β is calibrated from the steady-state version of the Euler equation for bonds by using a 4% annual interest rate (as in, for example, Litsios *et al.* 2021); the resulting value is $\beta = 0.962$. In the utility function, the weight to labour supply μ

TABLE 1 Parameter values.

Parameter	Description	Value	
β	Time discount factor	0.962	Calibrated
κ	Frisch elasticity of labour supply	0.5	Set
ν	Risk aversion parameter	1.5	Set
μ	Preference parameter in utility	131.13	Calibrated
δ	Depreciation rate of private capital	0.074	Calibrated
δ^g	Depreciation rate of public capital	0.075	Calibrated
A	TFP	1	Set
α	Exponent on private capital in production	0.377	Calibrated
σ	Importance of public capital in production	0.05, 0.1	Set
ε	Elasticity of substitution/complementarity	0.5, 0.65, 0.8, 1, 1.2, 1.35, 1.5	Set

is set so as to target the fraction of work time in the data, which is 0.22. The Frisch elasticity of labour supply κ is generally inelastic in UK studies; we set it at 0.5, which is close to the average value across these studies (for a recent paper, see, for example, Millard *et al.* 2024). Finally, for the risk-aversion parameter ν, we follow Leeper *et al.* (2010b) and Malley and Philippopoulos (2023) by setting it at 1.5.

Regarding firms, we normalize the TFP parameter in the production function to 1, and keep it at this value over time unless stated otherwise. We set the exponent on labour in the production function, $(1-\alpha)$, at 0.623, which is the average labour income share in the Office for National Statistics (ONS) data. This in turn implies that the exponent on private capital, α, is 0.377. The private and government capital annual depreciation rates, δ and δ^g, are calibrated to 0.074 and 0.075, respectively; to set these values, we use ONS data for the UK capital stock, including both private and public assets.[12]

We now turn to two 'non-standard' parameters. The most common value for $\sigma > 0$, which measures the relative importance of public capital in production, has been 0.05; see, for example, Leeper *et al.* (2010b), Sims and Wolff (2018) and Ramey (2021). We therefore start with this value, but when we do sensitivity analysis, we will re-run our experiments with other values, such as 0.1 (this value has also been used by, for example, Leeper *et al.* 2010b). Regarding the value of $\varepsilon > 0$, which measures the elasticity of substitution or complementarity between private inputs and public capital, as argued by Baier and Glomm (2001, p. 2024), we are rather agnostic. For instance, in An *et al.* (2019), the estimated elasticity of substitution between private and public capital differs between developed and less-developed or emerging economies; in Chang and Lee (2024), the same elasticity differs between firm- and state-level estimates; Jalles and Karras (2022) find that the elasticity of substitution between public and private consumption differs across different categories of public spending. In other words, as already said in Section 1, there is a wide range of noisy estimates both greater and less than the benchmark value 1. Therefore following Baier and Glomm (2001) and Caselli (2005), we will experiment with a variety of values of ε scattered symmetrically around 1, and investigate how this matters. In particular, we will solve the model with $\varepsilon = 1.5, 1.35, 1.2, 1, 0.8, 0.65, 0.5$ (results for a wider range of ε are available on request).

TABLE 2 Policy variables.

Parameter	Description	Value	
s^c	Government consumption as % of GDP	0.212	Data
s^t	Government transfers as % of GDP	0.158	Data
s^i	Government investment as % of GDP	0.033	Data
τ^c	Consumption tax rate	0.152	Data
b/y	Public debt to output ratio	1.006	Data

Sources: Bank of England, ONS, Office for Budget Responsibility.

TABLE 3 Initial steady state.

Variable	Description	Solution (%)	Data (%)
c/y	Consumption to output	60.4	60.9
i/y	Investment to output	15.2	14.3
k_g/k	Public to private capital	21.5	20.5
τ^y	Income tax rate	35.1	29.2

3.2 | Policy variables

Values for the policy variables are listed in Table 2. In both the steady state and the transition path, we set $s^c = 0.212$, $s^t = 0.158$, $\tau^c = 0.152$ and $b/y = 1.006$ as in the current UK data. Regarding s_t^i, in the initial steady state, we set it to be 0.033 as in the current UK data, then allow for a permanent increase by 1 percentage point (pp) (in which case the economy will travel to a new terminal steady state) or a temporary increase by 1 pp (in which case the economy will return to the initial steady state). In all cases—that is, in the steady state (initial and terminal) as well as along the transition path to a steady state—it will be the income tax rate τ^y that adjusts to close the government budget constraint in equation (14).[13]

3.3 | Initial steady-state solution

Before we start, we compare the model's initial steady-state solution to the data. This solution is defined as the case in which variables do not change, and we use the parameter and policy values listed above. The resulting values of the key endogenous variables—when we set ϵ at 1, say, which is the most common value in the literature—are reported in Table 3.[14] As can be seen, the solution makes sense, hence we feel that it can serve as a departure point for the simulations that follow next.

Before we move on, it is worth noticing that in this solution, $k_g/k = 0.215$, which is a value very close to the data (0.205).[15] Thus k_g is in shortage relatively to k (we report that k_g is also smaller than the bundle of private inputs, $k_{t-1}^a l_t^{1-a}$); hence public capital can be considered as the weak link in production (on this see further below).[16]

4 | MAIN RESULTS

Using the above parameter and policy values, and departing from the initial steady state, we now assume a rise in public investment spending as share of GDP s_t^i, by 1 pp, say (i.e. it rises from

0.033 in the data to 0.043), and examine what happens depending on the different values of $\varepsilon > 0$. Following, for example, Baxter and King (1993), we begin by considering the case in which the exogenous increase in s_t^i is permanent (Subsection 4.1), then study the case in which the same increase is temporary (Subsection 4.2).

4.1 | Effects of a permanent increase in s_t^i

In this subsection, we examine the effects of a permanent increase in s_t^i by 1 pp, *ceteris paribus*. Since the change is permanent, we present both steady-state and transition effects.

4.1.1 | Steady-state results

We focus on the steady-state output multiplier defined as

$$M \equiv (y - y_0)/(g^i - g_0^i),$$

where variables subscripted 0 refer to initial steady-state values before the increase in public investment spending, and variables without subscripts refer to new steady-state values with the increase in public investment spending. We do this for various values of $\varepsilon > 0$, as mentioned above. Results are reported in Table 4.

As can be seen in Table 4, the public investment multiplier gets bigger and bigger as ε becomes smaller and smaller, and this happens monotonically.

Consider first the benchmark case in which $\varepsilon = 1$. As said already, in this case, the CES function in equation (9) converges smoothly to the Cobb–Douglas function in equation (10). The latter is similar to the typical Cobb–Douglas function used in the relevant literature. As can be seen, the size of the multiplier is 1.01, which is within the usual range in the literature (see note 1).

When private inputs and public capital are strong substitutes vis-à-vis the benchmark Cobb–Douglas case (namely, when $\varepsilon > 1$), an increase in public investment that augments public capital, k_g, is accompanied by a decrease in private inputs, namely, capital k and labour l (see below on this), and this adverse—or crowding out—effect on private inputs weakens the growth-enhancing impact of the public investment stimulus. By contrast, the growth footprint of an increase in public investment becomes substantial—that is, the multiplier becomes clearly higher than unity—when $0 < \varepsilon < 1$, in which case private and public inputs are good complements vis-à-vis the Cobb–Douglas case. Under complementarity, an increase in public investment that augments k_g not only increases the weak link (namely, k_g) but also enhances—or crowds in—the usage of private inputs, and this reinforces the positive effect of the fiscal stimulus. Notice the high values of the multiplier when $\varepsilon = 0.65, 0.5, \ldots$.

Therefore good production complementarity can restore the social desirability of public investment spending, and actually this happens even if it is the distorting income tax rate that finances the increase in public investment spending in our solutions. These results are similar to those of Baier and Glomm (2001), except that here we focus on how ε affects output multipliers rather than growth rates.

TABLE 4 Steady-state public investment multipliers.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M	0.32	0.46	0.64	1.01	1.69	2.66	4.72

Notes: Permanent increase in public investment as share of GDP by 1 pp.

TABLE 5 Changes in private productive inputs.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
Private capital	−1.74	−1.54	−1.26	−0.67	0.48	2.34	7.11
Labour	−0.18	−0.17	−0.16	−0.14	−0.08	0.04	0.37

Notes: Percentage changes (final relative to initial steady state) following a permanent increase in public investment as share of GDP by 1 pp.

TABLE 6 Changes in consumption and utility.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
Consumption	−0.82	−0.69	−0.53	−0.18	0.18	1.48	3.92
Utility	−0.34	−0.28	−0.21	−0.05	0.24	0.70	1.84

Notes: Percentage changes (final relative to initial steady state) following a permanent increase in public investment as share of GDP by 1 pp.

To support the above narrative, Table 5 reports the associated effects on private inputs, namely, capital and labour, expressed as percentage changes from their initial steady-state values. As can be seen, the relative changes between the end-of-horizon private capital and labour (i.e. after the stimulus) and the initial private capital and labour (i.e. before the stimulus) are both negative in the range $\varepsilon \geq 1$, while they turn positive (especially capital) when $0 < \varepsilon < 1$, and actually, they become more and more positive as ε becomes smaller and smaller. This explains the output multipliers in Table 4.

Also, for completeness, Table 6 presents the percentage changes of household's consumption and utility from their initial steady-state values as a result of the same public investment stimulus. Obeying the same logic as above, the fiscal stimulus hurts consumption and utility in the range $\varepsilon \geq 1$, but improves them in the range $0 < \varepsilon < 1$. Notice that under enough complementarity, steady-state utility rises despite the increase in work time or equivalently decrease in leisure time (see Table 5).

We report that these results are robust to changes in parameter values (a sensitivity analysis involving more substantial modelling modifications is deferred to Section 6). With respect to parameter values, we have already reported robustness to alternative capital depreciation rates. Here, we also report robustness with respect to the value of σ, which captures the relative importance of public capital in production; naturally, the higher the value of σ, the larger the multiplier (see Appendix Subsection A.1 for details).

4.1.2 | Transition results

We now study transition dynamics, again for various values of ε. We thus depart from the initial steady state of Subsection 3.3 (where $s_0^i = 0.033$ at $t = 0$), and analyse the transition effects of a permanent increase in the public investment to output ratio by 1 pp, that is, from 0.033 to 0.043.

In particular, the economy starts at $t = 0$ with $s_0^i = 0.033$, then s^i rises by 1 pp permanently, meaning that $s_t^i = 0.043$ at all $t \geq 1$, and the economy travels towards its new steady state, which will be the one of the previous subsection.

TABLE 7 Cumulative public investment multipliers (first 50 periods) under a permanent increase in public investment.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M_t	−0.03	0.04	0.14	0.33	0.68	1.21	2.36

Notes: Permanent increase in public investment as share of GDP by 1 pp.

To measure how this affects the economy over time, following the literature—see, for example, Uhlig (2010), Leeper *et al.* (2010b), Coenen *et al.* (2013) and Malley and Philippopoulos (2023)—we compute cumulative discounted present-value output multipliers, defined as

$$M_t \equiv \sum_{j=1}^{t}(R^{-j})(y_j - y_0) \Big/ \sum_{j=0}^{t}(R^{-j})(g_j^i - g_0^i), \tag{16}$$

where $R = (1 + r^b)$ is the steady-state value of the sovereign interest rate, and as above, variables subscripted 0 refer to initial steady-state values at $t = 0$, before the exogenous increase in s_t^i. Also recall that $g_t^i = s_t^i y_t$.

Table 7 presents the results for M_t, as defined in equation (16), for various values of ε. The number of periods over which we compute these multipliers is, for instance, 50.[17]

As can be seen, and consistent with the steady-state results in the previous subsection, the cumulative multiplier increases as ε decreases. Moreover, we show that as the time horizon becomes sufficiently long, the (non-discounted) cumulative multipliers converge to the steady-state multipliers reported in Table 4.

4.2 | Effects of a temporary increase in s_t^i

In this subsection, we examine the effects of a temporary 1 pp increase in s_t^i, *ceteris paribus*. Since the change is temporary, the economy starts from, and returns to, the same steady state of Subsection 3.3. Accordingly, we can report transition results only.

In particular, the economy again starts at $t = 0$ with $s_0^i = 0.033$, then s^i rises by 1 pp at $t = 1$ only, meaning that $s_t^i = 0.043$ at $t = 1$, and the economy returns gradually to its initial steady state following an AR(1) rule that holds for all $t \geq 2$, and looks like

$$s_t^i = \rho^s s_{t-1}^i + (1 - \rho^s) s_0^i,$$

where $0 \leq \rho^s \leq 1$ is a persistence parameter that determines the speed of adjustment. (For our numerical solutions, we follow Ramey (2021) and set $\rho^s = 0.81$.)[18]

To measure how the temporary increase s_t^i affects the economy over time, we again compute cumulative discounted present-value output multipliers, as defined in equation (16). Table 8 presents results for various values of ε. Again, the number of periods over which we compute the cumulative present-value output multipliers is, for instance, 50. As can be seen, and as was the case in the previous subsection with a permanent change, the cumulative multiplier becomes larger and larger as ε becomes smaller and smaller.

Moreover, comparison of the results in Table 8 to those in Table 7 reveals that a temporary rise in public investment spending is less effective than a permanent one when public capital and private inputs are gross substitutes or mild complements, whereas when they become relatively strong complements (in our parametrization, this starts around $\varepsilon = 0.65$), a temporary rise becomes more effective. It is known that the comparison between the effects of a permanent fiscal stimulus and a temporary one is in general ambiguous. For example, Baxter and King (1993)

TABLE 8 Cumulative public investment multipliers (first 50 periods) under a temporary increase in public investment.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M_t	−0.38	−0.28	−0.16	0.10	0.59	1.31	2.87

Notes: Temporary increase in public investment as share of GDP by 1 pp.

find that when the increase in spending is financed via lump-sum taxes, multipliers for a permanent increase are larger than multipliers for a temporary increase. By contrast, Coenen *et al.* (2012) find the opposite, because with distorting public financing, when a rise in public spending is permanent, distorting taxes need to remain elevated over time so as to continue financing the persistent increase in public spending, and this proves to be counter-productive relative to a temporary increase. Our results in Tables 7 and 8 show that even when the increase in public investment spending is financed via distorting income taxes as in Coenen *et al.* (2012), the comparison also depends on the elasticity of substitution. When $\varepsilon \leq 0.65$, the multiplier for a temporary increase is larger than that for a permanent increase; intuitively, when, due to relatively strong complementarity, private inputs have been crowded in and are therefore relatively abundant anyway, higher distorting taxes associated with a permanent increase hurt the economy so a temporary stimulus is better. On the other hand, when $\varepsilon \geq 0.8$, implying that private inputs are less abundant, a permanent rise in public investment spending is more beneficial than a temporary one even with higher distorting taxes over time. However, as we will see in Section 7, during economic downturns, the results become monotonic, providing arguments in favour of a permanent stimulus over the whole range of ε.

Before proceeding, we also assess the robustness of our results. The transition dynamics reported above—for both permanent and temporary increases in s^i_t—remain qualitatively unchanged when we assume, as in, for example, Leeper *et al.* (2010b), Ramey (2021) and Malley and Philippopoulos (2023), the presence of time lags in the accumulation of public infrastructure capital, for example in the form of time-to-build delays. Details and numerical solutions for this extension are provided in Appendix Subsection A.2.

5 | NORMATIVE IMPLICATIONS

We now examine how the above positive results translate into normative lessons. To do so, we solve for the optimal value of the public investment to output ratio again for each value of ε assumed. In particular, we assume a benevolent, Ramsey-type policymaker who chooses the path of the public investment to output ratio $\{s^i_t\}^{\infty}_{t=0}$ to maximize expressions (1) and (2) subject to the macroeconomic equilibrium system, namely equations (3)–(9), (11)–(15). This is for given values of the remaining independently set policy instruments $\{s^t_t, s^c_t, \tau^c_t, b_t/y_t\}^{\infty}_{t=0}$, which are again kept at their data values.[19] Recall that in the UK data, the investment to output ratio s^i and the associated public capital to private capital ratio k_g/k are, respectively, 3.3% and 20.5%.

Steady-state results are reported in Table 9. As can be seen, the effects of ε are again monotonic in each row. More specifically, in the first two rows, the smaller ε, the higher the socially optimal public investment to output ratio and the associated public to private capital ratio. These results are consistent with the positive findings above. Thus when choosing s^i, the Ramsey-type policymaker internalizes the crowding-out effect on private inputs in the region of gross substitutability ($\varepsilon > 1$) and the crowding-in effect in the region of gross complementarity ($0 < \varepsilon < 1$); hence it is optimal to choose higher s^i and k_g/k as complementarity rises. The third row reports

TABLE 9 Optimal steady-state public investment to output ratio.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
s^i (%)	1.33	1.60	1.94	2.49	3.20	3.86	4.65
k_g/k (%)	8.20	9.98	12.19	15.97	21.06	25.93	31.97
M	1.08	1.20	1.32	1.52	1.78	2.01	2.28

Notes: First row: optimal public investment ratio. Second row: public to private capital ratio. Third row: multipliers of a permanent exogenous increase in the optimal public investment ratio by 1 pp.

steady-state multipliers M for each value of ε, when we increase the socially optimal public investment to output ratio exogenously by 1 pp, as we have done so far in the positive analysis. As can be seen, the monotonicity result remains unchanged; that is, as ε falls, the multiplier becomes bigger. It is also worth noting that the monotonic effect of ε on the multiplier holds across the entire range of values that we consider (and, as we report, it continues to hold for values of ε greater than 1.5 or less than 0.5). In other words, the result does not depend on whether the public investment to output ratio observed in the data (3.3%) lies above or below its corresponding socially optimal level.

The results in Table 9 also reveal Laffer-curve-type effects for the public investment spending ratio.[20] For example, consider the popular benchmark Cobb–Douglas case in which $\varepsilon = 1$. In this case, the Ramsey-type maximum is attained at $s^i = 2.49\%$, which is below its current data value 3.3%. This means that for $\varepsilon = 1$, the current public investment spending ratio lies on the decreasing segment of the Laffer curve when the latter is expressed in terms of social welfare, or equivalently, that lowering s^i to 2.49% would be welfare improving. By contrast, when, for example, $\varepsilon = 0.5$, which means rather strong complementarity, the Ramsey-type maximum is attained at $s^i = 4.65\%$, which is above its current data value 3.3%. This means that in this case, the current public investment spending ratio lies on the increasing part of the Laffer curve, or equivalently, that increasing s^i to 4.65% would be welfare improving. Finally, notice that in the case in which ε is around 0.66 (which is the value implied by the econometric estimates of An *et al.* (2019) for advanced economies in general), the optimal share of public investment is around 3.86%. If we use this value of ε as a plausible value for the UK economy in which s^i is 3.3%, then our results can provide an argument for an increase in public investment, although not a drastic one. A more drastic increase could be rationalized only under a stronger degree of complementarity between private inputs and public capital (however, see also the discussion in Section 8).

6 | WHAT DRIVES OUR RESULTS?

We next explore the possible drivers of our results. In particular, we examine whether our results depend on (i) the economy's initial position, as this is shaped by different values of ε, (ii) the exact form of the production function, and (iii) the role of public capital as the weak link.

6.1 | Does the initial position matter?

So far, when solving the model under different values of ε and computing the output multiplier for each ε, the solutions can differ at all $t \geq 0$—in other words, including the initial, starting period $t = 0$. So one may wonder whether it is this different starting value that drives our results. To investigate this, we now resolve the model by adjusting first, the value of A so that the starting level of output becomes the same even when ε differs (we choose, for example, the starting

TABLE 10 Steady-state public investment multipliers and starting values.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M	0.32	0.46	0.64	1.01	1.69	2.66	4.72
	0.31	0.45	0.64	1.01	1.68	2.62	4.44
	0.32	0.46	0.64	1.01	1.70	2.72	4.77

Notes: Permanent increase in public investment as share of GDP by 1 pp. In the second row, the initial output level is the same irrespective of ε. In the third row, the initial public to private capital ratio is the same irrespective of ε.

output level of the benchmark Cobb–Douglas case with $\varepsilon = 1$, although this is not important to our results), and second, the value of δ^g so the starting capital ratio k_g/k becomes the same even when ε differs (again, we choose, for example, the common starting value of k_g/k to be the one of the benchmark Cobb–Douglas case of $\varepsilon = 1$, although again this is not important to our results).

Results for long-run multipliers M are in Table 10. The second row presents the values of M when we adjust the value of A so that the starting value of output is the same under all values of ε, while the third row presents the values of M when we adjust the value of δ_g so that the starting value of k_g/k is the same again under all ε (the first row repeats, for comparison, the baseline solutions of Table 4). As can be seen, the main result is not affected; namely, as complementarity increases, the multiplier gets bigger.[21] Therefore although one cannot exclude the possibility that the initial values of other endogenous variables may differ (there are several other endogenous variables in addition to output and the capital ratio),[22] our experiments indicate that our key qualitative property is robust to different starting values.

6.2 | Does the exact specification of the production function matter?

Here, we consider two variants of the production function employed thus far. The first assumes that labour is complementary to both types of capital, while the second extends the production function to allow for increasing returns to scale (IRS) in all factors.

6.2.1 | Labour as a complement to both types of capital

Following, for example, Baier and Glomm (2001) and Chang and Lee (2024), we assume that labour is complementary to both types of capital, meaning that it multiplies a CES composite of private and public capital. Thus instead of equation (9), we now use

$$y_t = A_t l_t^{1-\alpha}\left[(1-\sigma)(k_{t-1})^{(\varepsilon-1)/\varepsilon} + \sigma(k_{g,t-1})^{(\varepsilon-1)/\varepsilon}\right]^{\alpha\varepsilon/(\varepsilon-1)}, \quad (17)$$

and in turn, when $\varepsilon \to 1$, instead of equation (10), we now use

$$y_t = A_t l_t^{1-\alpha}\left[(k_{t-1})^{1-\sigma}(k_{g,t-1})^{\sigma}\right]^{\alpha}. \quad (18)$$

Results regarding the steady-state public investment multiplier M are reported in the second row of Table 11.[23] The first row repeats, again for comparison, the baseline solution of Table 4.

As can be seen, the key qualitative result continues to hold: namely, as ε falls, the output multiplier increases. Moreover, note that the multipliers obtained under specification (17) are smaller than those obtained under equation (9); compare the values in the second row of Table 11 to the corresponding ones in the first row. This reflects the fact that the beneficial effects of an

TABLE 11 Steady-state public investment multipliers when labour is complement to both types of capital.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M	0.32	0.46	0.64	1.01	1.69	2.66	4.72
	−0.59	−0.51	−0.39	−0.13	0.41	1.28	3.03

Notes: Permanent increase in public investment as share of GDP by 1 pp.

increase in public capital are stronger when public capital supports all private inputs, rather than only a subset of them.

6.2.2 | Allowing for IRS

As mentioned in Subsection 2.2, several papers in this literature have used Cobb–Douglas production functions with CRS in private inputs and hence IRS in all inputs including public capital; see, for example, Baxter and King (1993), Glomm and Ravikumar (1994), Leeper *et al.* (2010b), Sims and Wolff (2018), Ramey (2021), Malley and Philippopoulos (2023) and Peri *et al.* (2023, 2026). To test if this specification matters to our results, we enrich the CES production function in equation (9) so that now

$$y_t = A_t\left[(1-\sigma)(k_{t-1}^{\alpha} l_t^{1-\alpha})^{(\varepsilon-1)/\varepsilon} + \sigma(k_{g,t-1})^{(\varepsilon-1)/\varepsilon}\right]^{\varepsilon\psi/(\varepsilon-1)}, \tag{19}$$

where $\psi > 0$ governs the degree of returns to scale. When $\psi = 1$, equation (19) exhibits CRS as equation (9). Also, in the limiting case in which $\varepsilon \to 1$, equation (19) becomes

$$y_t = A_t(k_{t-1}^{\alpha} l_t^{1-\alpha})^{(1-\sigma)\psi}(k_{g,t-1})^{\sigma\psi}, \tag{20}$$

which is the Cobb–Douglas production function used by the above listed papers if we set $(1-\sigma)\psi = 1$ and $0 < \sigma\psi < 1$. More specifically, if we use the parametrization typically used in these papers (namely, $\sigma\psi = 0.05$), then $\sigma = 0.0476$ and $\psi = 1.050$.

Using equations (19) and (20) instead of equations (9) and (10), adjusting accordingly the firm's optimality conditions in equations (12) and (13), and resolving the model by using $\sigma = 0.0476$ and $\psi = 1.050$ for comparability with the literature, the steady-state public investment multipliers M for different values of the elasticity of substitution ε are reported in the second row of Table 12, where again, the first row repeats the baseline solutions of Table 4 for comparison.

As can be seen, as ε falls, the output multiplier increases. Thus the main result is robust to the degree of returns to scale embedded in the production function. Moreover, notice that the multiplier with IRS is larger than the one with CRS when the degree of complementarity is relatively high (here, $\varepsilon \leq 0.65$).

TABLE 12 Steady-state public investment multipliers when we allow for IRS.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M	0.32	0.46	0.64	1.01	1.69	2.66	4.72
	0.24	0.37	0.56	0.99	1.65	2.68	4.93

Notes: Permanent increase in public investment as share of GDP by 1 pp.

TABLE 13 Steady-state public investment multipliers when public capital is not the weak link.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M	0.32	0.46	0.64	1.01	1.69	2.66	4.72
	1.13	1.11	1.08	1.01	0.89	0.72	0.44

Notes: Permanent increase in public investment as share of GDP by 1 pp.

6.3 | The importance of public capital as the weak link

We finally check the insight of Jones (2011) about the role of weak links. Recall that so far we have investigated what happens when public investment spending increases by 1 pp of GDP when, at the same time, public capital k_g has been in relative shortage. Specifically, recall that in the solutions so far, we started with a public capital to private capital ratio equal to $k_g/k = 0.215$, which is a value close to the one in the UK data (actually, this is also the case in most countries; see, for example, Baier and Glomm (2001), Leeper *et al.* (2010b) and, more recently, Malley and Philippopoulos (2023) for the USA). To investigate if this matters, let us now imagine the counterfactual case in which k_g is relatively abundant. For instance, imagine that k_g/k is 1 in the initial, starting steady-state solution,[24] although the exact number is not important to our qualitative results, since what matters is to assume that k_g/k is above a threshold value.[25] Results regarding the steady-state public investment multiplier M for this counterfactual case are reported in the second row of Table 13. Notice that the first row repeats, for comparison, the baseline solution of Table 4. As can be seen, the results of Table 4 are now reversed: namely, in Table 13, the public investment multiplier gets smaller and smaller as ε falls—that is, as complementarity rises—while it was exactly the opposite in Table 4. This happens because now public capital is not the factor in shortage, and as said above, allocative efficiency calls for increasing the units of the low-efficiency factor, or in our model, the factor that is provided inadequately. That role was played by public infrastructure in the main results above. By contrast, when we make the counterfactual assumption that the factors that are provided inadequately are the private ones, the results are reversed.

Therefore the relationship between k_g and k matters not only quantitatively but also qualitatively. It is the combination of complementarity and the relative shortage of k_g that drives the main result. Complementarity on its own is not enough. In other words, the beneficial effects of an increase in public infrastructure spending increase with the degree of complementarity only in economic environments in which public infrastructure is little relative to private inputs. The importance of this condition has escaped the attention of the related literature on the effects of public investment spending. On the other hand, as already said in the Introduction, it is consistent with the Jones (2011, p. 7) insight that 'a stronger degree of complementarity puts more weight on the weakest link'. It is also consistent with Caselli (2005, p. 732), who says that with $0 < \varepsilon < 1$, 'allocative efficiency calls for boosting the overall efficiency units provided by the low-efficiency factor'. However, it should be stressed that since, in practice, there is no a single public capital but instead there are different categories of public capital (see the discussion in Section 8), abundance or shortage relative to private inputs may differ across those different categories.

7 | A RICHER POLICY EXPERIMENT: PUBLIC INVESTMENT DURING ECONOMIC DOWNTURNS

Here, we examine a richer policy scenario in which there is also an adverse TFP shock that triggers an economic downturn, and thus investigate what an increase in public investment spending can

TABLE 14 Cumulative output gap (COG_t) under an adverse TFP shock (first 50 periods).

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
No policy	−3.83	−3.83	−3.83	−3.84	−3.86	−3.89	−3.96
Permanent policy	−4.40	−2.92	−0.89	3.33	11.27	23.47	52.39
Temporary policy	−5.47	−5.08	−4.54	−3.42	−1.30	1.98	9.85

Notes: First row: without policy reaction. Second row: permanent increase in public investment as share of GDP by 1 pp. Third row: temporary increase in public investment as share of GDP by 1 pp.

do to counter this and, more importantly, how this depends on the degree of substitutability or complementarity.

In particular, we assume a temporary 1 pp fall in A_t in equation (9).[26] We then examine what happens again for various values of ε, first, when there is a permanent increase in public investment spending as share of output by 1 pp, and second, when there is a temporary increase in public investment spending as share of output by 1 pp, both of which are modelled as defined in Section 4. For comparison, we will also repeat the experiment under the assumption that public investment spending as share of output remains unchanged, meaning that only A_t falls, and there is no policy reaction to this recessionary shock. As our metric, in each case, we compute the present discounted value of cumulative output gaps, expressed as percentage deviations from the initial steady state. Formally, this measure, denoted COG_t, is

$$COG_t \equiv \left[\sum_{j=1}^{t} (R^{-j}) \left(\frac{y_j - y_0}{y_0} \right) \right] \times 100.$$

Results for the cumulative output gap in the first 50 periods are reported in Table 14. As can be seen—and as is probably expected given the results presented above—when ε is high (in our parametrization, when $\varepsilon = 1.5$), the use of public investment as a countercyclical fiscal instrument does not benefit the economy, in the case of both permanent and temporary policy reactions; on the contrary, this makes the recession even deeper relative to the no-policy scenario. This occurs both because private inputs are substituted for public capital, as discussed above, and because the income tax rate must increase in order to keep public debt on its target path. In other words, when private inputs are good substitutes for public inputs, it is preferable to allow the economy to absorb the recessionary shock on its own. By contrast, as ε decreases—so that complementarity starts to kick off—the result is reversed, and the public infrastructure stimulus becomes increasingly beneficial. Finally, notice that within this recessionary environment, a permanent fiscal stimulus is always better than a temporary one.

Finally, in Appendix Subsection A.3, we present solutions when, in the presence of the same adverse shock to A_t, the increase in public investment spending is characterized by time-to-build lags. Again, the main results remain unchanged.

8 | CONCLUSIONS, DISCUSSION AND POSSIBLE EXTENSIONS

This paper revisited the issue of the public investment multiplier through the lens of production complementarity/substitutability between private inputs and public infrastructure capital. We showed that when there is a good degree of complementarity and, at the same time, public capital is in relative shortage, the multiplier can be substantially large, other things equal.

We worked with a version of the stylized neoclassical growth model. This was deliberate to make our arguments clearer and our results directly comparable to the literature. An extension could be to embed our story into a fully fledged dynamic stochastic general equilibrium

(DSGE) model estimated for the UK economy, which would allow us to get, among other things, a data-consistent value for the key parameter ε (see also, for example, Leeper *et al.* (2017) and Chang and Lee (2024) for the US economy). It should be stressed, however, that although most of the empirical evidence seems to suggest that public capital is a gross complement to private inputs (i.e. $\varepsilon < 1$), this is at the aggregate level only. In reality, the estimated degree of complementarity or substitutability can differ considerably across different categories of public capital (see, for example, Jalles and Karras 2022). And the same can apply to the relative shortage of public capital; that is, although public capital appears to be in relative shortage at the economy-wide aggregate level, this can vary depending on the category of public capital. All this implies that such a DSGE model should be rich enough to permit different categories of public infrastructure (e.g. hard or physical infrastructure, education, health, R&D, government institutions) to play distinct roles from each other, and hence possibly feature different degrees of complementarity/substitutability and shortage/abundance with the associated private inputs. Another extension could be to allow for different efficiency units delivered by one unit of public capital. In the present framework, it was implicitly assumed that the units of public capital generated by public spending coincide with public capital measured in efficiency units. These two concepts could be treated separately, allowing the actual public capital in equation (9) to be augmented not only through increased public spending, but also through improvements in the degree of public sector efficiency. The challenge in this case would be to endogenize public sector efficiency through a micro-founded channel. We leave these extensions for future research.

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ENDNOTES

[1] For instance, when studying temporary increases in public investment spending, Leeper *et al.* (2010b), Coenen *et al.* (2012, 2013), Buakez *et al.* (2017), Sims and Wolff (2018), Ramey (2021), and Malley and Philippopoulos (2023), among many others, report cumulative public investment multipliers around unity, especially in normal times (i.e. when the economy is not at the zero lower bound) and when the increase in public spending is not assumed to be financed through lump-sum taxes. Moreover, under such conditions, the multipliers associated with a permanent increase in public investment spending do not appear to differ substantially from those associated with a temporary increase (see, for example, Coenen *et al.* (2012); further details are provided in the text).

[2] 'Hard' infrastructure, defence capability, courts, police, and so on, must be good complements to private inputs. On the other hand, energy, telecoms, rail, public spending on certain types of R&D, education and health, and so on, can be complements or substitutes to private inputs and spending (see, for example, the discussions in Baier and Glomm 2001; Jalles and Karras 2022; Schuknecht 2021). We revisit this issue in Section 8.

[3] The critical level of public capital above which the results are reversed is, as expected, model-specific, and depends on several factors, such as the efficiency of public capital and the tax-debt burden associated with public investment spending. Importantly, while we conduct a wide range of robustness checks throughout the paper, the only case in which the results are reversed is when we assume that the public to private capital ratio exceeds a threshold level. See Subsection 6.3.

[4] By contrast, Baxter and King (1993), Glomm and Ravikumar (1994), Leeper *et al.* (2010b), Bouakez *et al.* (2017, 2023), Sims and Wolff (2018), Ramey (2021), Malley and Philippopoulos (2023) and Peri *et al.* (2023, 2026) study public investment multipliers working with a Cobb–Douglas production function, so they abstract from the issue of complementarity or substitutability (see the text for further details).

[5] For estimates, see, for example, An *et al.* (2019), Jalles and Karras (2022) and Chang and Lee (2024), while earlier papers are reviewed in Baier and Glomm (2001). Subsection 3.1 provides more details on these papers.

[6] Since we do not include a separate technology term for $k_{g,t-1}$, the quantity of public capital is tantamount to public capital in efficiency units (this will be discussed further in Section 8).

[7] In Subsubsection 6.2.1, we also present results when we use a slightly different specification where private and public capital are combined into a CES technology and the latter is combined with labour by a Cobb–Douglas function (see, for example, Baier and Glomm 2001; Coenen *et al.* 2013; Chang and Lee 2024).

[8] See, for example, Silberberg (1981, pp. 320–1) and Varian (1984, pp. 30–1). Silberberg (1981, pp. 315–22) also provides details on the calculation of the elasticity of substitution.

[9] In Subsubsection 6.2.1, we also present results when the CES function is such that its limiting Cobb–Douglas version exhibits constant returns to scale in private inputs, and increasing returns to scale to all factors; see, for example, Baxter and King (1993), Glomm and Ravikumar (1994), Leeper *et al.* (2010b), Sims and Wolff (2018), Ramey (2021), Malley and Philippopoulos (2023) and Peri *et al.* (2023, 2026). Also note that using Cobb–Douglas production functions in models enriched with intermediate goods, Jones (2011), Bouakez *et al.* (2023), Malley and Philippopoulos (2023) and Peri *et al.* (2023, 2026) also demonstrate that multipliers increase as we move from one-sector models to models with input–output linkages.

[10] Government consumption is included mainly for numerical/calibration reasons.

[11] The data used come from various institutions, including the Bank of England, the Office for National Statistics and the Office for Budget Responsibility.

[12] Specifically, the depreciation rates are computed as the ratio of current cost depreciation to the net stock of fixed assets at the end of the previous year, averaged over the period from 1995 to 2019 (see also Economides *et al.* 2025). See Ramey (2021) for the same methodology applied to the USA. In Ramey's case, this yields estimates $\delta^g = 0.01$ and $\delta = 0.015$ in quarterly terms, or $\delta^g = 0.04$ and $\delta = 0.06$ in annual terms. For robustness, we have experimented with these values, and report that our results do not change qualitatively.

[13] We report that our main results are not affected when it is lump-sum income transfers that adjust to close the government budget constraint in each period, or when this happens by adjustments in the end-of-period public debt. (In the latter case, dynamic stability requires that one or more exogenous fiscal instruments also react to deviations of the debt to GDP ratio from its long-run target value; see, for example, Leeper *et al.* 2010a; Sims and Wolff 2018; Malley and Philippopoulos 2023.) Results for these alternative public financing cases are available on request.

[14] Concerning the effective income tax rate, we use data from Eurostat for 2019 (implicit tax rates, European Commission Taxation Trends) and calculate it as the weighted average of labour and capital tax rates over the period 2007–19 when the weights are the associated shares in the production function. It is interesting to notice that this solution for the income tax rate is clearly higher than its value in the data, which gives a hint about long-run fiscal unsustainability if nothing changes.

[15] This is also close to the US data; see, for example, Baier and Glomm (2001), Leeper *et al.* (2010b) and Malley and Philippopoulos (2023).

[16] This is not sensitive to the value of ε used. For instance, when we resolve the model for $\varepsilon = 1.5, 1.35, 1.2, 1, 0.8, 0.65, 0.5$, the resulting values of k_g/k are, respectively, 0.2123,0.2128,0.2135,0.215,0.2174,0.2211,0.2298, all of which are again close to the data value.

[17] Cumulative multipliers at different time horizons are available on request.

[18] Our key results are not sensitive to the value of ρ^s or to the magnitude of the shock. In particular, regarding ρ^s, we have additionally considered, for example, the cases $\rho^s = 0$, $\rho^s = 0.95$ and $\rho^s \to 1$. While the results differ quantitatively from those reported in Table 8, they remain qualitatively unchanged. We also report that when $\rho^s \to 1$, which means that the change is like a permanent one, we go back to the results in Subsection 4.1. All these results are available on request.

[19] This exercise is executed by using a routine in Dynare, which allows us to compute the optimal policy choices of a planner who takes the macroeconomic equilibrium conditions into account and commits to future policy choices.

[20] See also D'Erasmo *et al.* (2016, section 3.3) for a similar analysis of Laffer curves, although in a different economic environment in which the optimal (maximum) value of the policy instrument (such as a tax rate) is defined in terms of maximum total tax revenues.

[21] We report that transition results are similar to these long-run results. Results are available on request.

[22] On the other hand, our solutions also show that even when there are differences in the initial values of the other endogenous variables, these differences are quantitatively small, particularly for variables expressed as rates or ratios. Results are available on request.

[23] In these solutions, we use $\sigma = 0.05$, as in the baseline parametrization so far. Baier and Glomm (2001) use $\sigma = 0.3$, which can generate larger multipliers, *ceteris paribus*. Since we consider equations (17) and (18) only as a robustness exercise, we prefer to retain the same value $\sigma = 0.05$ for comparability.

[24] To target an initial public to private capital ratio k_g/k equal to 1, we adjust accordingly the depreciation rate of public capital δ^g. For example, for $\varepsilon = 1$, $k_g/k = 1$ implies $\delta^g = 0.016$.

[25] As mentioned in the Introduction, the value of the threshold value of k_g/k, above which the baseline results are reversed, is naturally model-specific depending directly on the values of the parameters in the production function (9) as well as indirectly on the other features of the model. But our results show clearly that when k_g ceases to be underprovided relative to k, the results are reversed.

[26] We assume an AR(1) process with persistence parameter 0.5 and long-run value equal to that in the baseline calibration. Our qualitative results are not sensitive either to this parametrization or to the size of the shock.

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APPENDIX A

A.1 Sensitivity with respect to the importance of public capital

In Table A1, the first row repeats, for comparison, the baseline solution of Table 4 where $\sigma = 0.05$. Then the second row shows the values of the output multipliers when $\sigma = 0.1$ (results with $\sigma < 0.05$ are symmetrically opposite). As in the main text, as ε decreases, the output multipliers increase. Naturally, there are quantitative differences; for instance, for given ε, a higher σ gives higher multipliers, as should be expected.

A.2 Cumulative public investment multipliers with time-to-build lags

In Table A2, the first and second rows repeat, for comparison, the baseline solutions of Tables 7 and 8. Then the third and fourth rows present cumulative multipliers under a permanent and a temporary increase, respectively, except that now there are time-to-build lags in the accumulation of public capital. In particular, public capital is now assumed to evolve according to $k_{g,t} = (1 - \delta_g)k_{g,t-1} + g^i_{t-2}$. Again, as ε decreases, the output multipliers increase. Of course, there are quantitative differences; for instance, time lags weaken the effectiveness of public spending, other things equal.

TABLE A1 Steady-state public investment multipliers with different σ.

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M ($\sigma = 0.05$)	0.32	0.46	0.64	1.01	1.69	2.66	4.72
M ($\sigma = 0.1$)	1.52	1.79	2.14	2.84	4.08	5.79	9.12

Notes: Permanent increase in public investment as share of GDP by 1 pp.

TABLE A2 Cumulative public investment multipliers with time-to-build lags (first 50 periods).

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
M_t	−0.03	0.04	0.14	0.33	0.68	1.21	2.36
	−0.38	−0.28	−0.16	0.10	0.59	1.31	2.87
	−0.10	−0.04	0.04	0.22	0.54	1.01	2.05
	−0.50	−0.41	−0.30	−0.06	0.39	1.05	2.50

Notes: First row: permanent increase in public investment by 1 pp of GDP. Second row: temporary increase in public investment by 1 pp of GDP. Third row: permanent increase in public investment by 1 pp of GDP plus time-to-build lags. Fourth row: temporary increase in public investment by 1 pp of GDP plus time-to-build lags.

A.3 Cumulative output gap under an adverse TFP shock and time-to-build lags

In Table A3, the first three rows reproduce, for comparison, the results of Table 14. Then in the last two rows, we also add time-to-build lags under a permanent fiscal stimulus (second row from bottom) and under a temporary fiscal stimulus (last row). As can be seen, all qualitative results remain as discussed in Table 14. Quantitatively, time lags make public spending less effective, as expected; also, in the presence of time lags, the superiority of fiscal action relative to no policy action kicks off a little later than in the second and third rows.

TABLE A3 Cumulative output gap (COG_t) under an adverse TFP shock plus time-to-build lags (first 50 periods).

ε	1.5	1.35	1.2	1	0.8	0.65	0.5
No policy	−3.83	−3.83	−3.83	−3.84	−3.86	−3.89	−3.96
Permanent policy	−4.40	−2.92	−0.89	3.33	11.27	23.47	52.39
Temporary policy	−5.47	−5.08	−4.54	−3.42	−1.30	1.98	9.85
Permanent policy (lags)	−6.02	−4.70	−2.89	0.88	7.97	18.84	44.46
Temporary policy (lags)	−5.96	−5.61	−5.12	−4.10	−2.16	0.82	7.94

Notes: First row: without policy reaction. Second row: permanent increase in public investment as share of GDP by 1 pp. Third row: temporary increase in public investment as share of GDP by 1 pp. Fourth row: permanent increase in public investment as share of GDP by 1 pp plus time-to-build lags. Fifth row: temporary increase in public investment as share of GDP by 1 pp plus time-to-build lags.