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Delays in Public Goods

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Abstract

In this paper, we analyze the consequences of delays and cost overruns typically associated with the provision of public infrastructure in the context of a growing economy. Our results indicate that uncertainty about the arrival of public capital can more than offset its positive spillovers for private-sector productivity. In a decentralized economy, unanticipated delays in the provision of public capital generate too much consumption and too little private investment relative to the first-best optimum. The characterization of the first-best optimum is also affected: facing delays in the arrival of public goods, a social planner allocates more resources to private investment and less to consumption relative to the first-best outcome in the canonical model (without delays). The presence of delays also lowers equilibrium growth, and leads to a diverging growth path relative to that implied by the canonical model. This suggests that delays in public capital provision may be a potential determinant of cross-country differences in income and economic growth.

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1   Introduction

Infrastructure investment is a key feature of fiscal policy in both developed and developing countries. Over the past two decades, emerging markets such as China and India have allocated an increasing share of national resources towards the provision of public investment goods such as roads, ports, power, telecommunications, etc., with the objective of enhancing economic growth through the realization of higher productivity for the private sector. However, a critical challenge with such infrastructure projects is uncertainty with respect to their implementation: once a project is approved, public spending takes places continuously over time, but is relevant for private production only when the project is *completed*. As such, if the completion date for infrastructure projects is uncertain and subject to unexpected delays, it may critically affect private resource allocation decisions and, thereby, economic growth. Moreover, delays in project implementation can also lead to a significant escalation of costs, which is an additional drain on scarce national resources. Table 1 provides examples of specific infrastructure projects associated with implementation delays and cost overruns for India, the United States, and a sample of European countries.[1]

TABLE 1. Implementation Delays and Cost Overruns

Project	Sector	Country	Implementation Delay (yrs)	Cost Overrun (%)
Udhampur-Srinagar-Baramulla Line	Railways	India	17	700
Bankura-Damodar Line	Railways	India	11	1163
Belapur Electrified Double Line	Railways	India	10	277
Big Dig, Boston	Road	USA	8	477
San Francisco Bay Bridge	Road	USA	6	2500
Orlando VA Medical Facility	Medical	USA	5	143
Berlin International Airport	Airport	Germany	6+	250
Flamanville 3 Nuclear Power Plant	Power	France	6	266
Olkiluoto Nuclear Power Plant	Power	Finland	8+	300

In Table 1, implementation delays represent "time overruns," i.e., the difference between the actual and planned (expected) date of completion of a project. Similarly, "cost overrun" is defined as the difference between the actual and planned outlay for a project.[2] As can be seen, implementation delays are a feature that affects infrastructure provision in both developed and developing countries, with delays ranging from 5-17 years and cost overruns

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[1]See the appendix for sources.
[2]See, for example, Singh (2010).

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varying between 140-2500 percent, for the projects listed. The central objective of this paper, therefore, is to analyze the consequences of implementation delays for public infrastructure in the context of economic growth.

The quantitative importance of public investment for economic growth has been a long-standing subject of economic research, starting with the work of Arrow and Kurz (1970), Aschauer (1989), and Barro (1990), among others.[3] However, a standard assumption in this literature is that public investment *instantaneously* adds to the stock of public capital, so that every unit of GDP spent on infrastructure adds to its stock in the same period. In other words, there are no implementation lags in the canonical model of public investment and growth. Even when a "time to build" feature is incorporated into the framework, as in Leeper et al. (2010), the implementation lag is fully *anticipated* and internalized by private agents, thereby having little or no consequence for the economy's long-run growth path.[4]

In reality however, the implementation (completion) of public infrastructure projects is frequently subject to unanticipated delays and cost overruns. For example, Engerman and Solokoff (2004) find evidence of significant cost overruns for a large number of infrastructure projects in the United States, starting with the construction of the Eerie Canal in the early 19th century. Edwards and Kaeding (2015) review evidence of time and cost overruns for a variety of sectors in the United States, ranging from the International Space Station, hospital construction by the US Department of Veterans Affairs, and the Healthcare.gov website. In many cases, not only have there been unanticipated delays in completing these projects, but these delays have been associated with implementation costs being 75-500 percent higher than their initially planned outlays. Flyvbjerg et al. (2003) and Ansar et al. (2014) document that at a global level, it is common for large infrastructure projects to be associated with cost overruns in the range of 50-100 percent in real terms, predominantly due to unexpected delays in their completion. In a study covering 894 infrastructure projects in India between 1992-2009, Singh (2010) documents an average time overrun (i.e., delay beyond the anticipated completion time) of about 79 percent, with 82 percent of the projects in the sample being subject to unanticipated delays. Sectors such as railways, health, finance, and

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[3]Both the theoretical and empirical literature on this issue is voluminous. On the theoretical front, see Futagami et al. (1993), Glomm and Ravikumar (1994), Turnovsky and Fisher (1995), Turnovsky (1996, 1997), Chatterjee et al. (2003), Rioja (2003), Chatterjee and Turnovsky (2007, 2012), Agenor (2013), and Gibson and Rioja (2016). Gramlich (1994) provides an excellent review of the early empirical literature on this issue, while Bom and Ligthart (2014) conduct an exhaustive meta-analysis of the more recent empircal findings.

[4]The deterministic time-to-build specification, as developed by Kydland and Prescott (1983), and extended to the case of infrastructure spending in Leeper et al. (2010), does have implications for the business cycle, but not for long-run growth. A key difference between our specification and the time-to-build literature is that while infrastructure projects do have a time-to-build component, the completion date for such projects is uncertain, causing delays that go beyond the deterministic time-to-build aspect.

power had cost overruns between 90-300 percent during the sample period.[5] A report by McKinsey & Co.(2009) also finds that about 60 percent of infrastructure projects in India are associated with time and cost overruns. The report estimates that these could result in a GDP loss of USD 200 billion for India in 2017, and a loss of about 1.1 percentage points in the economic growth rate. The underlying reasons for delays in infrastructure projects have been attributed to factors such as imperfect information, technical constraints, corruption, weak institutions, and the political process.[6] However, the *consequences* of unanticipated implementation delays and cost overruns for aggregate consumption, investment, and economic growth have not been studied systematically. To this end, our paper fills an important gap in this literature.

How might delays in the provision of public investment goods affect economic growth and macroeconomic performance? First, if there is uncertainty regarding completion (or implementation), the *arrival* of infrastructure goods becomes a stochastic process. Given the complementary relationship between private investment and public infrastructure in the production function, this generates uncertainty for private allocation decisions. A priori, it is not obvious how private investment might respond to the stochastic and infrequent arrival of public infrastructure goods. On the one hand, the agent might delay the allocation of resources to private investment, since the higher productivity benefits of an infrastructure project can only be realized after it has been implemented. In other words, the presence of uncertainty induces a desire to substitute future private consumption with current consumption, in order to avoid consumption risk in the future (intertemporal substitution effect). On the other hand, given the uncertainty with the arrival of public capital goods, private agents may choose to increase private investment in order to maintain the flow of output. This works through the precautionary savings motive, as the agent might want to build up a "buffer" against lower productivity in the future (due to delays in the arrival of public capital goods). The implications for economic growth will then depend on which of these two effects dominate. Second, if time delays lead to cost overruns, then government spending will have to increase beyond the initially planned outlay for the project, in order to cover the higher cost of implementation. While the higher than anticipated public spending will not lead to a larger than anticipated stock of public capital, it will increase the resource cost of public good provision, and might crowd out private investment. Finally, it is not clear how the presence of delays and the associated cost overruns might affect the first-best outcome for a growing economy, relative to the first-best outcome implied by a standard growth

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[5]Morris (1990, 2003) also provides similar evidence on time delays and cost over-runs for infrastructure projects in India.

[6]See for example, Gaspar and Leite (1989), Pritchett (2000), Flyvbjerg et al. (2002), Ganuza (2007), Cantarelli et al. (2010), and Dabla-Norris et al. (2012).

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model without such delays. Will a social planner allocate more resources to consumption or investment when public goods provision is characterized by delays? This will then have implications for the optimal growth path for an economy.

We address the above issues within a context of a canonical model of endogenous growth where public capital accumulation is an engine of growth, such as in Futagami et al. (1993), Glomm and Ravikumar (1994), and Turnovsky (1997). We introduce into this general framework the stochastic arrival of public capital goods in the form of a Poisson process. Specifically, while the government allocates resources to public investment continuously every period, this spending translates into units of public capital (the relevant input for production) only infrequently, via a stochastic arrival rate. Second, we assume that not all public investment is associated with implementation delays. For example, government spending on goods such as software and equipment may be continuous, while that on structures and R&D may be more prone to delays. As such, this distinction allows us to examine the implications of the *composition* of public investment as it relates to implementation delays.[7] Finally, we also assume that the stochastic arrival of public capital affects the over all resource cost of public investment. Specifically, the cost of implementing public capital in our model depends on (i) the share of government investment subject to delays, and (ii) the arrival rate of public capital goods. This helps characterize the phenomenon of cost overruns caused by implementation delays in the provision of infrastructure. To stress the value-added of our results, we compare at every step the results of our model with those from the canonical growth model without delays. In doing so, we can draw some conclusions on the relative importance of delays in understanding cross-country differences in growth rates and income levels.

Given the lack of systematic data on delays and cost overruns within or across countries, we do not attempt a quantitative exercise that pins down observed moments and correlations in the data. Instead, our aim is to present a plausible numerical characterization of a growing economy and examine how implementation lags and the infrequent arrival of public capital goods affect long-run growth and the economy's transitional adjustment path. We start our analysis by comparing the first-best equilibrium outcomes for the stochastic model specification with delays with those in the canonical deterministic model without delays. The presence of implementation delays and cost overruns leads to a lower level of consumption and public capital (relative to private capital), both in transition and along the optimal balanced growth path, when compared to the corresponding first-best equilibrium of the canonical deterministic model. The social planner, facing the infrequent (and uncertain)

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[7]For example, between 1947-2014 the average share of U.S. government investment spending on structures and R&D was about 68 percent (source: authors' calculations from the NIPA and BEA).

arrival of public capital goods, must continuously allocate resources towards the flow of public investment every period. Given that the flow of public investment does not necessarily translate into new units of public capital every period, the return to private capital declines, thereby reducing the flow of output and consumption. In equilibrium, this is manifested in a lower consumption-to-private capital ratio and public-to-private capital ratio, along with a lower balanced growth rate for the economy. In other words, the presence of implementation lags and the uncertainty associated with the accumulation of the public capital stock significantly alters the characterization of the first-best optimum relative to the canonical model without delays.

We find that in the presence of delays in implementation, the decentralized version of the model implies a higher rate of consumption relative to the first-best rates in both the stochastic and deterministic specifications. This happens because the social planner allocates more resources to private capital (relative to consumption) to offset for the productivity losses due to the infrequent arrival of public capital. Therefore, implementation delays for public capital generates a negative externality for the private sector in a decentralized economy, by generating too much consumption and too little private investment relative to the social optimum. This also leads to a lower equilibrium growth rate in the decentralized model relative to the social optima in both the stochastic and canonical model specifications. This result is interesting along two dimensions. First, the existing literature typically introduces public investment and infrastructure as an engine of long-run growth, by virtue of it being a positive spillover for private capital and labor in the production process. Our results indicate that the presence of implementation lags and the infrequent arrival of public capital generates a negative externality that can more than offset its positive productivity spillover effect. Second, several authors such as Edwards (1990), Barro and Sala-i-Martin (1992), Turnovsky (1996), Eicher and Turnovsky (2000), Chatterjee and Ghosh (2011), and Agenor (2013), among others, have examined the consequences of negative externalities associated with public capital, specifically with respect to congestion. However, in that literature, the presence of a congestion externality increases the long-run growth rate, due to too much private investment and too little consumption, relative to the social optimum. By contrast, our results indicate that delays in the provision of public capital have the opposite effect: higher private consumption, lower private investment and growth relative to the first-best allocation. Finally, we show that the lower long-run (expected) growth path in the stochastic model with delays to be gradually diverging from the one implied by the canonical deterministic model, indicating that the presence of delays and associated cost overruns might be a potential determinant of differences in cross-country income levels and growth rates.

The rest of the paper is organized as follows. Section 2 describes the analytical framework

with time delays and cost overrun for the provision of public capital. Section 3 presents the calibration of the baseline model specification and numerical analysis of its dynamic properties. Section 4 compares the dynamic effects of some counterfactual fiscal policy shocks between the stochastic and deterministic model specifications and, finally, Section 5 concludes.

2 Analytical Framework

We consider a closed economy with a representative household-firm that maximizes utility from consumption over an infinite horizon. The final consumption good is produced using two inputs, namely the stocks of private and public capital. Public capital is provided by the government, and hence generates a productivity spillover for the representative agent. It is also the key source of uncertainty in the model: while the government allocates resources every period to public investment, the timing of its transformation into the stock of public capital is not known to the agent. Since it is the *stock* of public capital that is the relevant input in the production function, rather than the *flow* of government spending, this generates uncertainty for the agent's private allocation and production decisions. By making the "arrival" of public capital goods random, we seek to proxy for the various lags and delays associated with the implementation of government investment programs, while being agnostic to their underlying cause.

2.1 First-Best Equilibrium

We begin our analysis by solving the social planner's problem, and characterizing the economy's first-best optimum. A benevolent planner maximizes the lifetime utility of the agent, given by

$$\mathbb{E}_0 \int_0^\infty e^{-\rho t} u\left(C_t\right) dt, \tag{1}$$

where C_t denotes consumption and $\rho > 0$ is the rate of time preference. The mathematical expectation operator (conditional on the information set at $t = 0$) is denoted by $\mathbb{E}_0$ and $u\left(C_t\right)$ is the agent's utility, specified by the following iso-elastic function

$$u\left(C_t\right) = \frac{C_t^{1-\gamma}}{1-\gamma}, \tag{1a}$$

where γ is the parameter of relative risk aversion, which is also related to the intertemporal elasticity of substitution in consumption, given by $1/\gamma$.

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Output is produced using a Cobb-Douglas production technology

$$Y_t = AK_{G,t}^{\alpha}K_t^{1-\alpha}, \ \alpha \in (0,1) \tag{2}$$

where K_t is the agent's stock of private capital, $K_{G,t}$ represents the stock of public capital, provided by the government (or social planner), and α is the output elasticity of public capital. Private capital accumulates according to

$$dK_t = (I_t - \delta_K K_t)dt, \tag{3}$$

where I_t is the rate of private investment, and $\delta_K \geq 0$ denotes the rate of depreciation of the private capital stock.

The accumulation process for the stock of public capital is given by

$$dK_{G,t} = [\theta G_t - \delta_G K_{G,t}] \, dt + [(1-\theta) \, G_{t-}] \, dN_t, \ \theta \in [0,1] \tag{4a}$$

where $\delta_G \geq 0$ is the depreciation rate for public capital, and the parameter θ represents the share of public investment, G_t, that is *not* subject to implementation lags or delays. In other words, when $\theta = 1$, each unit of the flow of public investment *instantaneously* adds to the accumulating stock of public capital. On the other hand, when $\theta < 1$, then $(1-\theta)$ denotes the share of public investment that adds to the stock of public capital with a delay or lag. While these lags are anticipated, the completion (implementation) date of a given infrastructure project is uncertain, and is modeled through a Poisson process, dN_t, that counts the number of new implementations of public capital with an arrival rate of $\lambda \geq 0$.[8] Therefore,

$$\mathbb{E}_t\left[dK_{G,t}\right] = [(\theta + (1-\theta)\lambda)G_t - \delta_G K_{G,t}] \, dt. \tag{4b}$$

According to (4a) and (4b), some public infrastructure projects, such as bridges, dams, roads, or air or sea-ports require continuous investment spending before completion, i.e., they only contribute to the stock of public capital (and hence production) only at the time they have been successfully implemented. In our specification, this implementation or completion date is random, and serves as the source of uncertainty for private investment decisions. Therefore, (4b) denotes the expected (or average) rate of accumulation of the stock of public capital over time, with these capital goods arriving stochastically at the rate λ. The arrival rate of public capital goods (λ) is an exogenous parameter, which may reflect the underlying strength of the country's institutions, efficiency of the public sector, degree of corruption, etc.

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[8]We define $G_{t-} \equiv \lim_{s \to t} G_s$ for $s < t$ as the left-limit at t. Intuitively, this variable represents the level of government expenditure an instant *before* the successful implementation of a new public capital good.

The term $1/\lambda$ then denotes the *expected* implementation lag for an infrastructure project. For example, if $\lambda = 0.2$, then an economic agent expects a project to be completed in 5 years. Given that the arrival of new public capital goods is modeled as a stochastic process, this implies that the *actual* implementation lag can be different from the expected lag, i.e., more or less than the expected 5 years.[9]

The economy's aggregate resource constraint is given by

$$Y_t = C_t + I_t + G_t. \tag{5}$$

We assume that the rate of public investment, G_t, is proportional to aggregate output, such that $G_t = gY_t$. However, given that the transformation from public investment to public capital is subject to delays, it is plausible that the actual rate of spending, g, is subject to not only time overruns (i.e., unanticipated delays in implementation), but also to cost overruns.[10] To capture this channel, we propose that the share of GDP spent on public investment is a function of both the arrival rate and the composition of public investment subject to delays, such that

$$g \equiv g(\lambda, \theta) = \frac{\bar{g}}{\theta + (1-\theta)\lambda}, \tag{6}$$

where $\bar{g}$ is the baseline or planned spending on public investment. For $\theta + (1-\theta)\lambda < 1$, the actual rate of spending will exceed the planned rate, i.e., $g > \bar{g}$. When $\theta = 1$, government spending is not subject to implementation delays, and $g = \bar{g}$. Additionally, when $\lambda = 1$, i.e., a public capital good is installed every period (consistent with the flow of public investment in that period), the actual and planned rates of government spending coincide. Our specification of g therefore captures the fact that longer implementation lags are typically associated with higher costs of provision. As we will argue below, empirically the most plausible scenario is $0 < \lambda \ll 1$. We can then express (3) as

$$dK_t = \left[\{1 - g(\lambda, \theta)\} AK_{G,t}^{\alpha} K_t^{1-\alpha} - C_t - \delta_K K_t \right] dt. \tag{7}$$

The social planner maximizes (1) subject to (4a) and (7). Defining the value function by

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[9]In the limit, if $\lambda \to \infty$, then the actual cost of government investment in infrastructure, $g \to 0$. In this case the expected duration of implementation of a project approaches zero, $1/\lambda \to 0$, i.e., the implementation of public infrastructure takes place instantaneously.

[10]Singh (2010) defines "time overrun" as the difference between the actual and planned (expected) date of completion of a project. Similarly, "cost overrun" is defined as the difference between the actual and planned outlay for a project.

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$V\left(K_t, K_{G,t}\right)$, we can write the corresponding optimization problem as

$$\rho V\left(K_t, K_{G,t}\right) = \max_{C_t \in \mathbb{R}_+}\left\{u\left(C_t\right) + \frac{1}{dt}\mathbb{E}_t dV\left(K_t, K_{G,t}\right)\right\}, \tag{8a}$$

subject to

$$dK_t = \left[(1-g)AK_{G,t}^\alpha K_t^{1-\alpha} - C_t - \delta_K K_t\right]dt, \tag{8b}$$

$$dK_{G,t} = \left[\theta g AK_{G,t}^\alpha K_t^{1-\alpha} - \delta_G K_{G,t}\right]dt + \left[(1-\theta)g AK_{G,t-}^\alpha K_{t-}^{1-\alpha}\right]dN_t, \tag{8c}$$

along with given initial conditions for the stocks of private and public capital, i.e., K_0 and $K_{G,0}$, respectively. Note that, in (8c), the variables $K_{G,t-}$ and K_{t-} denote the levels of the stocks of public and private capital, respectively, an instant before the arrival of a new public capital good.

We express the macroeconomic equilibrium in terms of the following stationary variables

$$z_t \equiv \frac{K_{G,t}}{K_t}, \quad q_t \equiv \frac{V_{K_{G,t}}}{V_{K,t}}, \quad \text{and} \quad c_t \equiv \frac{C_t}{K_t}, \tag{9}$$

where z_t is the ratio of public to private capital, q_t is the ratio of the shadow price of the two capital stocks (co-state variables), and c_t is the consumption-private capital ratio. The equilibrium dynamics can be expressed as[11]

$$\frac{dz_t}{z_{t-}} = \left[\left\{\theta g Az_t^{\alpha-1} - \delta_G\right\} - \left\{(1-g)Az_t^\alpha - c_t - \delta_K\right\}\right]dt + [\hat{z}_{t-} - 1]dN_t, \tag{10a}$$

$$\frac{dq_t}{q_{t-}} = \left[\begin{array}{c}\left(\rho - \theta g\alpha Az_t^{\alpha-1} + \delta_G\right) - \left(\rho - (1-g)(1-\alpha)Az_t^\alpha + \delta_K\right) \\ +\lambda\left\{1 + ((1-\theta)(1-\alpha)gAz_t^\alpha)q_t - \left(1 + (1-\theta)\alpha gAz_t^{\alpha-1}\right)\hat{q}_t\right\}\hat{c}_t^{-\gamma} \\ +q_t\theta g A(1-\alpha)z_t^\alpha - \alpha A(1-g)z_t^{\alpha-1}/q_t\end{array}\right]dt$$
$$+\left[\hat{q}_{t-} - 1\right]dN_t, \tag{10b}$$

$$\frac{dc_t}{c_{t-}} = \frac{1}{\gamma}\left[\begin{array}{c}\left\{(1-g)(1-\alpha-\gamma) + \theta g(1-\alpha)q_t\right\}Az_t^\alpha - \left\{\rho + (1-\gamma)\delta_K\right\} \\ +\lambda\left\{\left(1 + q_t\left((1-\alpha)(1-\theta)gAz_t^\alpha\right)\hat{c}_t^{-\gamma} - 1\right)\right\} + \gamma c_t\end{array}\right]dt$$
$$+\left[\hat{c}_{t-} - 1\right]dN_t, \tag{10c}$$

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[11]The details of the derivations are available from the authors on request.

where

$$\hat{z}_{t-} = 1 + (1 - \theta) \, g A z_{t-}^{\alpha-1}, \tag{11a}$$

$$\hat{c}_{t-} = \frac{c\left(K_{t-}, K_{G,t-} \left(1 + gA(K_{G,t-}/K_{t-})^{\alpha-1}\right)\right)}{c\left(K_{t-}, K_{G,t-}\right)}, \tag{11b}$$

$$\hat{q}_{t-} = \frac{q\left(K_{t-}, K_{G,t-} \left(1 + gA(K_{G,t-}/K_{t-})^{\alpha-1}\right)\right)}{q\left(K_{t-}, K_{G,t-}\right)}, \tag{11c}$$

denote the "jump" in the public to private capital ratio, the consumption-private capital ratio and the ratio of shadow prices an instant after the successful implementation of a public capital project, i.e., following the arrival of a Poisson shock. Then, the quantities $(\hat{z}_t - 1)$, $(\hat{q}_t - 1)$, and $(\hat{c}_t - 1)$ denote the percentage deviations of z_t, q_t, and c_t following a successful implementation. The (stochastic) steady-state is attained when $dz_t = dq_t = dc_t = dN_t = 0$, and the economy is on a stochastic balanced growth path, given by[12]

$$\tilde{\phi} \equiv \theta g A \tilde{z}^{\alpha-1} - \delta_G = (1 - g) \, A \tilde{z}^{\alpha} - \tilde{c} - \delta_K, \tag{12}$$

where $\tilde{z}$ and $\tilde{c}$ denote the stochastic steady-state levels of the ratio of public to private capital and the consumption-capital ratio, respectively. The dynamic evolution of the economy, as described in (1)-(12) nests two special cases:

(i) $\theta = 1$: there are no implementation lags for public investment, and hence no uncertainty in the model specification. This case represents the canonical deterministic growth model with public capital, as in Futagami et al. (1993), Glomm and Ravikumar (1993), Turnovsky (1997), and Rioja (2003), among others.

(ii) $\theta = 0$: the entire flow of public investment is subject to implementation delays, making the accumulation of public capital a fully stochastic process. This specification generates the highest level of uncertainty for the private agent's resource allocation decision.

2.2 Decentralized Equilibrium

The decentralized version of the model involves the representative agent making resource allocation decisions, while taking the level and stochastic process for public capital accumulation as exogenously given. The government plays a passive role in this version, by issuing debt and raising tax revenues to finance public investment. The representative

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[12]The stochastic steady state is a distribution that characterizes the economy at a point in time when there are no realizations of shocks. This point is also sometimes referred to in the literature as the "risky" or "conditional deterministic" steady-state; See for, example, Juillard and Kamenik (2005) and Coeurdacier et al. (2011).

agent maximizes lifetime utility according to

$$\mathbb{E}_0 \int_0^\infty u\left(C_t\right) e^{-\rho t} dt, \tag{13}$$

with the instantaneous utility function given by (1a). The agent's maximization problem is subject to the following flow budget constraint

$$dK_t + dB_t = \left[(1 - \tau_y)\left[Y_t + r_t B_t\right] - C_t - T_t\right] dt, \tag{14}$$

where B_t is the agent's holding of government bonds, which pay a return of r_t each period. The tax rate on capital and bond income is taxed at the rate τ_y, and T_t is a lump-sum tax.

The representative agent's resource allocation problem in the decentralized economy is given by

$$\rho V\left(K_t, B_t\right) = \max_{C_t \in \mathbb{R}_+, I_t \in \mathbb{R}_+} \left\{ u\left(C_t\right) + \frac{1}{dt}\mathbb{E}_t dV\left(K_t, B_t\right) \right\}, \tag{15}$$

subject to

$$dK_t = \left[I_t - \delta_K K_t\right] dt, \tag{16a}$$

$$dK_t + dB_t = \left[(1 - \tau_y)\left[Y_t + r_t B_t\right] - C_t - T_t\right] dt, \tag{16b}$$

along with the initial conditions on the state variables, K_0 and B_0.

The stock of public capital accumulates according to

$$dK_{G,t} = \left[\theta g A K_{G,t}^\alpha K_t^{1-\alpha} - \delta_G K_{G,t}\right] dt + \left[(1 - \theta)g A K_{G,t-}^\alpha K_{t-}^{1-\alpha}\right] dN_t. \tag{17}$$

The government finances its per-period spending on public capital, G_t, by using tax revenues and debt-financing:

$$dB_t = \left[G_t + (1 - \tau_y) r_t B_t - \tau_y Y_t - T_t\right] dt. \tag{18}$$

Combining (14) and (18) leads to the economy's aggregate resource constraint

$$Y_t = C_t + I_t + G_t. \tag{19}$$

In the decentralized economy, the representative agent's resource allocation problem treats the relationships in (17)-(19) as given. The corresponding equilibrium dynamics, expressed

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in terms of the stationary variables $z_t = K_{G,t}/K_t$ and $c_t = C_t/K_t$, are given by

$$\frac{dz_t}{z_{t-}} = \left[\theta g A z_t^{\alpha-1} - \delta_G - (1-g) A z_t^\alpha + c_t + \delta_K \right] dt + \left[(1-\theta) g A \hat{z}_{t-}^{\alpha-1} \right] dN_t, \quad (20a)$$

$$\frac{dc_t}{c_t} = \left[\frac{(1-\tau_y)\left((1-\alpha) A z_t^\alpha - \delta_K\right) - \rho}{\gamma} - (1-g) A z_t^\alpha + c_t + \delta_K \right] dt. \quad (20b)$$

As before, the economy attains a (stochastic) steady-state when $dz_t = dc_t = dN_t = 0$, while converging to a stochastic balanced growth path. The key difference between the decentralized and the social planner's equilibrium is that the evolution of the relative shadow price of public capital is not internalized in the decentralized specification, and is therefore not a part of the macro-dynamic equilibrium.

3   Numerical Analysis

We now proceed to a numerical exposition of the analytical model's mechanism and implications. Given the paucity of systematic data on implementation lags and associated cost overruns for infrastructure projects both across and within countries, we do not attempt a full quantitative exercise that matches the moments for a specific or set of countries. Instead, our objective is to present a plausible calibration for a growing economy, with a focus on the model's underlying mechanisms. Table 2 presents the parameterization of our model specification, evaluated at an annual frequency. The rate of time preference, ρ, is set to yield an annual interest rate of 3 percent, while the parameter γ is set to 2.5 to generate an intertemporal elasticity of substitution in consumption of 0.4, consistent with the evidence reviewed by Guvenen (2006). The output elasticity of public capital is set to 0.15, which is the average value estimated in the meta-analysis by Bom and Ligthart (2014). The rate of depreciation of private capital is set at 5 percent, following the evidence in Schündeln (2013). The depreciation rate for public infrastructure is set at a lower rate of 2 percent, following the evidence in Arslanalp et al. (2010). The 2014 World Economic Outlook (WEO) reports that the average share of public investment in GDP for advanced economies was about 3.5 percent between 1970-2011. On the other hand, the corresponding share of developing economies and emerging markets was about 8 percent. We assume that the planned outlay for public investment, $\bar{g}$, is 5 percent of GDP, which is within the range reported by the WEO (2014). According to the IMF's Fiscal Monitor Database, the share of government tax revenues in GDP varies between 18 percent for developing countries to about 37 percent for advanced economies. We therefore set the income tax rate, τ_y, at an intermediate value of 25 percent. The productivity parameter, A, is set to 0.5, to ensure a plausible long-run
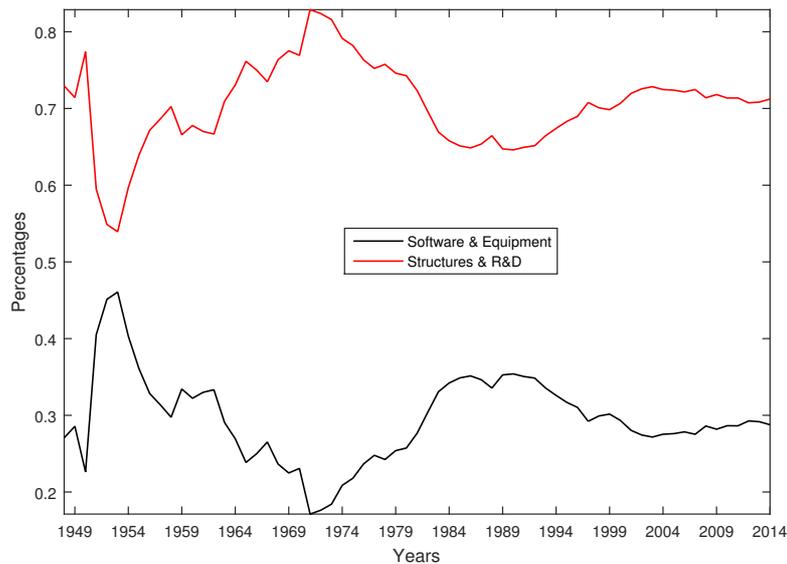
Figure 1: Composition of Government Investment Expenditures, United States, 1947-2014.

growth rate for the economy.

The two remaining parameters to be set are θ, the share of government investment that is not subject to delays, and λ, the frequency with which public capital is implemented. For θ, we take the United States as a baseline example, mainly to understand how implementation delays for public investment affect a frontier economy. Specifically, we use data from the Bureau of Economic Analysis' National Income and Product Accounts (NIPA) to classify government investment into two broad categories, namely (i) software and equipment, and (ii) structures and research & development (R&D). Figure 1 plots the share of government investment for these two categories (software and equipment-black line, and structures and R&D-red line) for the period 1947-2014.

Our working assumption is that while investment in software and equipment increases the government's capital stock without a lag (within the same year), investment in structures and R&D are associated with implementation lags (delays). We therefore set θ to equal the average share of public investment in software and equipment during this period, which is about 32 percent. This implies that 68 percent of public investment in our model is subject to implementation lags.

The next step is to calibrate the arrival rate of public capital goods, λ. The literature on the "time overrun" of investment projects is sparse. Sovacool et al. (2014) present results for the time and cost overrun of electricity projects in a world-wide sample. They report average time overruns between 0 and 4 years. The Ministry of Statistics and Program

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Implementation in India reports that about 251 projects in various sectors such as atomic energy, civil aviation, railways, and road and transport, among others, were delayed between 1 and 5 years in 2011. Morris (2003), analyzing 1,529 infrastructure projects between 1986-1998, reports time overruns in the range of 2.3 to 5.1 years. Using this information, we set $\lambda = 0.2$, implying that the expected arrival rate of an infrastructure project is once every 5 years. Given the lack of systematic data on both the share of government investment not subject to delays (θ), and the arrival rate of public capital (λ), we conduct a sensitivity analysis for both these parameters in Section 3.2.

TABLE 2. Benchmark Calibration

Parameter	Description	Value
α	Output elasticity of public capital	0.15
ρ	Rate of time preference	0.03
$1/\gamma$	Elasticity of substitution in consumption	0.4
A	Productivity index	0.5
$\bar{g}$	Share of public investment in GDP	0.05
δ_K	Rate of depreciation-Private capital	0.05
δ_G	Rate of depreciation-Public capital	0.02
θ	Share of public investment without delays	0.32
λ	Arrival rate of public capital	0.2
τ_y	Income tax rate	0.25

3.1 Benchmark Equilibrium

Table 3 describes the benchmark equilibrium for three model specifications, namely the first-best allocation in the deterministic version of the benchmark model, and the first-best and decentralized allocations for the stochastic model with delays ($\theta = 0.32$ and $\lambda = 0.2$). It is important to note here that the first-best solution to the deterministic version of the model is essentially the canonical growth model with no delays in the public capital accumulation process, as in Turnovsky (1997). Specifically, we focus on three observable quantities: the consumption-output ratio, the capital-output ratio, and the equilibrium (balanced) growth rate.[13] For the stochastic version of the model specification, the steady-state quantities are obtained by simulating the model for 500 years, and averaging over 500 simulations. Even though the objective of our numerical exercise is not intended to match moments for a specific country, but rather to focus on the mechanisms of the underlying model, we present a comparison of the equilibrium generated by the different model specifications with the

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[13]The capital-output ratio is defined as $(K + K_G)/Y$.

corresponding averages for the United States, for the period 1947-2014.[14]

TABLE 3. Equilibrium (Steady-State) Allocations

	First-best Canonical	First-best Stochastic	Decentralized Stochastic	U.S. Data 1947-2014
C/Y	0.56	0.55	0.64	0.64
$(K + K_G)/Y$	2.63	2.96	2.53	2.84
Ψ	4.96	3.94	3.72	3.20

The existence of delays in the implementation of public capital leads to different first-best allocations for the deterministic and stochastic models. For example, the first-best solution in the stochastic framework with delays implies a lower consumption-output ratio and higher capital-output ratio, along with a lower equilibrium growth rate relative to the canonical deterministic model without delays. The delay in the arrival or implementation of public capital leads the social planner to reallocate resources away from consumption towards private investment, in order to maintain an optimal flow of output. Consequently, this raises the capital-output ratio relative to the deterministic model. It is also interesting to note that the stochastic decentralized model with delays generates an equilibrium allocation with a consumption-output ratio that exceeds its corresponding first-best allocation, and a capital-output ratio and equilibrium growth rate that is below their corresponding first-best levels. Therefore, implementation delays for public capital generates an externality for the private agent's resource allocation problem, leading to "too much" consumption and "too little" capital (and economic growth) relative to the stochastic first best equilibrium. We also find that the deterministic canonical model, by not incorporating time and cost overruns in the provision of public capital, significantly overstates the economic growth rate relative to the stochastic specification. This also suggests that the presence of implementation delays for public capital can be a source of cross-country difference in both income levels and growth rates.

The steady-state comparisons in Table 3 highlight a previously unexplored channel through which the provision of a productive public good might affect aggregate economic activity. In models such as this, public investment (or capital) enters the aggregate production function as a positive spillover for private capital. As such, its role is to enhance the marginal product of private factors of production and increase economic growth. Our results indicate that the presence of implementation lags and uncertainty regarding the arrival of public capital

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[14] The averages for U.S. data in Table 3 were calculated from the NIPA Tables (Bureau of Economic Analysis), the Federal Reserve Economic Database (FRED), and the Penn World Tables (PWT 9.0).

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goods can generate a negative externality which can lower the equilibrium growth rate, both at the social optimum as well as in the decentralized version of the model. Further, there is substantial literature on public investment and growth that focuses on negative externalities associated with public infrastructure provision such as congestion. In the presence of congestion, the decentralized and deterministic version of the model would imply "too much" private investment (and higher economic growth) and "too little" consumption, relative to the deterministic first-best equilibrium. By contrast, in the presence of delays, we obtain the opposite result, with private agents reallocating resources away from private investment and towards consumption. This, in turn, leads to an equilibrium growth rate that is lower than optimal.

3.2 Policy Functions

In this section, we characterize the model's dynamic properties. To do so, we use the waveform relaxation algorithm suggested by Posch and Trimborn (2013), which numerically computes the transition process in dynamic models with Poisson shocks. Technically, the system of stochastic differential equations (SDE) is transformed into a system of retarded functional differential equations. Then, a waveform relaxation algorithm is used which involves an initial guess of the policy function, and then a solution to the system of deterministic ordinary difference equations using existing methods.

Figure 2 illustrates the policy functions (or saddle paths) for the three model specifications from Table 3, namely the (i) first-best solution to the deterministic (canonical) model (red plot), (ii) first-best solution to the stochastic model with delays (blue dashed plot), and (iii) decentralized solution to the stochastic model with delays (black dashed plot). Specifically, we plot the joint evolution of the consumption-private capital ratio and the ratio of public to private capital, with points on these loci marked with "×" denoting the respective steady-states for each model specification.

We start with a comparison of the first-best equilibria between the canonical deterministic model and the stochastic model with delays. The presence of uncertainty associated with the implementation lag for public capital lowers both the optimal consumption-private capital and public-private capital ratios relative to the first-best equilibrium in the canonical deterministic model. This happens because the delays in the implementation of public capital imply that the social planner has to wait intermittently for new public capital goods to arrive in the stochastic model specification, while at the same time continuously allocating the economy's final output to expenditure on public investment. Moreover, the infrequent arrival of public capital leads to a lower accumulated stock of infrastructure in equilibrium
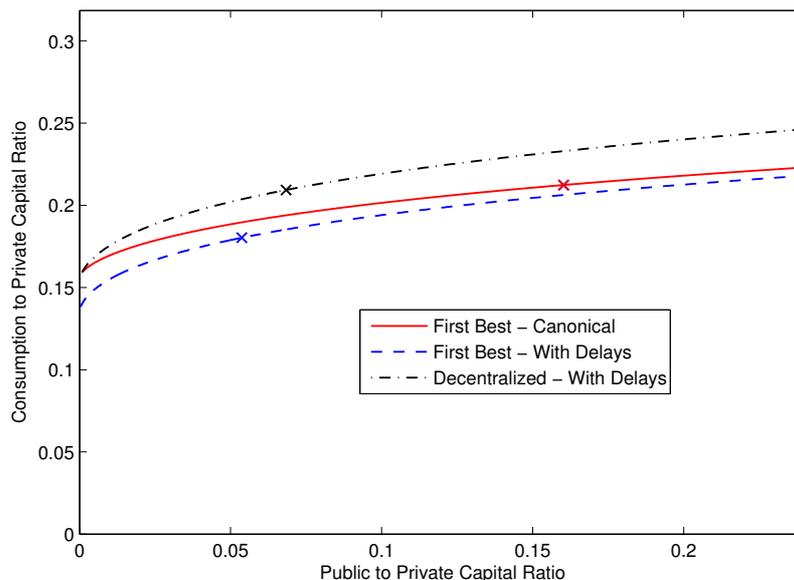
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Figure 2: Policy Functions and Steady-State (Baseline Model).

relative to the deterministic model, despite similar planned outlays for public investment across the two specifications. Consequently, private capital is less productive in the model with delays, thereby leading to lower consumption and, ultimately, long-run growth.[15]

Comparing the first-best and decentralized equilibria for the stochastic model with delays in Figure 2, we find that the private agent allocates "too much" resources to private consumption and "too little" to private investment relative to the first-best optimum, in the presence of unexpected delays in the provision of public capital. Unlike the social planner, the private agent takes the rate of investment in public capital as given, and therefore does not internalize the evolution of its shadow price. The delayed arrival of public capital lowers the expected return from private investment for the agent, leading to a reallocation of resources towards consumption. In equilibrium, this lowers the long-run growth rate relative to the social optimum (see Table 3).

An important aspect of the model that guides the steady-state outcomes are the values of θ and λ, which are the shares of public investment not subject to implementation delays, and the arrival rate of public capital, respectively. To see how these parameters affect the steady-state, Figures 3 and 4 plot the stochastic policy function for the first-best equilibrium

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[15]Public capital accumulation in an environment with delays is expected at a lower rate. Precisely, this rate is $\theta + (1 - \theta)\lambda < 1$. If government spending was not subject to delays, i.e., $\theta = 1$, then this expected rate would imply that a new public capital good is installed once every year, consistent with the annual flow of public investment. Analogously, $\lambda = 1$ would also lead to the same outcome.

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for the following cases:

(i) $\theta = 0.1, 0.32$, and 1 (Figure 3). When $\theta = 0.1$, 90 percent of the flow of public investment is subject to delays, and when $\theta = 1$, there are no delays in the implementation of public capital (each year's spending results in a new unit of public capital in the same year).

(ii) $\lambda = 0.01$, 0.2, and 0.6 (Figure 4). Specifically, $\lambda = 0.6$ implies public capital is implemented, on average, once every 1.67 years, while $\lambda = 0.01$ implies an average implementation frequency of 100 years. Recall that $\lambda = 0.2$ is our benchmark case, with public capital arriving once every 5 years.

As can be seen from Figure 3, larger the share of public investment that is *not* subject to delays, i.e., as $\theta \to 1$, the higher are the steady-state levels of consumption and public capital, relative to private capital. In other words, as θ increases, it offsets the uncertainty with respect to implementation delays, i.e., a lower share of public investment is subject to unanticipated delays, which in turn reduces the adverse effects of delays on the return on private capital. Ultimately, this permits higher rates of consumption and output growth in equilibrium.

From Figure 4, we see that as λ increases, i.e., an increase in the frequency with which public capital is implemented, both the steady-state ratio of public capital and the consumption-capital ratio increase: more frequent implementation of public capital raises not only the aggregate stock of public capital over time, but also the return on private capital and consumption.

3.3   Transition Paths

In this section, we present a time series simulation of the decentralized versions of the deterministic and stochastic model specifications over a span of 60 years. Both specifications have identical planned annual rates of public investment (set at the benchmark rate of 5 percent of GDP per year). In the deterministic model (without implementation lags), each unit of GDP spent on public investment increases the stock of public capital in the same period (set $\lambda = 1$ in (4b)). By contrast, in the stochastic model, the stock of public capital is expected to increase once every 5 years (with $\theta = 0.32$ and $\lambda = 0.2$), with actual expenditures on public investment exceeding their planned outlays, according to (6). Therefore, over a 60-year period, private agents expect new public capital to arrive 12 times, even though the actual realization of this shock may be different from the rate expected. The transition paths for the key macroeconomic aggregates and growth rates for the two models are illustrated in Figure 5. The red dashed lines represent the deterministic model without delays, while
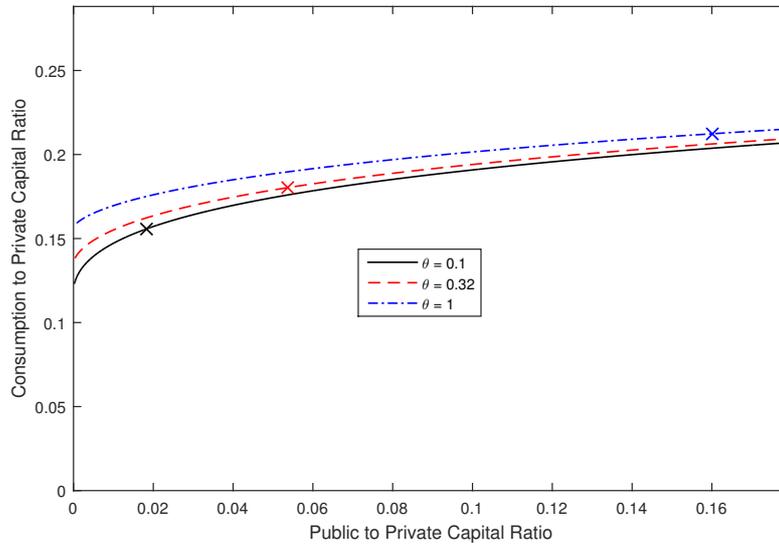
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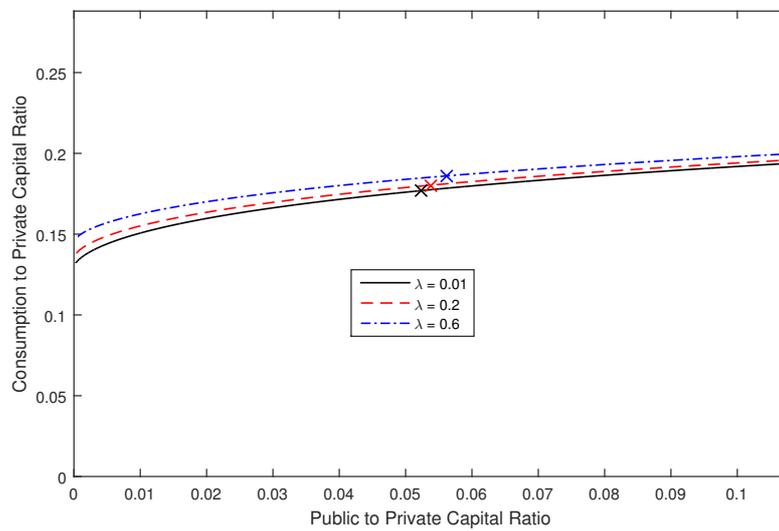
Figure 3: Policy Functions and θ (First-best Equilibria).

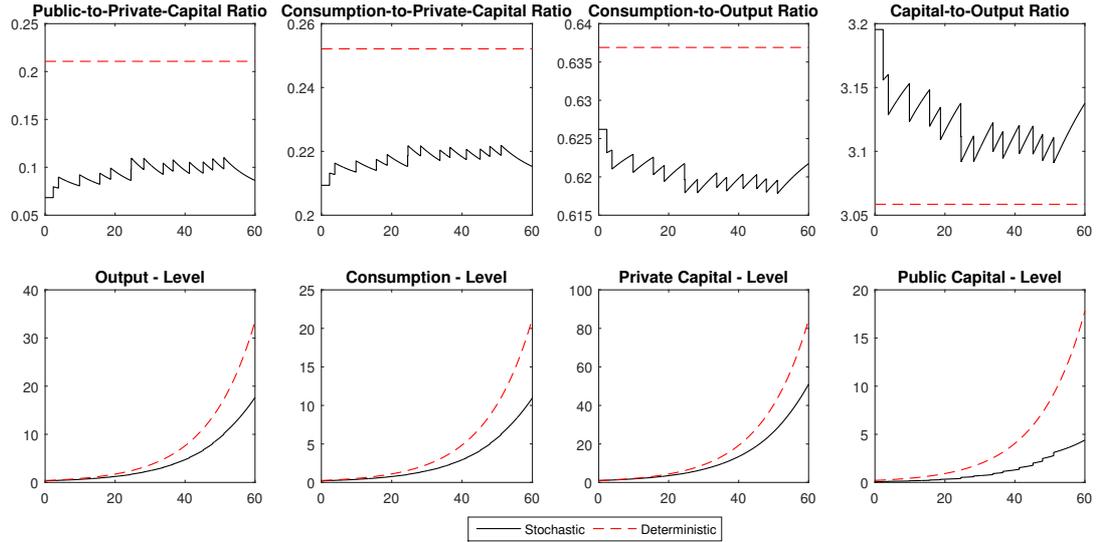Figure 4: Policy Functions and λ (First-Best Equilibria).

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Figure 5: Transition Paths: Deterministic and Stochastic Models.

the solid black line denotes the stochastic model with delays.

For the deterministic model, since there are no delays in the implementation of public capital and the rate of public investment does not change over the time horizon considered, the key macroeconomic ratios (first row of Figure 5) remain at their stationary steady state levels, while the non-stationary paths for output, consumption, private and public capital display exponential growth along the balanced growth path. By contrast, in the stochastic model the ratios of the macroeconomic aggregates jump each time a new unit of public capital is implemented. Note that even though the average frequency of the arrival of new units of public capital is known to the private agent, their actual realization is unanticipated. In general, the presence of delays raises the capital-output ratio, but lowers the rate of consumption and public capital (relative to private capital) along the transition path. The second row of Figure 5 depicts how the presence of implementation delays affect the growth paths between the two models: over time, the infrequent arrival of public capital not only leads to a lower equilibrium growth path, but also creates a divergence in the time paths of output, consumption, and the two capital stocks relative to the deterministic model. This suggests that the presence of delays in the arrival of public capital might be a potential source of cross-country divergence of per-capita income across countries, even when planned expenditures on public investment are identical across countries.

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4 Fiscal Policy Shocks

We consider two counterfactual policy experiments in this section, namely (i) an increase in the planned outlay on public investment, $\bar{g}$, and (ii) an increase in the income tax rate, τ_y. Specifically, we consider two scenarios for each shock for the decentralized stochastic model with implementation delays. We first consider a version of the model with no policy change, i.e., public capital arrives at the stochastic rate of λ, with no other changes in the policy variables. Next, we introduce a fiscal shock into the benchmark model, keeping the arrival rate λ unchanged, and compare the dynamic response of the economy in the two scenarios. Additionally, we also decouple the consequences of time and cost overruns in the case where government spending on public investment increases.

4.1 Increase in Public Investment

In this section, we consider an increase in the planned outlay for public investment, $\bar{g}$, from its baseline rate of 5% to 8% of GDP.[16] Figure 6 plots the simulated time series of the key macroeconomic variables over 60 years with (black) and without the policy change (red dashed), conditional on the same realization of Poisson shocks, i.e., keeping λ unchanged.

An increase in the rate of public investment, $\bar{g}$, increases the jump size of the Poisson shocks (i.e., the size of the public capital stock). This is visible, for example, in the time series for the public capital stock (bottom right panel). This raises output in the simulation with the policy shock relative to the simulation without the shock, thereby lowering the capital-output and consumption-output ratios, and raising the equilibrium growth rate. Given the exponential growth property of the underlying model, these small initial differences accumulate over time and lead to increasing differences in the time path of the public capital stock and, consequently, other macro variables like output, consumption, and private capital.

4.1.1 Time Delay versus Cost Overrun

A related issue in this context is how time and cost overruns influence the dynamic response to an increase in public investment spending. As discussed in (6), total government spending

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[16]The increase in the rate of new public investment considered in this section is consistent with recent trends in many emerging market economies. For example, the Planning Commission of India reports that the share of total infrastructure spending in GDP rose from about 5 percent in 2006 to 8 percent in 2011, with this share expected to rise to 11 percent by 2017; See the discussion in Chatterjee and Mursagulov (2016) and Chatterjee and Narayanan (2016).
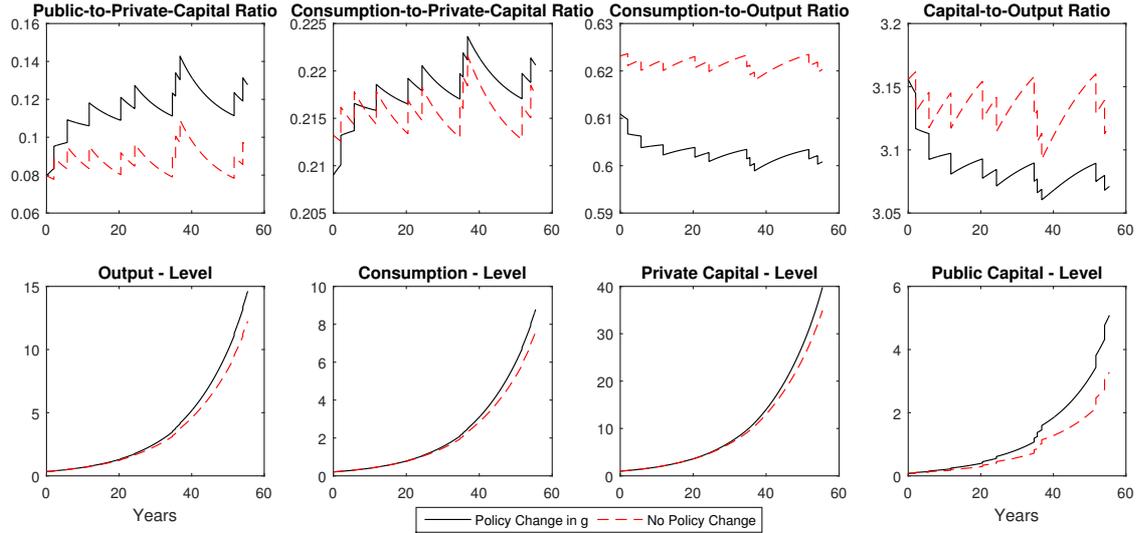
Figure 6: Increase in Public Spending ($\bar{g}$).

on public investment is a markup over its initially planned outlay:

$$g = \frac{\bar{g}}{\theta + (1-\theta)\lambda},$$

with the markup reflecting the cost overrun generated by implementation delays. To decouple the effects of cost and time overruns, we simulate the dynamic response of the economy to an increase in government spending $\bar{g}$ in two scenarios: (i) in the presence of a cost overrun, i.e., $g > \bar{g}$, according to (6), and (ii) in the presence of *only* an implementation delay, so that $g = \bar{g}$. Figure 7 plots the transitional responses for these cases. The presence of the cost overrun channel associated with delays implies that installing a unit of public capital has a higher underlying resource cost which, in turn, crowds out private investment and lowers output and consumption. The presence of the cost overrun channel also reduces the long-run growth rate relative to a specification where delays are present but not associated with higher implementation costs.

4.2 Increase in the Income Tax Rate

In this policy experiment, we consider a permanent increase in the income tax rate, from its benchmark level of 25% to 30%. As before, we compare the transitional paths for the stochastic model without a tax change with those generated by the tax change.

Figure 8 plots the simulated time series of key variables over 60 years with (black) and without the tax change (red dashed), conditional on the same realization of Poisson shocks
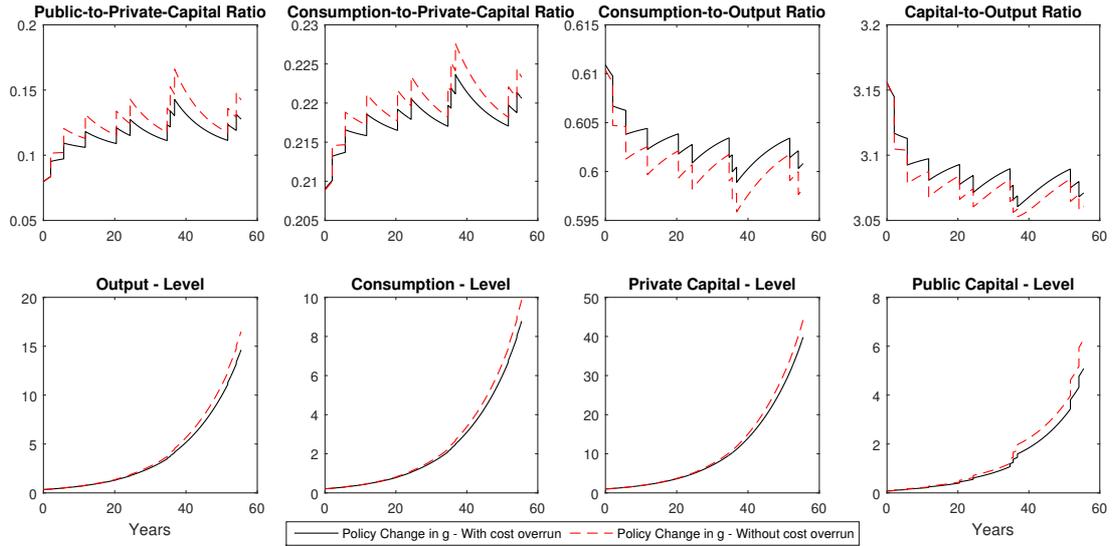
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Figure 7: Increase in Public Investment: Time Delays vs. Cost Overrun.

(λ) that we have used in the previous sections. Since the higher tax rate lowers the after-tax return on private capital, the private agent reallocates resources away from investment and into consumption. This leads to an increase in the ratio of public-to-private-capital over time, with this ratio jumping up each instant a new public capital good arrives. Consequently, the consumption-capital ratio is higher than if there were no tax increase. The higher tax rate and the resulting decline in the rate of private investment lowers the growth rate of output and other macro variables.

5 Conclusions

In this paper we have analyzed an ubiquitous issue related to the provision of public infrastructure, namely unexpected delays in implementation, and the associated escalation of costs. While the existing public investment-growth literature assumes that every unit of public investment contributes concurrently to the accumulating stock of public capital, a large number of country-specific case studies have documented the presence of significant time and cost overruns for infrastructure projects, both in developed and developing countries. Our objective in this paper is to demonstrate how these overruns affect the equilibrium outcomes and dynamics of a canonical model of endogenous growth. In doing so, we not only illustrate how unanticipated delays in the provision of public goods may be modeled in a dynamic context, but also highlight how this previously unexplored channel may be a potential determinant of cross-country differences in per-capita income and economic growth.
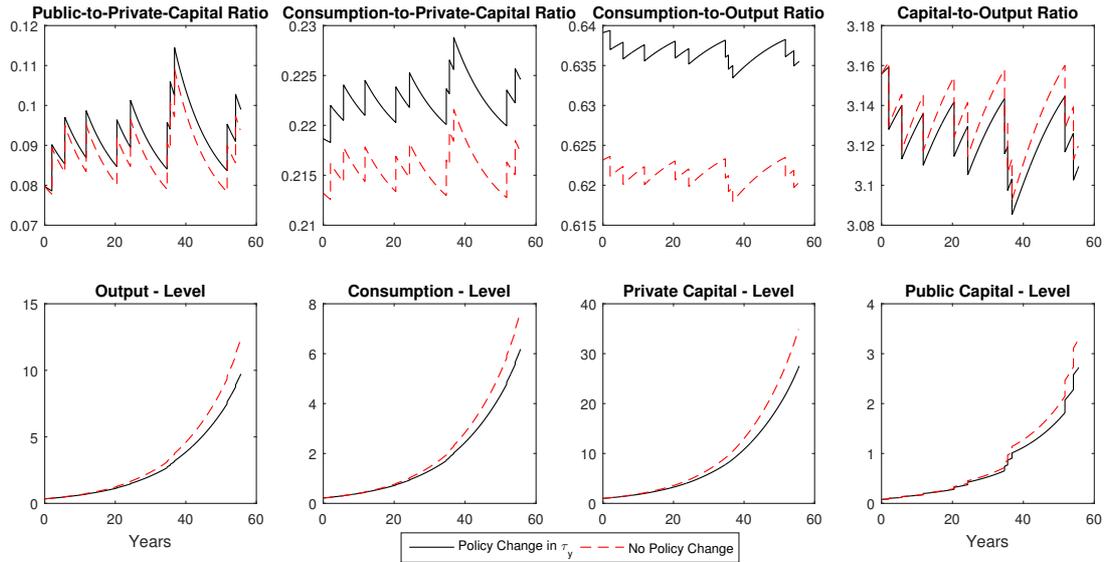
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Figure 8: Increase in the Income Tax Rate (τ_y).

Our results indicate that the presence of unanticipated time and cost overruns generate too much consumption and too little private investment relative to the social optimum. This further leads to a higher capital-output ratio and lower equilibrium growth compared to the social optimum. On the other hand, the social planner, facing an infrequent arrival rate of public capital goods, must allocate resources away from private consumption into private investment in order to maintain an optimal flow of output. Comparing the first-best outcomes for the model with delays with those in the canonical deterministic model, we find that the presence of delays lowers both the optimal rate of consumption and investment and, hence, economic growth. Therefore, time and cost overruns might be a potential source of differences in growth rates and income levels across countries.

We end with a caveat. The lack of systematic data across countries on time and cost overruns for infrastructure provision did not permit us to conduct a quantitative exercise where the model can be mapped closely to the data. Instead, our focus has been on understanding the channel through which delays in public good provision affect economic growth and macroeconomic performance. There are other issues we have left unexplored in this paper, such as those related to the implications of delays for the labor market, as well as for the understanding of poverty traps in the process of economic development. We hope to pursue these ideas in future research.

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6 Appendix

Source of implementation delays

- Udhampur-Srinagar-Baramulla Line, Bankura-Damodar Line, Belapur Electrified Double Line

    - Salunkhe, A. A. and Patil, R. S., 2014. "Effect of Construction Delays on Project Time Overrun: Indian Scenario." *IJRET*, 3(1): 543-547

- Big Dig, Boston

    - https://www.bostonglobe.com/magazine/2015/12/29/years-later-did-big-dig-

- San Francisco Bay Bridge

    - http://www.citylab.com/politics/2015/10/from-250-million-to-65-billion-the-bay-bridge-cost-overrun/410254/

- Orlando VA Medical Facility

    - http://www.gao.gov/assets/670/669833.pdf

- Berlin International Airport

    - https://www.bloomberg.com/news/features/2015-07-23/how-berlin-s-futuristic-airport-became-a-6-billion-embarrassment

- Flamanville 3 Nuclear Power Plant

    - http://uk.reuters.com/article/edf-nuclear-flamanville-idUKL5N1190M820150903

- Olkiluoto Nuclear Power Plant

    - http://energypost.eu/epr-nuclear-reactor-fit-current-market/